Academy of Finland

TUKEVA

Research Programme on Future Mechanical Engineering

2000 - 2003

FINAL REPORT

TEKES

Työsuojelurahasto
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The Finnish Work Environment Fund

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TUKEVA

Research Programme on Future Mechanical Engineering 2000 - 2003

FINAL REPORT

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EXECUTIVE SUMMARY

The Finnish mechanical engineering industry enjoys a strong and leading market position in some special areas of the industry world wide. As an export oriented industry it has a key role in the economy of Finland. Mechanical engineering industry has a strong and experienced network of subcontractors and suppliers. The cross value (year 2002) of the mechanical engineering industry was 18 billion € and export 9.4 billion €, the industry employed 133 000 people.

The R&D activity of the industry is supported by universities and research institutes. The global position of the Finnish mechanical engineering is based on the product and process know-how of the companies and the active product development. The cooperation between companies and universities and institutes has been good and beneficial.

The public support for research and development of the industry has been mainly provided by the National Technology Agency, Tekes. For some time it has been realised not only by the researchers, but also by the industry, that the applied research and development oriented funding by Tekes is not enough to guarantee the basic knowledge necessary in the further development of mechanical engineering. On this background the Academy of Finland decided to launch its first research programme in mechanical engineering, the Research Programme on Future Mechanical Engineering (TUKEVA) for the years 2000-2003. The aim of the programme has been the basic research for mechanical engineering and the researcher training.

TUKEVA research programme covers a wide range of engineering research and is very multitechnological in nature. The total volume of public funding for TUKEVA has been € 4.25 million, four projects by consortia and nine projects by individual research teams were selected for TUKEVA. Most of the participating institutes and laboratories have also more applied oriented work and projects going on. TUKEVA has, however, made possible the researchers to concentrate to research for the period of the TUKEVA project without need for applying short term funding annually.

The results reported by the projects show that the scientific level of the research done in the TUKEVA programme is high and the aim has been fulfilled. The projects are described in this final report of TUKEVA programme, but the detailed research results achieved in the projects can be found in the publications of the projects. The aim to train researchers has been achieved as research for seven doctoral dissertations will be completed during the year 2003, 13 dissertations will be finished during the year 2004 and research started in the TUKEVA programme will lead to 12 dissertations in the year 2005.

The new potential for the Finnish mechanical engineering is in the even deeper combination of high knowledge of information and communication technologies with mechanical engineering knowledge of products and processes. There are several good examples of this already in the markets, but the development is still in early stages. A strong research challenge exists for collaboration over the traditional borders between research areas.

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ABSTRACT: Mechanical Engineering Industry is one of the major industries in Finland and has as an export oriented industry a key role in the economy of Finland. The industry is well developed and active in many fields of R&D. Industry has indicated need for increased efforts in basic research. The Academy of Finland decided to launch the Research Programme on Future Mechanical Engineering (TUKEVA) for the years 2000-2003. The main objective of TUKEVA was to strengthen existing research efforts and open new lines of high-quality basic research which will support ongoing and future R&D work in Finnish industries.

In the fifteen projects approved for funding in the TUKEVA programme the large scope of mechanical engineering was covered. The very valuable results are reported in this Final Report of TUKEVA, and can be further studied in the numerous publications made during the programme. TUKEVA more than any other programme in the past has given a strong kick to the basic research in mechanical engineering in Finland. The effect of TUKEVA extends over the results achieved and reported by the projects. The applicability of the results is good and will give much new base for the Finnish industry to carry on its R%D work. TUKEVA opened a new approach for basic research in mechanical engineering successfully, and this road needs to be continued.

1.1 INTRODUCTION

Mechanical engineering industry is the main employer among the Technology Industries in Finland. The gross values of electronics and electrotechnics industries and mechanical engineering industries are about the same, but there is a difference in value-added and in the expenditure in R&D (Fig. 1). Electronics industry has grown rapidly with the advance of IT technology and industry. The expenditure in R&D has been the necessary base for the growth of IT.

Teknologiateollisuuden päätoimialat pähkinänkuoressa 2002*
Technology Industries 2002*

	Elektroniikka- ja sähköteoll. Electronics and electrotechnics	Kone- ja metalli-tuoteteollisuus Mechanical engineering	Metallien jalostus Metals industry	Teknologia-teollisuus yhteensä Technology industries total
TUOTANTO/PRODUCTION				
Liikevaihto/Gross value, million €	19300	18000	4800	42100
Jalostusarvo/Value-added, million €	8300	6100	1200	15600
Aineelliset investoinnit/Investements, million €	378	676	348	1402
Tutkimus ja kehittämis/R&D, million € (v. 2001*)	1701	363	37	2101
HENKILÖSTÖ/WORK FORCE				
Henkilöstön määrä/Employees, total (1000)	65	133	17	216
- toimihenkilöiden osuus, % white collar, % of total	56	31	30	39
Kokonaistyövoimakustannukset / Toatl labour costs, million €	2625	4593	710	7928
VIENTI/EXPORTS				
Tavaravienti/Exports, million €	12953	9417	3323	25693
- osuus Suomen tavaraviennistä, % / % of total Finnish goods exports	27	21	7	55
Yrityksiä (väh. 5 työntekijää) / Companies (min. 5 employees)	550	2430	80	3050

Teknologia teollisuus

Lähde: Tilastokeskus, Tullihallitus m:\vuosikirja\mjvu05af.ppt 27.5.2003/JP/mh

Figure 1. Gross Value, Work Force and Exports of Technology Industries in Finland 2002

Mechanical engineering industry has a long tradition in Finland and has in many product areas a well established market position globally. The average share of export is well over fifty % of the gross value. The structure of the industry is such that there are few bigger enterprises and a lot of smaller companies. The companies have focused their activities more and more in the key areas. Several Finnish companies are globally market leaders in their product areas. The customers of the mechanical engineering industry are in various parts of the world and the industry is active in several product and process areas. This means that mechanical engineering industry is not so much affected by the economic disturbances as some other business areas like information technology.

The number of employees in the mechanical engineering industry has grown since the beginning of nineties and is on the same level as in the mid seventies (Fig.2). During that time mechanization and automation in the industry has increased remarkably and the gross value has grown a lot. Mechanical engineering is a backbone of Finnish industry and important part of the economy of Finland.

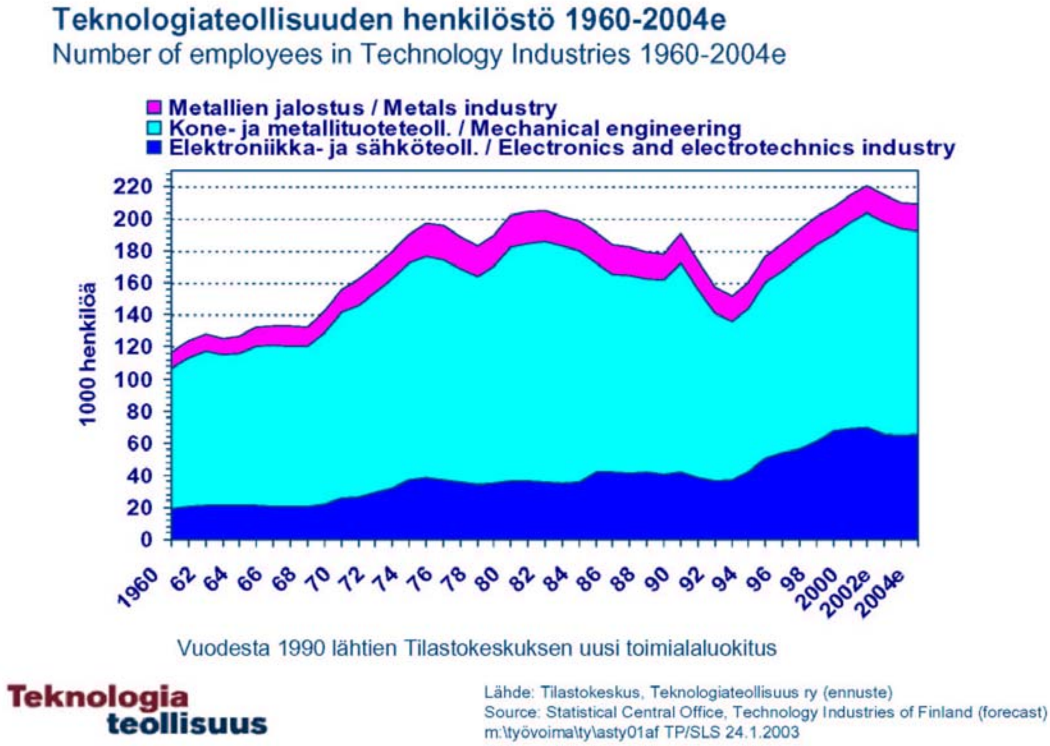

Figure 2. Number of Employees in Technology Industries 1960-2004e

The success of the Finnish mechanical engineering industry is based on good technological knowledge and know-how. Mechanical engineering is well adjusted to the new developments and uses advanced technological applications. The National Technology Agency (Tekes) has supported technological applications and product development successfully. There has, however, been a growing need for more basic research in mechanical engineering both for the development of existing technology and applying new technologies.

The new potential for the Finnish mechanical engineering is in the combination of high knowledge of information and communication technologies with the mechanical engineering products and processes. There are several good examples of this already in the markets, but the development in this area is still in its early stages. There is a challenge for collaborative research over the traditional borders between research areas.

1.2 TUKEVA RESEARCH PROGRAMME

The need for increased effort in basic research in mechanical engineering was realized in the Academy of Finland. The Academy started the preparation for the Research Programme on Future Mechanical Engineering in the autumn 1998. On June 1, 1999, the Board of the Academy of Finland decided to launch the Research Programme on Future Mechanical Engineering (TUKEVA) in the year 2000. The programme was opened for proposals in the autumn 1999. Funding of the selected projects started June 1, 2000 and ends December 31, 2003. TUKEVA is the first research programme on mechanical engineering launched by the Academy of Finland.

1.2.1 *Objectives*

The main objective of the Research Programme on Future Mechanical Engineering is to strengthen existing research efforts and to open up new lines of high-quality basic research which will support ongoing and future R&D work in Finnish industries. The programme will also aim to increase the number of post-graduate and doctoral students in mechanical engineering and manufacturing technology.

The objective of the research programme is also to establish closer links of collaboration between theoretical and applied research and to strengthen the research culture which seeks to extract new product innovations from basic research. The promotion of national and international networking among individual researchers and research units has a value in the programme.

The widely spread research areas in the TUKEVA research programme emphasize the multidisciplinary nature of mechanical engineering research.

1.2.2 *Programme implementation and organization*

Research proposals for funding were applied by individual research teams and by consortia of several teams. Special attention was given to the creation of research teams, long-term targets for research, and researcher training. The scientific content of the selected research projects was the first criteria for funding decisions.

Selection of the projects was done in two phases. First short plans, few pages, were submitted. On this basis a shortlist of projects was formed, and these projects were asked to submit applications proper and full research plans. The international panel evaluated the project proposals, and the final selection was made by the Selection Committee set by the Board of the Academy of Finland.

For the first selection phase 67 plans of intent were submitted by 13 consortia and 54 individual research teams. The steering committee selected 6 consortia and 14 individual research teams for the shortlist. The size of the projects varied in a large scale. In the final selection 4 projects by consortia and 9 projects by individual research teams were approved. The Finnish Work Environment Fund joined TUKEVA programme in funding two subprojects and the National Technology Agency, Tekes, joined by funding three additional projects.

The TUKEVA Research Programme has a steering committee chaired by Prof. Riitta Keiski, University of Oulu and co-chaired by Prof. Markku Tuominen, Lappeenranta University of Technology. The other members of the steering committee are Research Director Mikko Karvinen, Metso Paper Oy, Technology Manager Timo Laurila, Tekes, Prof. Mauri Määttänen, Helsinki University of Technology, Senior Research Scientist Leena Norros, VTT Industrial Systems, Scientific Secretary Pentti Pulkkinen, Academy of Finland (until June 2002), Scientific Secretary Eeva Karjalainen, Academy of Finland (from June 2002), Council Secretary Aila Hagelin, Academy of Finland, and TUKEVA Programme Director Kalle Hakalehto, Tampere Technology Centre Ltd.

1.2.3 *Projects of the TUKEVA Programme*

The following projects have been funded in the TUKEVA Research Programme.

1.2.3.1 *Consortia*

New Suspension Structures and Damping Systems in Off-Road Vehicles
(subproject funded by the Finnish Work Environment Fund)
Helsinki University of Technology, Laboratory of Automotive Engineering
University of Oulu, Laboratory of Machine Design
VTT Electronics

Extreme Values of Piston Engine
Helsinki University of Technology, Laboratory of Internal Combustion Engine
Tampere University of Technology, Institute of Hydraulics and Automation
Tampere University of Technology, Institute of Materials Science

The Effect of Parameter Uncertainty on the Reliability of Virtual Testing of Fluid Power Systems
Tampere University of Technology, Institute of Hydraulics and Automation
Helsinki University of Technology, Department of Mechanical Engineering

Intelligent Laser Surface Engineering
Lappeenranta University of Technology, Laboratory of Laser Processing
VTT Industrial Systems
Tampere University of Technology, Institute of Production Engineering

1.2.3.2 *Individual Research Teams*

User Interface of Robotic Machines Based on Perception and Cognition
(subproject funded by the Finnish Work Environment Fund)
Helsinki University of Technology, Department of Automation and Systems Technology

Analysis and Control of Vibrations in Electrically Driven Machine Systems
Lappeenranta University of Technology, Department of Mechanical Engineering

Condition Monitoring of High Temperature Power Plant Components Using Metal Embedded Fibre Optic Bragg-gratings
VTT Industrial Systems

Novel Ceramic Technologies in Realization of Miniature Actuators and Motors
(Related project funded by Tekes)
University of Oulu, Laboratories of Microelectronics and Materials Engineering

Coherence Microscope in Industrial Manufacture, Robotics and Imaging
University of Helsinki, Laboratory for Electronics and Industrial Physics

Axially Moving Materials and Composites
University of Oulu, Department of Mechanical Engineering

Simulation of Multiphase Flows in Industrial Processes
University of Jyväskylä, Department of Physics

The Modelling and Optimisation of Dynamic Production Networks Based on the Evolutionary Principles Observed in Animate Organisms
Tampere University of Technology, Institute of Production Engineering

Fatigue Strength Modelling of Laser Welded Joints
Helsinki University of Technology, Ship Laboratory

Advanced Surface Coatings by High Power Lasers
(funded by Tekes)
Tampere University of Technology, Institute of Materials Science

Fussy Classification and Neural Networks in Particle Recognition
(funded by Tekes)
VTT Industrial Systems

1.2.4 *Funding*

The Academy of Finland funded the main part of TUKEVA Research Programme, the additional funding was provided by the National Technology Agency (Tekes) and by the Finnish Work Environment Fund (TSR).

The total volume of TUKEVA Research Programme is € 4.25 million.

Academy of Finland	€ 3.53 million
Tekes	€ 0.58 million
TSR	€ 0.14 million

1.3 TUKEVA PROGRAMME DELIVERABLES

1.3.1 *Coverage of TUKEVA*

TUKEVA Research Programme covers a wide range of subjects in mechanical engineering. This was the choice when TUKEVA was launched as the first research programme in mechanical engineering by the Academy of Finland.

Technological research extends from the very basic research to applied research and to product development. There are very seldom clear cut lines between the various phases of research especially in mechanical engineering. This is very well demonstrated in the projects of TUKEVA. In some cases the results of the research projects can be applied almost immediately and in the other cases the research just opens possibilities which may lead to major new developments. The value of basic research in each case is evident but has not been previously so well commonly understood either by the scientific community or by the industry.

The subjects of the projects in TUKEVA touch many of the important research areas of mechanical engineering. On the other hand the projects differ from each other in size and scope and in the resources that are necessary to complete the whole set of research projects. In many projects laboratory facilities and equipment are the necessity to carry on the research. If the equipment has been available and only minor changes have been necessary, the project had better possibilities to be completed in tight project schedule. The Academy of Finland has been able to support the construction of new equipment only marginally.

The close co-operation of the Academy of Finland and Tekes in TUKEVA and the common use of resources in the more applied Tekes projects and in the TUKEVA projects has indicated an excellent understanding of the nature and need of the mechanical engineering research, especially the need of basic research.

1.3.2 *Scientific results*

The intermediate seminar of TUKEVA "Mechanical Engineering Research – New Possibilities by Cooperation" was organized in the Tampere University of Technology January 3rd, 2002. In this seminar each project of TUKEVA reported the work done and the results achieved and also the future work.

The projects report in this Final Report of TUKEVA briefly their main scientific results. Further scientific content can be found in the publications listed at the end of each report. It can be found that the culture of scientific reporting is not yet at the same level in all research organizations. On the other hand there are good examples of well developed scientific reporting. There are differences in the reporting of technological achievements, more common in mechanical engineering, and in the reporting of scientific results. The Academy of Finland has emphasized the importance of scientific research and reporting. Those research units which have been active in the research programmes and in the other Academy funded research have best adopted the proper scientific reporting.

Reporting of the engineering research has often limitations when the achieved scientific results lead to further research and to the development of commercial products. This point is, however, in many cases overstated. The good scientific engineering research can be reported and it should face the international discussion without hurting anybody's immaterial rights. TUKEVA projects have in large extent succeeded in their reporting.

In evaluating the scientific content of a diversified research programme like TUKEVA the problem is that the projects represent such a large scale of specific expertise that each of them should be evaluated by the experts of the specific scientific community. Most of this will happen in the scientific journals and conferences later on.

1.3.3 *Networking and collaborative research*

In many TUKEVA projects collaboration of researchers took place, both with the researchers of the same research area and with the researchers of the supporting areas as well. The ability to do collaborative research and to form networks around a research topic seems to be developed well in the research organizations that are used to carry on Tekes funded projects. In these projects industrial partners are usually actively with.

The reported TUKEVA projects indicate that it is very difficult to do mechanical engineering research without close collaboration with one or more other research areas. Materials science, information and communication technology, process technology, human behaviour are examples of subjects which have become important in mechanical engineering research in addition to the important traditional research areas.

The products of mechanical engineering are not unitechnological and this reflects more and more also in the research. Each research community must have deep knowledge of the special subjects of its own, but combination of technologies opens up new possibilities both for scientific findings and innovations. There are some projects in TUKEVA which bring very new technological solutions to the development of mechanical engineering in the years to come. We can just mention miniature actuators and motors or cognition research in the use of robotic machines. The application of new technologies in machines and processes requires, however, that the basic mechanical engineering is sound and is based on the top level knowledge and scientific research.

The international contacts in TUKEVA could have been more numerous. It seems to be difficult to do proper international cooperation just based on the activity of the operative research units. There is more will to do cooperation than there is possibility to find funding for it. International networking and cooperation as appeared in TUKEVA needs more attention than has happened up to now to establish co-operative international funding in addition to EU programmes.

1.3.4 *Researcher training*

Researcher training was one of the objectives of TUKEVA Research Programme. In the research plans of the approved projects 25 doctoral dissertations was planned to be based on the work done in the TUKEVA projects.

The projects report that research for seven doctoral dissertation will be completed during the year 2003. (The formal dissertation will in most cases take place 2004). Thirteen additional dissertations will be ready during the year 2004 and research started in the TUKEVA programme will lead to 12 dissertations in the year 2005. The total amount of doctoral dissertations is 32.

Engineering research where experimental part is necessary is often time consuming and it is not a surprise that the completion of the planned doctoral dissertations is delayed to the next couple of years. This can especially be seen in the projects in which the construction of the major experimental laboratory equipment started at the beginning of the project.

Several Master of Science degrees have been done in the TUKEVA projects either fully or partly. Even more researchers, an estimation of over fifty, have participated in the research work and has been in the researcher training. The cabability of the laboratories which participated the TUKEVA Research Programme has increased in providing researcher training in all levels of education.

1.3.5 *Applicability*

In most cases the research done in TUKEVA finds more than one application for the research results. As most of the participating research laboratories and institutes are also active in applied research mainly funded by Tekes, they do not find it difficult to point out the technological solutions and products in which the achieved research results can be used in the development of new solutions for products and processes.

The Science and Technology Policy Council of Finland in its sixth triennial review *Knowledge, innovation and internationalization* published this year draws the national lines for the technology policy for the next years. The Council pays attention to the determined development measures to develop further Finland's foremost strengths in knowledge, *the national competencies*. Finland will make systematic input into international science and technology cooperation both in Europe and globally with a view to increasing knowledge, know-how and innovation. Similarly, internationalization of education will be intensified by means of the research cooperation models.

The council emphasizes the strengthening of the existing business activity based on the national competencies and their further development. The mechanical engineering industry in Finland has such an important role in the economy of the country, that research programmes like TUKEVA are necessary also in the future to increase the basic knowledge on which the industry can build on its development and future.

1.4 CONTACT

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2 NEW SUSPENSION STRUCTURES AND DAMPING SYSTEMS IN OFF-ROAD VEHICLES

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ABSTRACT: The aim of this research project is to find new suspension structures and damping algorithms suitable to suppress vibration in off-road vehicles. A new approach to semi-active suspension, which takes kinematic properties of the suspension into account, was developed. Model based algorithms, where the damping characteristics are set in frequency scale, were studied, developed and tested in practice. The utilisation of modern DSP methods in active damping algorithms was studied and developed using simulations. The directives and standards considering human exposure to vibration were studied and an analysis tool was developed and tested. This tool simplifies the evaluation of vibration from the point of view of the vibration load of the driver. New techniques were tested and developed both with real and virtual prototypes. Virtual environment used in this study was implemented with ADAMS simulation environment, while control systems were implemented with C-language and Matlab. Virtual prototypes of mechanical systems were utilised when designing new suspension structures. Environment for simulating mechanical structures together with control systems was build up. During development of simulation environment of virtual prototypes it was found that commercial software have still a lot to develop in order to make them suitable for simulation of a whole system consisting of mechanics, actuators and control systems.

2.1 INTRODUCTION

The upcoming and tightening directives and standards considering the driver's exposure to vibration force the machine manufacturers to seek new methods to reduce this exposure. In heavy machines this requires improving the damping properties of either the tire or the cabin or the seat suspensions. The natural frequencies appear typically between about 1 to 10 Hz, in which range the human body is the most sensitive to the whole body vibration. Higher frequencies are usually generated by auxiliary equipment and they can be attenuated sufficiently with traditional passive vibration dampers. Many means of vibration control can be found in the literature, e.g. passive springs, hydraulic dampers, rubber bushings and usage of materials that have good damping characteristics.

An alternative to passive dampers is the use of active or semi-active suspension systems, in which the damping properties are defined by the control system. In active damping, vibration of the construction is damped with active counter-force or counter-movement. In semi-active damping, some characteristic of the construction component is altered, stiffness or damping for example, to achieve the desired damping result. Altering the characteristics of a construction component demands considerably less energy than the active counteraction.

In semi-active damping, the damping coefficient is typically the controlled variable. The response time of a semi-active suspension system is below natural frequency of the system to be damped, so it is possible to alter the system's response to different excitations. Semi-active suspension systems are like passive ones since they can only dissipate energy. Semi-active actuators which can be used are hydropneumatic springs, shape memory alloys (SMA), the shape of which can be controlled with temperature; or dampers based on electro- (ER) or magnetorheological (MR) fluids, the viscosity of which can be controlled with an electric or magnetic field. The amount of energy needed for control is relatively small compared to the energy dissipated in a damper.

However the shaping of the frequency response of the system is limited in semi-active damping. In order to effectively suppress low frequency vibration, relatively small spring constant is required. In fully active suspension external forces are induced to the suspension mechanism using e.g. hydraulic or pneumatic devices. In that case the system designer can affect the frequency response more freely and low frequency excitations can be attenuated without deteriorating the static properties of the suspension.

In the development of control systems there has been a lack of accurate mechanism models, in this case the vehicle models. Usually simplified models with linearizations and reduced degrees of freedom have been used. These don't take the kinematic effects of the suspension system into account. This leads into inaccuracies if relatively large movements and forces, typical to heavy machines, are considered. Because of this, accurate MBS (Multi-Body System) vehicle models have been developed during the project. The MBS model of agricultural tractor has been validated using experimental testing. New suspension structures have been developed for the agricultural tractor using virtual prototyping. The aim of the new structures has been to give more degrees of freedom for the suspension control. The other MBS model used in this project is a heavy off-road vehicle, which is based on commercially available military vehicle. With MBS models the controllers can be tuned and tested without physical testing. This prototyping technology is called virtual prototyping.

The ADAMS simulation environment used in the project is commercially available and it has been in use in automotive industry already for some time. However in the off-road vehicle industry it has not been used very widely. This is because of off-road vehicles move typically relatively slowly and their equations of motion can be based on static equilibrium equations. However also agricultural tractors are nowadays driven long distances on the highways and therefore the manufacturers are aiming to higher driving speeds. When driving speed is raised, vibration level can rise into unbearable levels. Upcoming standards also limit the duration of the permissible working time of the driver if the vibration level rises. Also pitching, which deteriorates handling properties of the tractor, occurs more easily with higher driving speeds.

For the development of simulation environment and simulating mechanical models with control systems, expertise of virtual prototyping, mechanical systems and control systems is required. The partners of this project have experience on these research areas. Lot of co-operation of the partners was needed inside the consortium when developing the models and simulation environment.

2.2 OBJECTIVES

Every objective in this project is characterised by the use of virtual prototypes. Virtual simulation environment was studied and developed during the project. If complex mechanisms, like vehicle suspension linkages, are considered, modelling of them requires a lot of experience both on the simulation software and on the mechanism itself. If a control system is included into the model, even more specialised expertise is needed. The manufacturers of commercially available simulation software claim that it is possible to link the mechanical models, models of the actuators and the models of the control systems easily into one virtual prototype. This is true for models, which don't take the advantage of any kind of special features of the simulation software. If accurate results of complex control systems are required the commercial systems does not seem to work.

Virtual prototyping technology was used to develop and test different suspension structures and control systems for the off-road vehicles. One of the objectives of this study was to develop suspension structures suitable for off-road use. At the moment agricultural tractors are poorly suspended. Typically only the cabin is suspended. If the front axle is suspended the suspension structures are relatively simple and not very effective.

In addition to modelling and testing suspension mechanisms also the development of the control methods for active and semi-active suspension systems were studied and developed. In the early stages of the development of the control systems it was obvious that manually tuned control algorithms like PID- algorithms don't work properly. So model-based control algorithms, which take the eigenfrequencies and the time delays of the systems into account, were studied. Also rapid development of DSP-technology offers interesting possibilities for new approaches to control algorithm design.

With virtual prototypes a new model-based semi-active suspension system is developed. In the most of the research done in controlling of the whole vehicle, linear models with reduced degrees of freedom are used. These linearized models don't take the effects of the suspension geometry into account, except the motion ratio. Due to change in kinematic effects of suspension system the axes of constrained motion of the vehicle body in relation to the ground can vary in a wide range. Because effective axles around which the body rolls move, the effective inertia and mass of the body varies in a wide range. In order to keep the complexity of this new model in the moderate level, only transverse kinematics are taken into account i.e. the model is based on widely known and accepted roll centre concept.

The directives and standards concerning driver's vibration have great importance when designing damping systems. Therefore development of methods and tools for analysing vibration and verifying the operation of the suspension and damping systems in accordance to these directives and standards is also one objective of the project.

2.3 RESULTS AND ACHIEVEMENTS

2.3.1 *Scientific*

2.3.1.1 Multi-body system modelling

MBS simulation program called ADAMS have been used for the modelling of the mechanics of the case vehicles. A MBS model of a commercial agricultural tractor has been developed. The driveline, engine, tires, etc. are included in the model. The tractor can be simulated with four-wheel drive or rear wheel drive. The basic model has 21 degrees of freedom, but different versions are in use. The developed tractor model (Figure 1) has been validated using experimental data from the measurements of the test tractor that were done together with the project partners. The model was found valid in the situations were it was tested. For the validation a test track with two different obstacles were developed. With different size obstacles the stiffness and damping properties of the tyres can be validated. The tyre model and its parameters play most important role in vehicle models, especially on vehicles that don't have suspensions. [Lehtonen 2003]

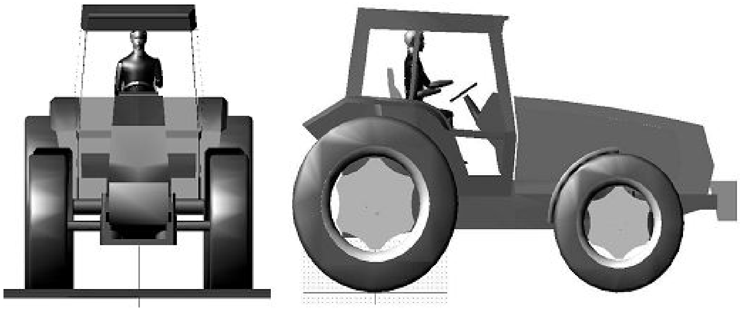


Figure 1. Agricultural tractor MBS-model

Figure 2 presents the acceleration of simulated and experimental tractor cabin on the test track. The velocities of the tractors have been 9 km/h. This figure shows that the model predicts the accelerations with reasonable accuracy [Lehtonen 2003].

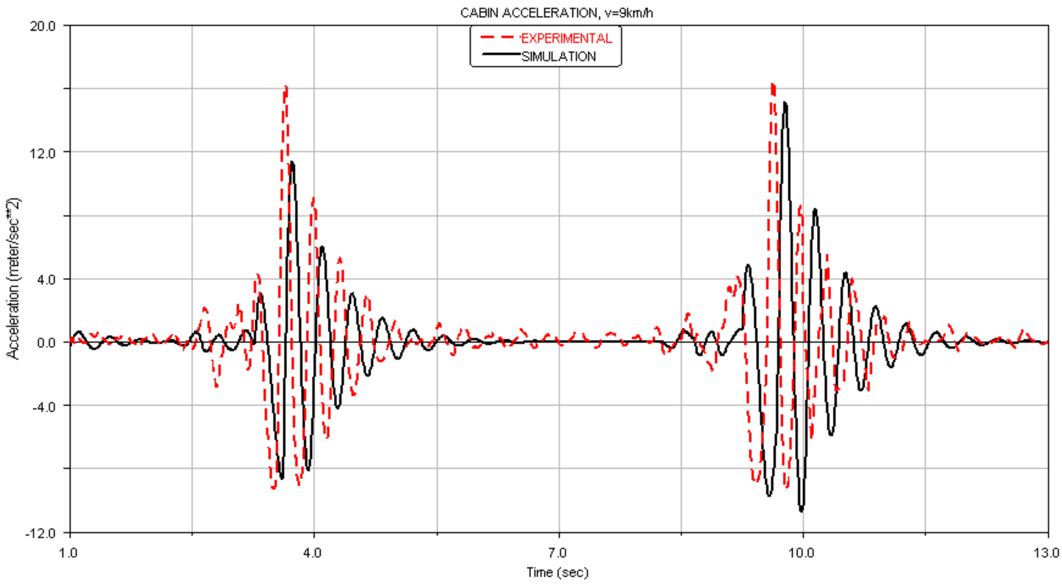


Figure 2. Tractor cabin vertical acceleration on test track at the velocity of 9 km/h.

Different suspension structures for the tractor front axle and cabin have been studied. After the study independent suspension of the tractor front axle has been modelled using virtual prototyping. This suspension can be implemented on different versions of the tractor model and study its advantages. The unsprung mass of the tractor front axle could be reduced with this kind of suspension and it also gives a possibility to increase spring travel, which leads to a possibility to decrease spring stiffness. Decreasing the spring stiffness enables designers to reduce the low frequency vibrations transmitted to the tractor body. Semi-active damping systems were implemented to the independent tractor front axle suspension and cabin suspension. Passive suspension will be compared to semi-active suspensions of the tractor on different tracks. These simulations are under progress. Figure 3 shows comparison of tractor with independent front suspension having passive and semi-active damping. The curves show clearly that the pitching of the front axle is damped with the developed semi-active suspension faster than with the passive damping.

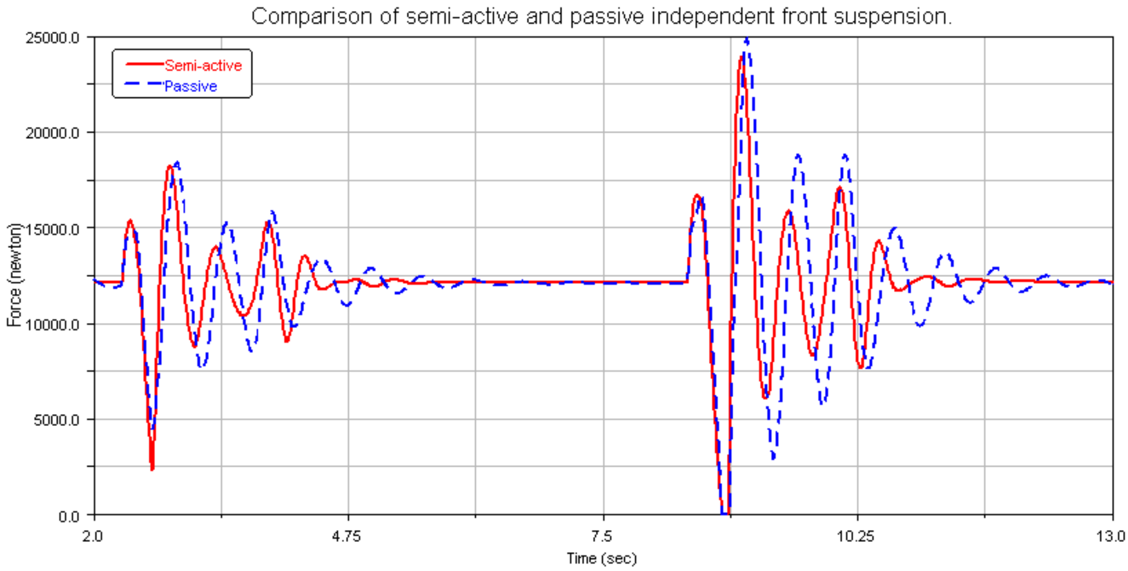


Figure 3. Tractor right front wheel vertical force with semi-active and passive damping with independent front axle suspension on test track at the velocity of 9km/h.

The first results of independent front axle suspension with passive springing and damping, that was also developed, show that in the tractor model the driver vibrations cannot be outstandingly reduced with front axle suspension. The reason for this is that the driver is seated above the rear axle and most of the vibrations are transmitted from rear axle. The most significant benefit of the front axle suspension is on the driving properties of the tractor. The agricultural tractors tend to start pitching after having some input from the road. This pitching can be significantly reduced with using front axle suspensions. The benefit of independent front axle suspension compared to the traditional rigid axles will be studied with final simulations.

New suspension structures have been developed also for the tractor cabin suspension. The aim of the development was to achieve more degrees of freedom. The basic ideas of the cabin suspensions are 3 or 4 point fixing with additional rods that take the longitudinal and lateral forces. The location, orientation and attachment of the rods are very critical to the degrees of freedom. Simulations with in the project developed controlled cabin suspension are under progress [Lehtonen 2004].

One of the problems with agricultural tractors is the steerability and driving behaviour of the tractor when it is equipped with accessories. Simulations with turning plough have been done and will be done with a tractor having controlled cabin and front axle suspension. With advanced front-axle suspension systems it is possible to control better the tire contact force to the ground and this enhance the steerability of the tractor. If the weight on steered wheels is reduced to 10% of total weight of the tractor, the steering becomes difficult.

The developed simulation model with all its versions gives great possibilities for researching agricultural tractor driving behaviour. Simulations with virtual prototypes with different suspension structures, suspension control systems and cabin suspension on different test tracks and tractor loads will be done to achieve knowledge of the efficiency of the controllers and suspension structures.

During the project also a model of military off-road vehicle has been modified suitable for the control system design. The model is based on the model received from industry. The model is platform for the semi-active suspension control research.

2.3.1.2 Modelling virtual test tracks

Master's Thesis, Modelling Virtual Test Tracks for Off-Road Vehicle Simulations, has been done by Jussi Määttänen [Määttänen 2002]. In the Thesis software, which can generate virtual test tracks for the simulation purposes of the ADAMS program, has been developed. In the program user can determine sinusoidal or rectangular track or a track consisting of series of sinusoidal waves using the wavelength, amplitude and phase of the sine. There is also a possibility to generate a track from the measured data. A measured data for this purpose can be gathered for example from the road-measuring vehicle of the VTT. Different meshing algorithms and mathematical functions were studied to find out the most effective way for generating the tracks. The tracks have significant effect on the computing time of the simulations that is why it was important to find most effective algorithms for the program.

The program has already been used in different projects and is considered useful from the industry's point of view.

2.3.1.3 Control algorithms for active damping (cabin suspension)

2.3.1.3.1 Model based controller tuning (H_∞)

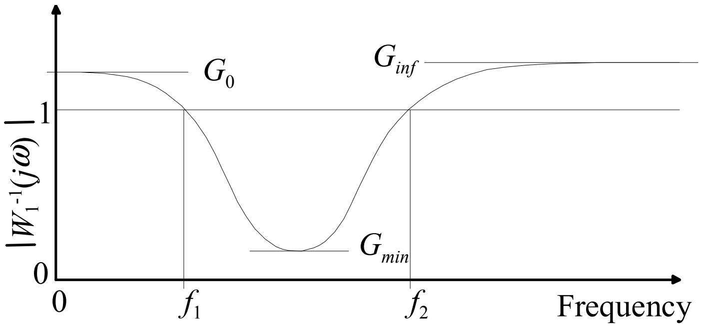
From the early prototypes with active cabin, seat or tire suspensions it was clear, that simple, manually tuned control algorithms like PID do not work properly. Hence, model based methods, which take into account the resonance frequencies and delays of the system, has to be used.

Theoretical modelling tends to lead into too complex models with poor accuracy, which is why fitting of transfer function models to measured data is preferred. Best results were achieved with frequency domain fitting, where the frequency response of the system is measured and computed using a test signal (noise, PRBS or a sum of sine signals) and the transfer function is fitted to the complex valued response. Some methods were tested including direct and logarithmic fitting. The best behaviour was obtained with weighted least squares fitting used in multiple stages.

The most natural way of tuning of the damping controller is to specify the characteristics of the damper in the frequency domain. This can be accomplished by using design methods, which restrict the sensitivity to disturbances of the controlled system in frequency domain, the best known of which are the LQG and H_∞ norm minimising controller designs. In H_∞ design the feedback controller is defined so, that the closed loop is stable and the weighted H_∞ norm of its sensitivity and complementary sensitivity are less than unity. The setting of the frequency domain weighting function for the sensitivity is directly the intended damping curve of the active damper and the selection of this function is the main design objective. The methods for finding the controller transfer functions, which satisfy the set restrictions, are available in e.g. Matlab software package.

Several different weighting functions were tried and the best results were obtained with the one shown in Figure 4. The shape of the weighting is defined with gains G_0, G_{min} and G_{inf} and corner frequencies f_1 and f_2. The nominal frequencies ω_N and ω_D and damping ratios ξ_N and ξ_D of the second order function can be computed from these with some limitations.

The flexibility of the rear tires in a wheeled tractor creates a resonance frequency for the vertical movement at around 2–3 Hz. The proper operation of the damper requires that the notch in Figure 4 extend beyond that frequency. This tends to lead to a controller, which contains phase lead and high gains at higher frequencies. As a result the higher frequency disturbances tend to get amplified. In fact, already in the design phase the G_{inf} parameter must be set to a value higher than 1, otherwise a controller which satisfies the H_∞ norm constraint cannot be found. The low frequency gain G_0 should also be greater than 1 in order to not to disturb the low frequency regulation of the state of the damping system, the purpose of which is to keep the system in the middle of its operation range. The choice of the limit frequencies f_1 and f_2 and the maximum damping G_{min} is also limited by the existence of a solution for the controller design problem. In practice there is an upper limit for f_2 and a lower limit for G_{min} and these limits depend on the choice of other parameters, which tends to turn the design task to a trial and error process.



$$\frac{1}{W_1(s)} = G_0 \frac{\frac{s^2}{\omega_N^2} + 2\xi_N \frac{s}{\omega_N} + 1}{\frac{s^2}{\omega_D^2} + 2\xi_D \frac{s}{\omega_D} + 1}$$

Figure 4. Weighting function used for the sensitivity in H∞ design.

An example of the tests with active damping of the vertical movement of a tractor cabin is shown in Figure 5. As can be noted the damping algorithm works well at the most critical frequency band 1−5 Hz. As excepted the higher frequency vibrations are amplified (the spill over effect). More results can be found from [Järviluoma 2002] and [Järviluoma et al. 2003].

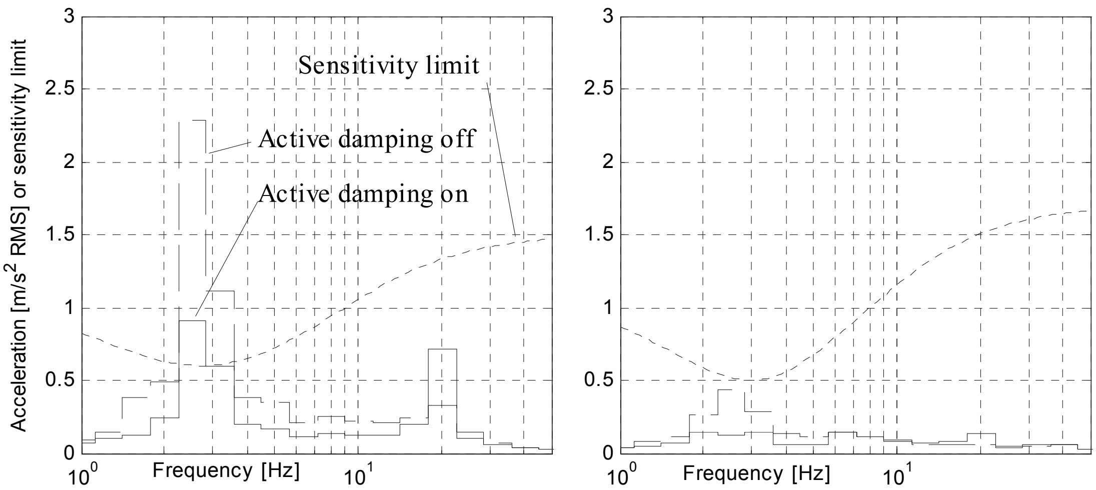


Figure 5. The effect of active damping on the vertical vibration of a tractor cabin when driving with 20 km/h speed on gravel road (left) and with 40km/h speed on asphalt road (right).

2.3.1.3.2 Internal model control

The H∞ method for tuning the damping controller is rather laborious and time consuming. The measurement and modelling of the frequency response of the system and the design of the frequency domain weightings require a lot of off-line computations. That is why some easier to use methods are searched. Also the problem of spill over, i.e. the inevitable amplification of higher frequencies motivates the search for new methods.

Especially in transport driving on a even road with relatively high speeds the vibration spectrum in a vehicle cabin is shaped by the nominal frequencies and damping ratios of the flexible structures of the vehicle. Especially the flexibility of the tires is in a dominating role. Hence, the vibration spectrum concentrates on distinct frequencies. The periodic component of this kind of disturbance can be modelled, which enables the application of the internal model control principle introduced by Francis and Wonham in 1976. If only one frequency and its multiples are dominating, the disturbance model is a periodic function and the widely studied field of repetitive control can be applied.

The idea of internal model principle is depicted in Figure 6. Control methods, which utilise the internal model principle, are mainly applied for the damping of vibrations in rotating machines and devices. In VTT Electronics research on this topic relates also to other projects concerning vibration damping of heavy rotors (TEKES/Pyöriväre and VTT/Sularotor projects) and partly concerning disturbance rejection in signal transmission. Some results from tests with a heavy rotor with hydraulic dampers and its simulation model can be found in Pyöriväre and Sularotor reports.

Traditionally the disturbance model for periodic disturbances is implemented by including a delay, equal to the duration of one period, with positive feedback in the controller. This will model the base frequency and its multiples up to infinite frequency. Other implementations include modelling of one or a few frequency components with oscillating modes in the control algorithms. A list of references and a short survey on repetitive control methods is presented in the report [Järviluoma 2003].

The algorithm used here to model the disturbance was originally designed for filtering of electromagnetic interference produced by a TDMA-based system from speech signal [Vuorinen & Seppänen 2001]. The main idea of the method is to transform the given signal segment from time domain to new space by over sampling the signal and filtering the signal in that new space. An overview of the method is in Figure 7. The over sampled model is created by collecting data for one cycle from a few disturbance periods. The rearranging is done by placing samples corresponding the same phase of the disturbance in a sequence. The result is a model for one cycle, where the main features are caused by the periodic disturbance. Other components of the signal are shown as noise, which can be removed by e.g. median filtering or wavelet approximation from the over sampled data. By rearranging back to the original time sequence the model for one cycle is obtained in the original time domain.

The main advantage of the over sampling method is, that the extraction of the disturbance model is done in time domain and it needs only a few periods of data for accurate modelling.

An example of the effect of the modelling is shown in Figure 8. The vertical acceleration of the tractor cabin is measured and a model with period 2.6 Hz (the resonance frequency of the rear tires) is created using 3 periods per cycle. The figure shows the effect of subtracting the model from the original signal as third octave RMS spectrums of the signals (sample interval 0.01 s, data length 60 s). In this case the model is directly subtracted in time domain from the same data from which it was created. The method for updating the model with new data in real time and in a feedback control loop is still under development.

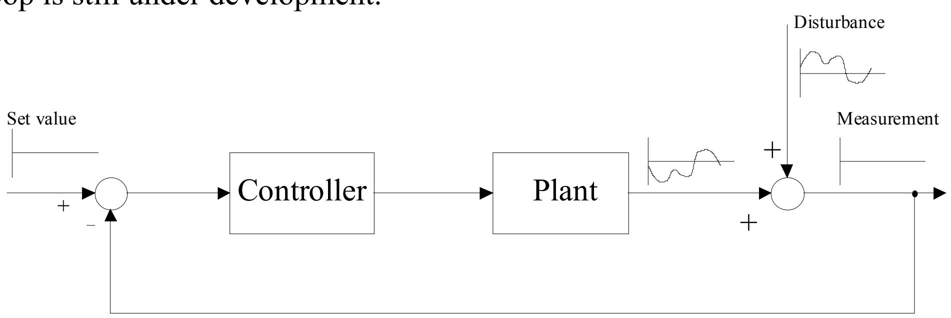


Figure 6.Internal model principle. The open loop system (controller and plant) should produce a signal, which cancels the disturbance even when the input to it is zero. Hence, the open loop system must include a model of the disturbance

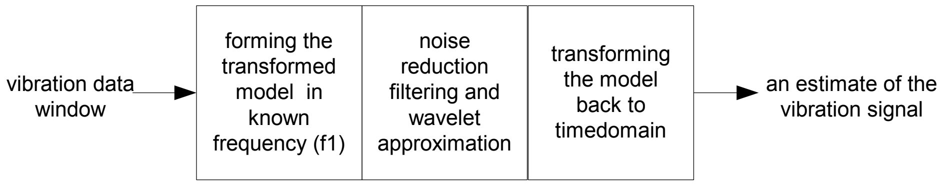


Figure 7. Block diagram of the principle of the used algorithm.

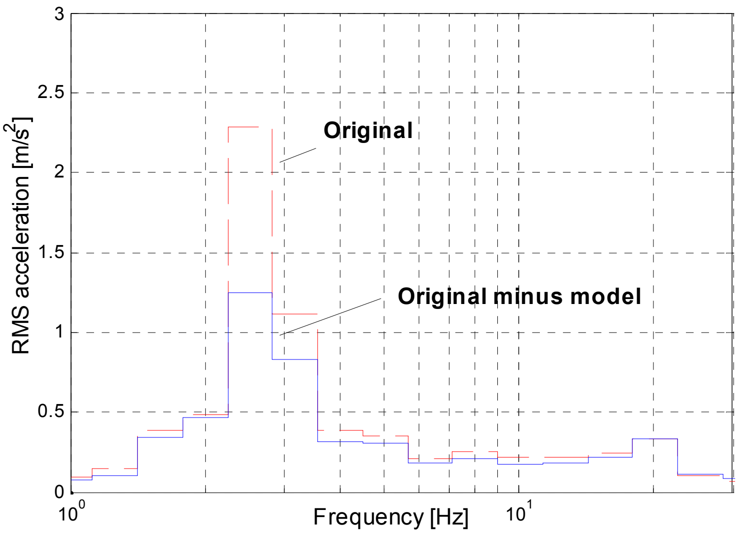


Figure 8. Effect of the subtraction of a periodic model with 2.6Hz base frequency from the original vibration signal.

2.3.1.4 Vibration measurement and analysis

A Master's thesis on whole body vibration analysis in work machines was made by Ykä Marjanen [Marjanen 2002]. A study on the whole body vibration effects on human health and comfort was a part of the thesis. An extensive literature research was made on vibration effects to health and to comfort thresholds, on vibration standards and on human modelling. One goal of the thesis was also to develop an analysis program, which would calculate the values described in EU-directive (2002) and ISO-standards (ISO 2631-1: Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - part 1: General requirements.1997). The program was tested in a test bench at VTT Electronics, Oulu. The purpose of the test was to gather information on human comfort thresholds and criteria. In the test the complexity of human comfort was noticed, especially with comfort thresholds. The test bench was also used to find a human-seat transfer function. The purpose was to use the transfer function as part of a tractor model made with ADAMS-software. The results from the human-seat transfer function modelling are published in the 10th Sound and Vibration conference, July 2003 in Stockholm [Marjanen & Nevala 2003].

2.3.1.5 Including suspension kinematics into semi-active suspension control (tire suspension)

In the control of an intelligent suspension system, model-based control algorithms are used frequently. Linearized models offer an attractive alternative to be used in modelling or controlling an intelligent suspension system. They are quite simple to derive, can be justified relatively easy and they are accurate enough to examine the basic vibration behaviour of a vehicle, for example the natural frequencies of the vehicle body and individual wheels or axes. However, if the wheel travels are extreme, which is typical in off-road usage, the kinematics of suspension system can alter in a wide range though motion ratio can stay virtually constant.

In literature a lot of different optimal control approaches and algorithms can be found for automotive use. Most of the researches use a linearized quarter car model. A simple reason for this is that different widely known optimal control schemes (LQR etc.) can be derived relatively easy for these models. A quarter car model is also easy to perceive as a system with multiple objectives (namely the tire contact force and the vibration of the vehicle body), which are partly contrary. Despite of the usefulness of quarter car model their shortages are obvious if a vibration control of a whole vehicle is considered.

A half- and whole vehicle models are also used widely as an example of multivariable system in control problems. One reason for this is that an ordinary passenger car represents a true MIMO-system (Multi Input Multi Output) with interdependencies that can be calculated if certain simplifications and linearizations are made. The interdependencies are also relatively easy to perceive compared to matching properties of chemical reactions for example. Vehicles also represent very universal example, because practically everybody have driven a passenger car, at least on western countries. With these more complex models contrary objectives of controlling a suspension system become more difficult to handle and they also affect more to the performance of the control system.

A widely known and used control scheme for controlling the vibration of the vehicle body is skyhook damping. It represents an optimal control strategy in sense that it minimises the mean square velocity of the vehicle body if the excitation is considered as white gaussian noise. The basis of the skyhook damping theory lies in the LQG approach. Same theoretical basis can also be used to minimise dynamic tire load variation, when groundhook damping is concerned. The theory of skyhook damping is derived with simple mass-spring-damper system. The state equation becomes then so simple that the Riccati equation can be solved analytically. Still it has been used with success in damping of systems with multiple degrees of freedom.

The roll centre and roll axis concepts are widely known and used when basic driving characteristics of a vehicle are of interest. They offer a practical tool when “paper and pen”-analysis is used. In this study the roll axis concept is used to derive a model to be used in model reference control. In order to keep the complexity of the model in moderate level, only transverse kinematics of the vehicle suspension system is concerned i.e. the effects of anti-dive, anti-squat and anti-lift as well as the kinematics concerning traction and braking are neglected.

In this study semi-active technology is used in order to control the vibration caused by rough terrain. Semi-active technology is a practical solution to vibration problems in heavy off-road vehicles, because masses and inertias are relatively large and therefore natural frequencies are relatively low. Because of the reasons mentioned above, the energy consumption of fully active suspension would become incontinent. Also the hardware (valves, pumps etc.) required to implement active system would be very expensive.

The simulation environment in this study is implemented with ADAMS and C-language. Mechanical parts of the models are made in ADAMS, while the control algorithms and simplified kinematics needed by controllers are programmed with C. The model used in this study is based on commercially available off-road military vehicle. The model is modified to be suitable for this study but the most fundamental features like the suspension geometry and passive suspension system are kept original. The ADAMS model is shown in Figure 9.

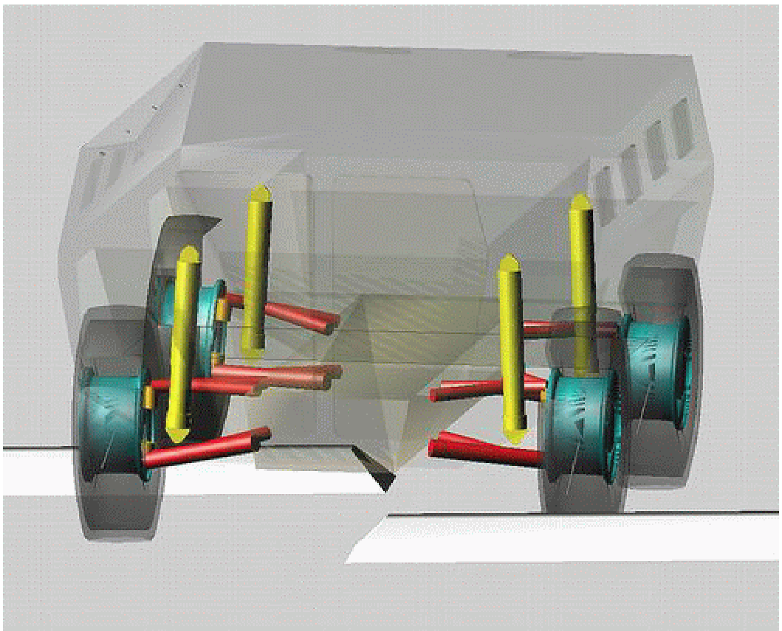


Figure 9. An off-road vehicle with independent suspension and asymmetric wheel travel.

The main focus of the study is to improve the driving characteristics of the vehicle while the driving comfort is of lesser importance. Still the possibilities to improve driving comfort on rough terrain are studied. The performance of model-based semi-active suspension system is compared to passive suspension system on different excitations.

2.3.2 *Technological, applicability*

2.3.2.1 Simulation environment

One of the important parts of the project has been the development of simulation environment for mechanical and control system research and design. Commercial programs have offered systems for linking two programs for the purpose to simulate mechanical models and control system models. These have not worked very well. Lot of problems with co-operation of different programs has occurred. At the beginning of the project the plan was to utilize the ADAMS/Matlab co-simulation procedure. The hydraulics and the control of the suspension systems were modelled in Matlab/Simulink environment. Models of the front suspension hydraulics and controls have been linked to the model of the case vehicle in ADAMS. Problems occurred at the linking of the two programs, because of the use of two integrators. After this the research of other methods was started. The researches concentrated on solutions were all the computation was done under one solver. Most easy and secure solution is to build up sub-program on ADAMS that has the control algorithm and data transfer from mechanical model to subprogram. The subprogram can be directly written with C code and then linked to the ADAMS solver or it can be build up by some program (e.g. Matlab) and transferred to C code and after that linked to the ADAMS solver. Now there is already a commercially available system for this. This new system to link control and mechanical models is a great advantage in the means of accuracy and computing time compared to co-simulation. In the industry there has also been interest for this kind of working environment. The commercially available version needs licences for two programs with certain type subprograms, but the environment used in this project does not require additional licences. That is also very important matter.

The fully active damping has been applied in two prototypes for tractor cabin suspension. Application in large scale requires further development especially considering controller tuning and costs. The studied DSP based methods are not yet applicable in industrial scale.

The developed vibration analysis program has been in test by VTT, HUT and University of Oulu with ADAMS-software. The program is considered useful.

The developed tool for generating virtual test tracks for simulations has received interest from industry and it is already in use in many Finnish companies and Universities outside the project consortium. It has been found practical and if needed it can be easily developed further or modified for certain type of use.

2.3.3 *Researcher training*

- Master's thesis, Ykä Marjanen, Whole body vibration analysis in work machines, 2002.

- Master's thesis, Jussi Määttänen, Modelling virtual test tracks for off-road vehicle simulations, 2002.

- Doctoral thesis concerning the modelling of disturbances with oversampling is under progress by Olli Vuorinen.

- Doctoral thesis concerning the effects of suspension kinematics to semi-active suspension in off-road vehicles is under progress by Jukka-Pekka Hyvärinen.

- Tero Lehtonen has started post-graduate studies and they are going on at the moment.

Very important aspect of the project has been the researcher training of the researcher in the project, because part of the researchers work is to give lectures in Universities. This project has given a good basis for these lectures. During the project the results have been exploited on the courses.

2.4 FUTURE ACTIVITIES

The applicability of fully active damping in larger scale in work machines is still suffering from too high costs and the complexity of the controller tuning. That is why research is still going on for developing easier tuning methods, possibly self tuning or adaptive, for relatively simple and low cost damping hardware. The study of the applicability of methods developed in signal processing domain, such as the oversampling method described above or the use of perfectly reconstructing filter banks for dividing the design to separate frequency bands, is continued in other projects. Plans for projects for further development are on going with funding from TEKES, VTT and industry.

The simulation of actively controlled suspensions was started in this project. There appeared problems in incorporating control systems into dynamic vehicle models, made in this case with ADAMS software. Possibilities, which were studied, include simultaneous use of Simulink and ADAMS models and creating a custom solver for ADAMS, where the control algorithms are written directly in C language. Both methods seemed to have some problems mainly concerning communication between ADAMS and Simulink and timing in custom solver case. Study on incorporating control systems into ADAMS models is continued in TEKES project Konemasina.

The developed vibration analysis program is developed further and a compact measurement device is under development. This device is to be used for the measurement of driver's vibration load in accordance with the ISO standard. Research projects, which include this goal, have already been started, funded by TEKES, TSR, VTT and industrial companies.

The validated agricultural tractor model that was developed in the project will be used in the future projects and in teaching purposes. The modelling and linking of mechanical systems and control systems will be further researched on ongoing EU project Vehicle Road Tyre and Electronic Control systems interaction (VERTEC). Also the validation procedures that were used on this project will be further studied on VERTEC project.

The significance of tyre models and tyre parameters on vehicle models has been highlighted during the project. During the project two widely used tyre models have been studied. Research on the tyres of off-road vehicles and tyre modelling of off-road vehicles will continue on future projects. In TEKES project called Konemasina new and improved tyre models will be studied and in TEKES project Negsimu determination of the tyre parameters will be studied. The knowledge of the tyre models that was achieved during this project can be exploited on those projects.

2.5 PARTNERS

Development time of an accurate MBS model is long and it is almost impossible to build a model without a lot of data from the vehicle manufacturer. During the project there has been co-operation with VTT Industrial Systems, Valtra Inc. and Patria Vehicles Oy on the development of the MBS models. The knowledge has been transferred in both directions. In future research the knowledge can be used for variety of research and product development purposes. Practical tests with the active damping of tractor cabin were done in co-operation with Valtra Inc.

2.6 BUDGET AND SCHEDULE

The total funding for the project has been 564521€. This sum consists of different sources. The Academy of Finland has funded the project with 350509€, TSR has funded the project with 67275€ and VTT with 143046€. The project is carried out between 28.8.2000 and 6.11.2003.

2.7 CONTACT ADDRESS

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2.8 PUBLICATIONS

Hyvärinen, Jukka-Pekka & Nevala, Kalervo: Semi-active damping of the front axle of a tractor. - The Eighth IFToMM International Symposium on Theory of Machines and Mechanisms, SYROM 2001, August 28 - September 1, 2001, Bucharest, Romania, Proceedings, Vol. IV, 2001. s. 171 - 176.

Hyvärinen, Jukka-Pekka & Nevala, Kalervo: Controlling the tire contact force in highway use of an agricultural tractor. - OST-01 Symposium on Machine Design, October 4 - 5, 2001, Tallinn, Estonia. Proceedings. Ed. By A. Folkeson. Stockholm 2001. s. 141 - 146.

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Marjanen, Y., Nevala, K., 2003. Whole body vibration analysis program for real measurements and virtual model. OST-03 Symposium on Machine Design, Oulu, Finland, June 2003.

Määttänen, J., 2002. Modelling virtual test tracks for off-road vehicle simulations. Helsinki University of Technology, Department of Mechanical Engineering, Master’s Thesis.

Vuorinen, O., Seppänen, T., 2001. Adaptive filtering of cyclostationary interference from speech. IEEE International Conference on Electronics, Circuits and Systems. ICECS

2.8.1 Submitted papers

Hyvärinen, J.-P., Nevala, K.: Semi-active damping of the front axle of a tractor, an experimental study. Tenth International Congress on Sound and Vibration, ICSV10, 7-10 July 2003, Stockholm, Sweden. (Submitted)

Järviluoma, M., Virtanen, T., Nevala, K., Marjanen, Y., 2003. Active damping of vertical vibrations of a tractor cabin. Tenth International Congress on Sound and Vibration, ICSV10, 7-10 July 2003, Stockholm, Sweden. (Submitted)

Lehtonen, T., 2003. Validation of an agricultural tractor MBS model. Heavy Vehicle Systems, A series of the Int. J. of Vehicle Design. (On referee process)

Marjanen, Y., Nevala, K., 2003. Constructing a transfer function for human – seat response. Tenth International Congress on Sound and Vibration, ICSV10, 7-10 July 2003, Stockholm, Sweden. (Submitted)

2.8.2 Papers under progress

Hyvärinen, J.-P. The effects of suspension kinematics to semi-active suspension in heavy off-road vehicles

Lehtonen, T., 2004. Development and simulation of agricultural tractor suspension systems using MBS modelling.

Mäkelä, S.-M., Järviluoma, M., Vuorinen, O., 2003. Periodic sample reorganising method for cyclic disturbance signal modelling.

2.9 ACRONYMS

ADAMS = Automatic Dynamic Analysis of Mechanical Systems

MBS = Multi-body system

HUT = Helsinki University of Technology

VTT = Valtion Teknillinen Tutkimuskeskus (Technical Research Center of Finland)

TEKES = Teknologian kehittämiskeskus (National Technology Agency of Finland)

TSR = Työsuojelurahasto (The Finnish Work Environment Fund)

LQR = Linear quadratic regulator

LQG = Linear, quadratic and Gaussian

PRBS = Pseudo random binary sequence

3 EXTREME VALUES OF THE PISTON ENGINE (HUT/ICEL)

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Helsinki University of Technology, Internal Combustion Engine Laboratory

ABSTRACT: During the history of the internal combustion engine, different development tendencies have been in foreground in turn. Such attributes as reliability, efficiency, low manufacturing costs, low exhaust emissions, ability to accept poor quality fuels are some examples of them. Increase of the power density (power per cylinder swept volume) has, however, always kept its position as a main trend.

The target of this project has been to develop a research diesel engine for experimental test and capable of very high power densities, that probably will appear in commercial engines after ten years or more, and to carry out tests with high power rating with it.

This report gives a general picture of the design of the "Extreme Value Engine" and describes theoretical and practical difficulties encountered during the project and the measures they were solved. Being targeted for a very high power density and purely for research purposes, many extraordinary solutions must have been used in the design.

The electrohydraulic intake and exhaust valve actuating system for this "Extreme Value Engine" (EVE) has been designed and built in the frame of another TUKEVA project in Tampere University of Technology, Institute of Hydraulics and Automation (TUT IHA). All other parts of the engine and its auxiliary systems has been designed and built in Helsinki University of Technology, Internal Combustion Engine Laboratory (HUT ICEL).

3.1 INTRODUCTION

Usual way to progress toward higher power densities in the engine industry is to design a new engine with the tools available, to build the engine and test it. Later, some minor improvements can be done on the design but the main construction stays as it was originally. This is rather safe way to proceed but there are some limitations with it: firstly, because of economy, one is not willing (particularly in the case of large engines), to try quite new designs and secondly, the commercial engines built are not very good pieces to be used on the tests of combustion, thermal stresses and tribology.

In this project the basic idea was to build a single cylinder research diesel engine without limitations of commercial engine. In the engine of this kind, novel solutions of design can be changed and tested somewhat freely. The conditions for experimental research can be arranged also much better than with commercial engines. Thus it is possible more easily to do basic studies with physical phenomena of diesel engine (fuel injection, gas exchange, combustion, heat transfer, stresses and tribology of components) than with commercial engine. This work is directed to the future. It is hoped to bring into view new technical solutions and to speed up technical development. Besides the tests that will be done later, the design work during this project has already been scientific research.

3.2 OBJECTIVES

In the beginning of the project, very severe target values for the design of the research engine were set:

Table 1. Design and target values

Bore	200 mm
Stroke	280 mm
IMEP, max	5 MPa
Mean piston speed, max	15 m/s
Cylinder pressure, max	40 Mpa

As can be seen from the figures of bore and stroke, the engine is somewhat large representing engine class, which is generally called as "medium speed engines". Brake mean effective pressure (BMEP) and mean piston speed are the two figures that determine the power density of the engine. In this case, however, in place of BMEP indicated mean effective pressure was used for the target value. The difference between IMEP and BMEP is friction mean effective pressure FMEP.

$$IMEP - BMEP = FMEP \qquad (1)$$

Because FMEP comes from mechanical friction and the use of engine driven auxiliary devices and because in this engine the crank mechanism and bearing have much larger dimensions as in common engine, IMEP gives a better picture of phenomena around combustion chamber and cylinder.

Typical IMEP of today's medium speed diesel engine is around 3 MPa and maximum cylinder pressure about 20 MPa whereas typical figure for the mean piston speed is 8-9 m/s.

It was targeted to build two versions of the research engine, one "high pressure version" with 5 Mpa IMEP with 8.4 m/s piston speed and "high speed version" with 3 MPa IMEP with 15 m/s piston speed. The aim was to use same basic components and auxiliary devices but the piston and connecting rod would be designed separately for each version. With both versions the power density would be about 70% more than in modern engines.

In the end of the project the objective was to run tests with both engine versions.

3.3 RESULTS AND ACHIEVEMENTS

The work was started 1999 with feasibility study, where thermodynamic and other theoretical possibilities to build such a research engine were evaluated. The preliminary design of engine layout, components and auxiliary systems was started in 2000. In the years 2001 – 2002 gradually to detailed design was shifted. In 2000 some larger auxiliary devices like power electric devices and charge air compressor were purchased but the main part of deliveries were carried out in 2001 and 2002. During the first part of 2003 the main components have been assembled to the engine, piping work completed and most of the sensors and actuators of the auxiliary control system implemented. In this project very much practical work must have been done besides those studies that one might consider as scientific achievements.

In Figure 1, a general layout of the engine is depicted.

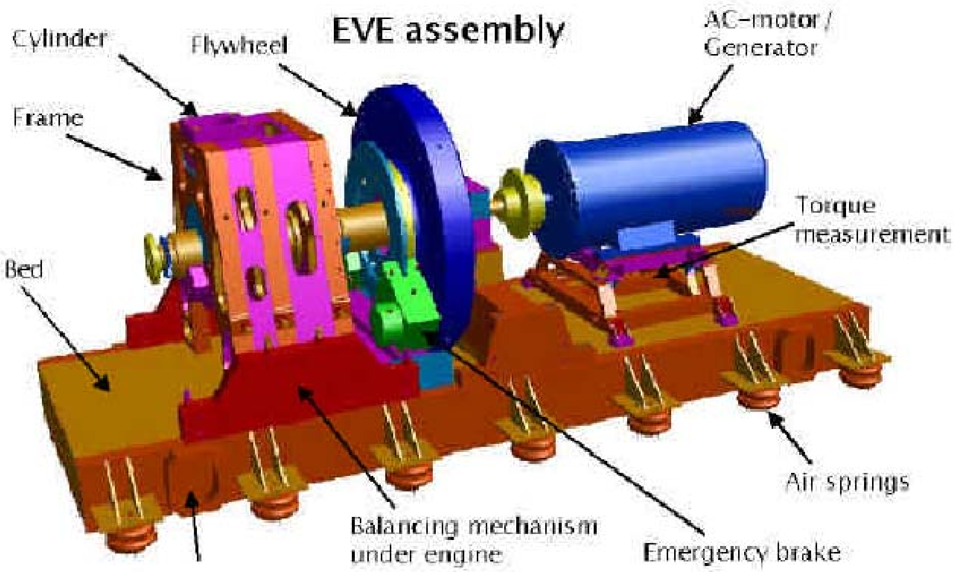

Figure 1. General layout of the extreme value engine, EVE.

As scientific research in this project, one can consider the modelling of combustion and shaping of the high-pressure combustion chamber. The special problem here is that large amount of fuel must be injected into very small combustion chamber without the impact of the spray to wall. Figure 2 presents results of calculation of 3D-combustion model

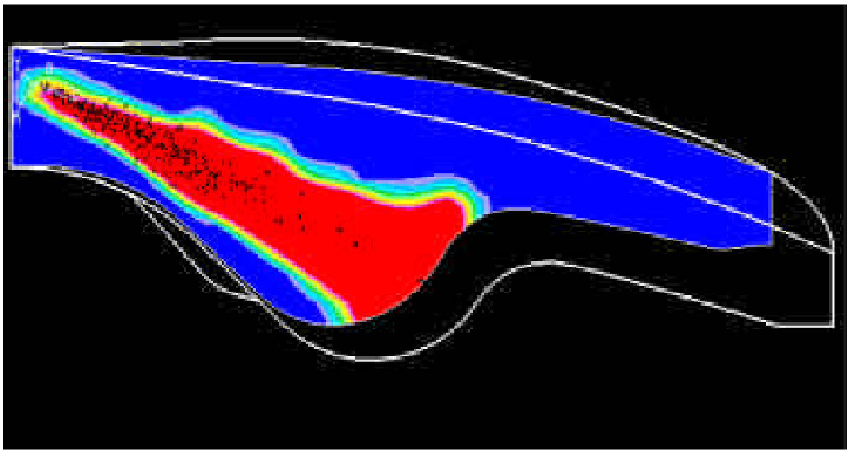

Figure 2. Combustion in EVE-high pressure combustion chamber.

Another practical problem with combustion chamber was that because of the large amount of fuel a very large injection nozzle was needed. This in turn brought about that the gas exchange valves must have been tilted from the way of nozzle. This is quite unusual in commercial engines and would have been impossible to carry out without electrohydraulic valve actuating system. Because of tilted valves the shape of the quiescent combustion chamber is somewhat conical, which is also something new. In Figure 3, a cross-section of the upper part of the cylinder is depicted.

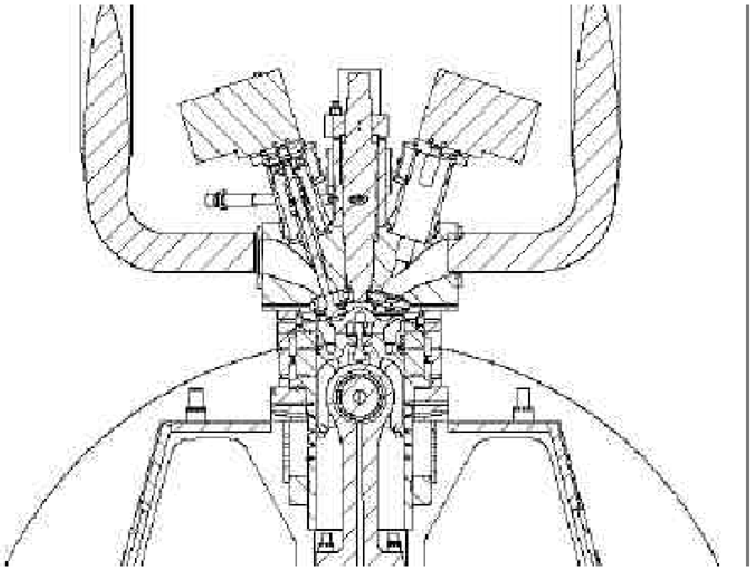

Figure 3. Cross-section of the EVE cylinder head and cylinder

Because of the high power density of the engine, very high mechanical and thermal load is directed to the engine components. This must have been taken into account in the materials, shape of components and design of cooling. As an example in Figure 4, an analysis result of temperature of cylinder head and exhaust valve can be seen. The layout of two opposite intake and two opposite exhaust valves is a new solution for keeping thermal loads between valve bridges low enough. Figure 4 presents hydraulic tightening of four large screws of cylinder head.

Figure 4. Tightening of the cylinder head.

The calculation of the fatigue resistance of the crankshaft is very difficult task. In this engine the target forces are much higher than in the ordinary engine of same size. Though the counterweights were moved outside the main bearings and the diameters of the pins were made very large, there were still problems to get strains down enough. At last the thin crank webs were found to place between crank and main bearing pins. Roundings needed for fatigue resistance could be machined into these webs. In Figure 5 strength analysis of crankshaft is depicted.

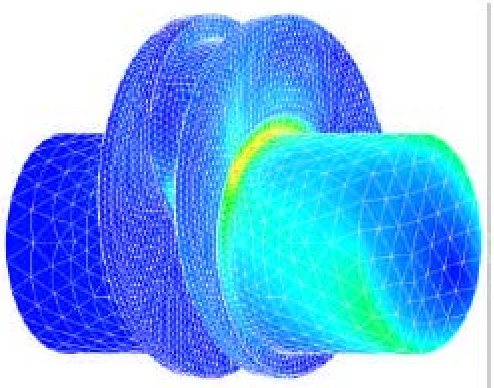

Figure 5. Strength analysis o fthe crankshaft

The auxiliary and control systems of the engine consists of

- power electrics system for brake generator with bidirectional frequency inverter
- separate lubrication system
- separate air compressor capable to give 800 kPa charge air overpressure (usual charge air pressure in modern engines is under 400 kPa)
- separate cooling circuits for charge air, lubrication, cylinder liner, flame ring and cylinder head, the engine component cooling circuits has been dimensioned for 180 °C maximum cooling liquid temperature (normal today 80...100 °C)
- separate hydraulic system for the control common rail injection and hydraulic valve actuating system
- common rail fuel injection system
- high speed control system to control in real time valve and fuel injection timing (in common engine of this size has usually mechanical valve operating system and fixed valve timing)
- integrated auxiliary control system to measure and set such slow speed values as charge air pressure and temperature, cooling water temperatures etc.

Because tests can be done with this engine much faster than with full sized commercial engine, new technical solutions that are proved successful are quickly applicable in commercial engines.

This project has offered very much technical and scientific problems and thus a good field for researcher training. Especially the skill to use modern design and analysis methods has improved very much. Practical work in this project has however, consumed a lot of resources and only few papers have been published. Several post graduate students have been appointed in this project in HUT and parallel projects in TUT and scientific papers and dissertations eill be published in increasing numbers starting next year 2004. The deeper scientific work with EVE is possible in the near future.

3.4 FUTURE ACTIVITIES

In the current project a big share of the work has gone to the design and building other parts and systems than the most interesting components in relation high power density. Besides that, the engine will not come quite ready within the project: there was not enough time to complete electrohydraulic valve actuating system and high-pressure piston.

The plan is to start immediately after current project two new projects:

> A commercial project with Finnish engine industry, in the beginning of which the engine with its systems will be completed and tested. Thereafter the flexible control possibilities of the engine will be used for evaluating the charging and valve operation possibilities to decrease exhaust gas emissions in the future.
>
> and
>
> A public project to complete and build a high-pressure piston for the engine, to run test series with high power density and to make comparisons between the results obtained by models and experiments.

The first project has already been ordered from HUT ICEL. For the second, an application has been left to TEKES. The main part of the current research group is planned to take part to these new projects.

3.5 PARTNERS

The work of project entity has been is done in three research institutes:

- Helsinki University of Technology, Internal Combustion Engine Laboratory, HUT ICEL
- Tampere University of Technology, Institute of Hydraulics and Automation, TUT IHA (design, simulation and manufacturing of electrohydraulic valve actuating system for EVE)
- Tampere University of Technology, Institute of Material Science, TUT IMS (research of the coatings of combustion chamber surfaces)

The EVE-project of HUT ICEL has obtained public funding from National Technology Agency TEKES (ProMOTOR-research programme) and from Academy of Finland (TUKEVA-research programme). Industrial funding has been got from following companies:

Wärtsilä Finland Oy (Finland)
Sisu Diesel Oy (Finland) and
Fortum Oil and Gas Oy (Finland)

Helsinki University of Technology has also taken part in costs.

Material and immaterial support has been obtained from the following companies:

Atoy Oy (Finland), managing group work, contacts
M. Jürgensen GmbH & Co KG (Germany), cylinder liners
Märkisches Werk GmbH (Germany), valves
KS Kolbenschmidt GmbH (Germany), pistons
Goetze Federal-Mogul Burscheid GmbH (Germany), piston rings
Hoerbiger Ventilenwerke GmbH (Austria), crankcase explosion valves

Financing structure and the roles of different research institutes are represented in Figure 6. Table 2 presents the budget of EVE-project of HUT ICEL. The contact information of the financiers, research institutes and partners can be found on the web page of EVE http://www.icel.hut.fi/eve/.

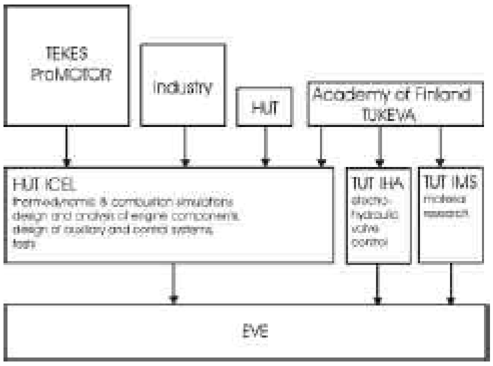

Figure 6. Diagram of EVE-project cluster.

This project has had its own managing group, the composition of which is following:

Matti Kleimola (chairman)	Wärtsilä Corporation
Kalle Hakalehto	Academy of Finland, TUKEVA
Ari Juva Fortum	Oil and Gas Oy
Martti Korkiakoski	TEKES
Martti Larmi	HUT ICEL
Timo Laurila	TEKES
Gösta Liljenfeldt	Wärtsilä Technology
Tapio Mäntylä	TUT IMS
Kalevi Salmén	Sisu Diesel Oy
Hannu Salmenpohja	Atoy Oy
Raimo Turunen	HUT ICEL
Matti Vilenius	TUT IHA

3.6 BUDGET AND SCHEDULE

The budget of the EVE-project of HUT ICEL is presented in table 2.

Table 2. Budget of EVE-project of HUT ICEL (k€)

	1999	2000	2001	2002	2003	Total
TEKES		43.1	393.6	377.6	151.7	966.0
Academy of Finland		21.5	41.4	41.4	21.5	125.8
Wärtsilä Finland Oy	8.1	63.9	100.9	98.3	40.3	311.5
Sisu Diesel Oy		3.4	3.4	3.4	3.4	13.6
Fortum Oil and Gas Oy		3.4	3.4	3.4	3.4	13.6
HUT ICEL	2.7			60.0	13.6	73.6
Total	10.8	135.3	542.7	584.1	233.9	1506.8

The original target to build two versions of research engine and to make tests with them proved quite too demanding and two revisions to project plan was made by the managing group. First, the design and tests of the high-speed piston and connecting rod were dropped out. Finally the objective was only to get the engine into running condition with normal power rating of today. However, at the time of writing this, even this objective has not been achieved. Valve actuating system and parts of hydraulic and cooling pipes are still missing. As described in chapter “future activities” these will be completed during in this year.

3.7 CONTACT ADDRESS

Contact address of EVE project of HUT ICEL is following:

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Tel. +358-9-451 3455

3.8 PUBLICATIONS

TEKES ProMOTOR-yearly report 1999, T09/99-1

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Introduction of the extreme value engine project. Proceedings of the 23rd CIMAC World Congress, Hamburg: 673-677, 2001

Turunen, R.
Extreme values of the piston engine, test engine for extreme value research. Proceedings of the TUKEVA-seminar "Mechanical engineering research new possibilities by co-operation", Academy of Finland, Tampere, pp. 73-83, January 2002 (Academy of Finland, TUKEVA)

4 EXTREME VALUES OF THE PISTON ENGINE (TUT/IHA)

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ABSTRACT: One way to improve diesel engine performance and to reduce emissions is improving power density and combustion cycle efficiency. This can be done by increasing combustion pressure and engine speed which require improving the controllability of the engine. Besides of the fuel injection system the key element in improving controllability is the valvetrain.

Extreme combustion pressure and engine speed set special requirements for valvetrain design. As the pressure is increased also the load on the valve plate increase and on the other hand as the engine speed is increased the higher acceleration is needed. Combination of these two makes instantaneous power required very high which makes electrohydraulic system a natural choice for actuation mechanism.

Several electrohydraulic gas exchange valve mechanisms for Extreme Value Engine (EVE) has been developed by Institute of Hydraulics and Automation of Tampere University of Technology. In each valvetrain the valve opening is actuated by the means of the electrohydraulic system and closing is actuated either by hydraulics or retainer spring. Power consumption of valvetrains is reduced by recovering the kinetic energy of the valve during deceleration. The electrohydraulic valvetrain has significant benefits in comparison to conventional design: valve motion can be controlled continuously and independently, space needed for valve actuation is reduced, valve opening and closing are faster and speed can be varied. A prototype valvetrain has been manufactured and is currently under laboratory testing and will be installed in a real scale engine during summer 2003 to be tested in a real operating conditions.

4.1 INTRODUCTION

Valvetrain research project is funded by the Academy of Finland (Suomen Akatemia) and it is one of three separate projects in the “Extreme Values of the Piston Engine” collaborative project. Valvetrain prototype and its testing in a live engine are funded by “Extreme Value Engine”-project (EVE), which is National Technology Agency (TEKES) and industry funded project of Internal Combustion Engine Laboratory of Helsinki University of Technology (ICEL/HUT).

4.1.1 *Electrohydraulic valve actuation*

Main reasons for utilising alternative valve actuation mechanisms, such as electrohydraulic valve actuations, are:

- Flexibility in valve timing
- Faster valve opening and closing
- Space taken by valvetrain in the cylinder head can be significantly reduced

- Design of combustion chamber geometry is not affected by fixed placement of valves

In comparison to other means of variable valve actuation electrohydraulic valve actuation is often considered inefficient, complex and expensive [2]. Which probably applies to most of the cases in automotive engines. However numerous electrohydraulically actuated valvetrains for automotive engines have also been introduced, which shows that electrohydraulic actuation can also be applied to high-speed applications [3][4][5][6][7][8][9]. Among current production engines electrohydraulic valvetrains are only used in low speed two stroke diesel engines. In low speed two stroke diesels the electrohydraulic valvetrain has shown significant advantages in comparison to traditional solutions [10][11][12][13].

As an idea an electrohydraulic subsystem for valve actuation is very straightforward and simple. Relatively complex camshaft mechanism is only replaced by hydraulic linear actuators, which directly operate gas exchange valves. Even valve retainer springs can be left out and hydraulic actuators also close valves. Linear actuators are controlled by hydraulic valves, which are controlled by an electronic control system on the basis of crankshaft angle and several other parameters.

Even thought the basic idea is as simple as described above and simple even compared to traditional solutions it contains numerous shortcomings and difficulties to over come. In this project also the nature of the EVE sets numerous special requirements to the electrohydraulic valvetrain, mainly because of the extreme cylinder pressure, high opening and closing speed requirements and also high ambient temperature.

4.2 OBJECTIVES

Benefits that camless valvetrain could offer are clear and proven, but both technically and economically sound way to realise them for operating engines of any speed and power range is missing, except for very slow speed 2-stroke diesels. The main scientific objective of the project was to research possibilities to realise electrohydraulic camless gas exchange valve mechanism for high and medium speed diesel engines, the final goal being a prototype valvetrain to be used in EVE experimental engine.

EVE was chosen to be the test environment for several reasons. Being a single cylinder experimental engine it is a good test bed for valvetrain, it offers a lot of freedom for actual component design and testing and the valvetrain itself is easier to realise than in a multicylinder engine. Also the nature of EVE, high combustion pressure and high speed, makes it far more demanding environment than current production engines and thus the valvetrain must exceed all demands of current engines. EVE also needs a camless valve actuation for controllability reasons and because of the cylinder head geometry.

The main objective being a technically and economically sound solution the utmost research problem is the solution itself as there are no readily available solutions for this kind of application. The main objective can be divided in several sub-objectives:

- Realisable electrohydraulic valve actuation mechanism
    - Technology
        - Fast high power hydraulic valves
        - Energy recovery in reciprocating actuator

        - Speed control of extremely fast and high power actuator
        - Repeatability of actuations
        - Syncronisation of the valve pair
        - Durability of actuators

    - Methodology
        - Computer simulation as a development tool
            - Simple models for evaluation of different solutions
            - More complicated models for component design purposes
            - Complete system model for fine tuning the system
        - Laboratory testing for fine tuning together with the complete system model
        - Testing in live engine for final evaluation of the design

    - Economically sound solution
        - Durability
        - Usability
        - Reliability

    - Researcher training
        - One PhD-degree

4.3 RESULTS

4.3.1 *Scientific and technological achievements*

As previously said several different variations of electrohydraulic camless valvetrain has been developed. Two of them apply valve retainer springs and one is springless. All valvetrains include energy conservation of some level. Significant differences in valvetrains are in their controllability and dynamical behaviour in different operating points. Behaviour and controllabity are one of the main issues since one the goals of the research and development project is developing a functional and reliable valvetrain for research engine which will be run in various different configurations during years to come. Key performance characteristics targeted are:

Table 1. Key performance characteristics of valvetrains

Opening	30 degC.A. @ 900 rpm or 60 degC.A. @ 1600 rpm
Closing	30 degC.A. @ 900 rpm or 60 degC.A. @ 1600 rpm
Timing	Infinitely variable
Lift	Variable / unequal lift

4.3.1.1 IHAflex v1.0 [14]

The first version of the valvetrain (*Fig 1.)* is loosely based on the *hydraulic pendulum* idea introduced by Schecter and Levin 1996 [3]. The hydraulic actuator is controlled by two cartridge valves, which control the flow from and to high and low pressure circuits. Low pressure circuit is used instead of an ordinary tank line to get oil supply to actuator via checkvalve during deceleration. Kinetic energy of the moving actuator is converted to potential energy of pressurised oil during decelerations in both opening and closing movement. During closing movement energy is also recovered in low pressure line. Pilot control of the system consists of two high response servovalves.

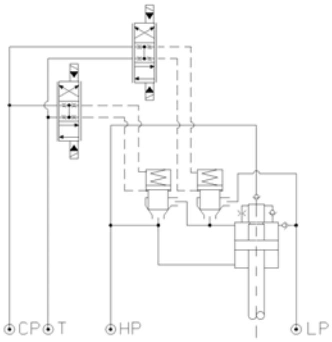

Figure 1. IHAflex v1.0 valvetrain

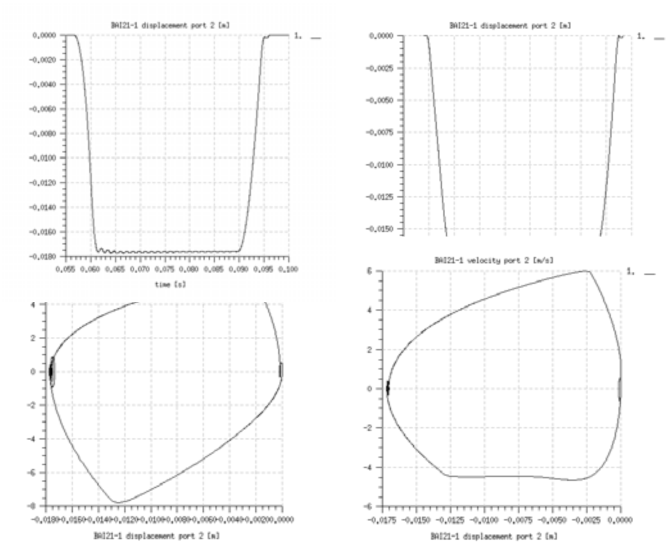

Figure 2. Performance of the valvetrain v1.0 according to simulations (left exhaust, right intake)

Performance of the valvetrain v1.0 is satisfactory (*Fig 2.*), how ever it is very difficult to control if operation points change drastically. Controlling the valvetrain needs very precise timing of control valves as well as very precise control of the pressure in both low and high pressure lines to keep contact speeds in both ends of the movement in reasonable limits. Also the vibration at fully open position is not a desirable effect, but can not be avoided without compromising contact speed. Improvements in control valves, i.e. new control valve technology, could make this construction very attractive, since its energy recovery ratio is relatively good.

4.3.1.2 IHAflex v1.1

The second version (*Fig 3.*) is almost similar to v1.0, the only difference is that a retainer spring is used. Using retainer spring makes it easier to set the high pressure circuit pressure to match different operating points. In v1.1 high pressure circuit pressure can be set only to meet force requirements of the opening movement and closing movement can be disregarded. Force requirements during closing movement are almost independent of operating point, there for spring gives more or less satisfactory results at wide variety of operating points.

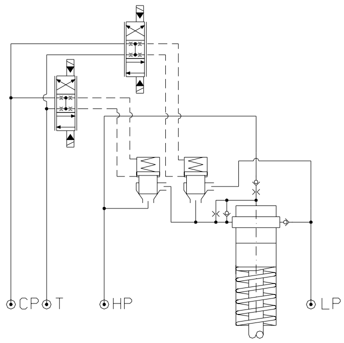

Figure 3. IHAflex 1.1 valvetrain

Dynamic performance (*Fig 4.*) is satisfactory, however it has many of the same problems than v1.0 including vibration at fully open position.

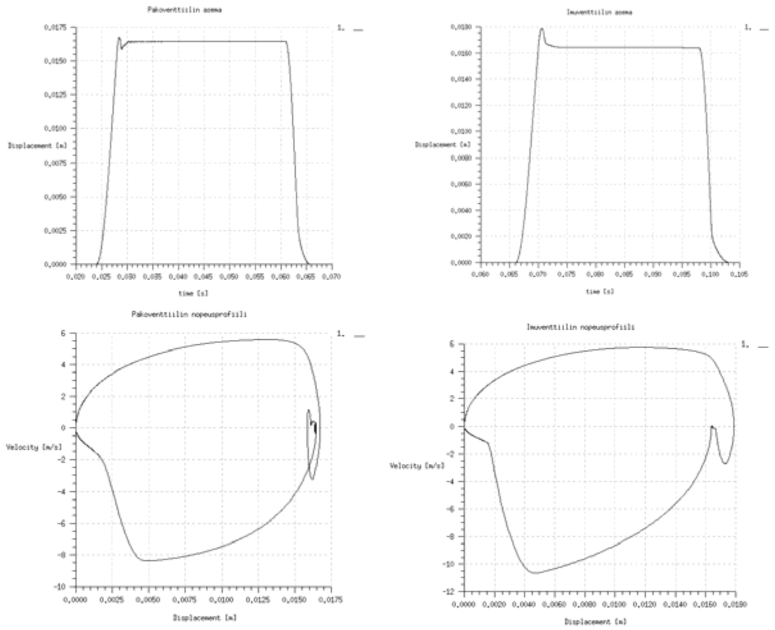

Figure 4. Performance of the valvetrain v1.1 according to simulations (left exhaust, right intake)

4.3.1.3 IHAflex v1.2 [15] [16]

The third (*Fig 5.*) version applies different type of control valve. Directional control valve is a spool valve pilot controlled by a single high response servovalve. Besides of it there is also a flow control valve integrated into the actuator. Flow control valve is used for controlling the actuator in-flow as a function of actuator displacement during the opening movement. As in v1.1 the closing movement is done by the retainer spring. Separate high and low pressure circuits are not used in this version, but oil supply to actuator during deceleration is done by an orifice. Besides of simplifying the system construction this also leads to one critical component less and thus the performance is not affected by the return flow and dynamic characteristics of the check valve. The orifice also forces the actuator move to always slowly fully open position and thus prevents or ceases all vibrations.

Over all performance of the actuator is relatively good (*Fig 6.*), even though ,as well as the v1.1, it can not operate as smoothly at nominal operating point as the v1.0. However it is easily controllable, does not require very accurate control valve timing or accurate pressure control and its basic construction is a lot simpler and cheaper than in other two constructions.

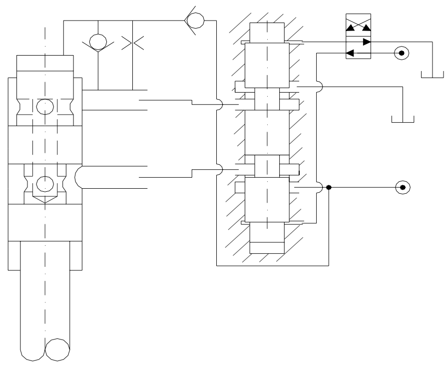

Figure 5. IHAflex v1.2 valvetrain

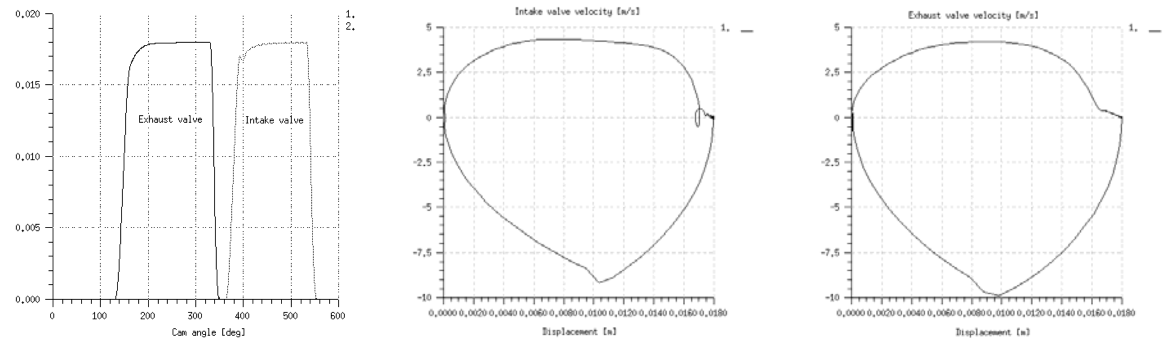

Figure 6. Performance of the valvetrain v1.2 according to simulations (left position vs crank angle, middle intake velocity profile, right exhaust velocity profile)

4.3.2 *Researcher training*

Objective for researcher training was one PhD-degree until end of the year 2003. However due to delays in prototype components manufacturing reaching this objective is delayed to early 2004.

Co-operation with other projects and wide scope of this one has made it possible to have one MSc-degree by the end of the year 2003.

4.4 FUTURE ACTIVITIES

The project will continue until the of the end year 2003. Activities taking place before the end of the project are completing laboratory testing and testing in a live engine. Also the researcher training objectives will be mostly completed during the rest of this year.

Future projects involving electrohydraulic valvetrain research and development have been planned. Even thought during this project several basic principles for realising hydraulic valve actuation has been introduced the electrohydraulic camless valveactuation is still very far from production ready idea. To bring this technology in state where it can benefit real engine manufacturers further research is needed in electrohydraulic valve actuation itself and also in fast response ON/OFF hydraulic valve (digital hydraulic valve) technology.

It is highly possible that some further R&D is also needed in the case of prototype valvetrain installed in EVE, since it is not likely that the first prototype will satisfy all needs of an experimental engine of which active lifespan is probably over ten years.

4.5 PARTNERS

The single most important partner in this project has been Internal Combustion Engine Laboratory of Helsinki University of Technology. The whole project has been carried out in very close co-operation with ICEL's Extreme Value Engine project. This co-operation has been very fruitful and essential to both parties. Close co-operation with a partly industry funded project has given more depth to this project by making it possible to have a working prototype as a goal and giving invaluable industry contacts.

4.6 BUDGET AND SCHEDULE

Project budget was according to *table 2.*

Table 2. Project budget

	Allocation (EUR)
2000	20 023.60
2001	39 710.60
2002	38 869.26
2003	20 191.80

Project was divided in separate tasks and scheduled according to *table 3.*

Table 3. Project schedule

	2000				2001				2002				2003			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Basic Research		■	■	■												
Operating principles				■	■	■	■	■								
- Evaluation by simplified models				■	■	■										
- More accurate models							■	■								
Actuator prototype							■	■	■	■	■	■				
- Modeling and simulation							■	■	■	■	■					
- Predesign								■								
- Design									■	■	■					
- Manufacturing												■				
Hydraulic system							■	■	■	■	■	■				
- Predesign							■	■								
- Design									■	■						
- Complete system modeling								■	■	■	■	■				
- Manufacturing												■				
Testing													■	■	■	■
- Laboratory													■			
- Live engine														■	■	■
Reporting					■	■	■	■	■	■	■	■	■	■	■	■

4.7 CONTACT ADDRESS

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4.8 PUBLICATIONS

Aaltonen J., Huhtala K., Vilenius M., Electrohydraulic Valvetrain for Extreme Value Diesel Engine, 2001, SAE paper 2001-01-3261, ATT 2001, Barcelona

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5 EXTREME VALUES OF THE PISTON ENGINE (TUT/IMS)
Advanced Thick Thermal Barrier Coatings

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ABSTRACT: In TUKEVA Programme, the research work carried out in Tampere University of Technology, Institute of Materials Science (TUT/IMS) was part of the Extreme Value Engine (EVE) project. The sub-project of TUT/IMS, "Advanced Thick Thermal Barrier Coatings", concentrated on studying thick thermal barrier coatings (TTBC) for combustion chamber components of diesel engines.

This report gives an introduction to the research field, the objectives of the study and the summary of the most important results. At the end of the report it is presented the budget and schedule of the project and listed the publications prepared during the TUKEVA Programme.

5.1 INTRODUCTION

Plasma sprayed zirconia coatings are widely used as thermal barrier coatings (TBC) in gas turbine hot section components such as burners, transition ducts, vanes and blades. Instead their use in diesel engine combustion chamber components has been quite rare, because of the long run durability problems in such conditions. For that reason, there have been many investigations in developing proper TBCs for diesel engines [1-7]. The conditions in diesel engine combustion chambers differ considerably from those of gas turbine hot sections. In diesel engines the mean temperature levels of TBC surfaces are much lower than in gas turbines, but the number of thermal cycles and shocks are correspondingly higher. The varying pressure within the diesel engine cycle causes severe mechanical loads and stresses to the surfaces of combustion chamber component that are not comparable to conditions of gas turbines. Low and medium speed diesel engines in marine and energy production applications use normally variable grades of liquid fuels which contain impurities such as S, V and Na. Because of the high amount of impurities and quite low mean temperature in the combustion chamber of diesel engines, the conditions are favorable for hot corrosion. For these reasons the major failure mechanisms that cause TBC spallation in diesel engines are hot corrosion, thermal cycling and mechanical loading while in gas turbine more presumable coating failure is caused by coating-substrate interface stresses induced by bond coat oxidation [8,9].

Increasing the turbine hot gas inlet temperature (TIT) is a potential way to improve the efficiency of the gas turbine driven combined cycle process. At the moment in land based gas turbines the maximum TIT is around 1500^{o}C and in aero engines even higher. Since the structural materials, nickel and cobalt based superalloys, can not face temperatures higher than 950^{o}C, TBCs with better insulation properties are needed. With thicker TBCs the mean combustion temperature of the diesel process can also be increased. The increased temperature does not affect directly to the efficiency of the diesel process, but this extra heat can be recovered in turbocharger or in flue gas boiler in combined cycle. Some studies have also shown that TBCs lower the fuel consumption of the diesel process [1,7].

At the moment in most applications the thickness of TBCs is below 500 μm, because of their limited reliability. Normally the increased thickness of TBCs leads to a reduced coating lifetime. Normally we can say that the thicker the coating – higher the temperature gradient through the coating – higher the stresses in the coating. Even if the coefficient of thermal expansion (CTE) of $8Y_2O_3$-ZrO_2 is close to that of the substrate material, the CTE difference of the substrate and coating induces stresses at high temperatures at coating interface. The strain tolerance of TTBC has to be managed by controlling the coating microstructure.

Use of thicker coatings generally leads to the higher coating surface temperatures that can be detrimental, if certain limit is exceeded. In long run, the phase structure of yttria stabilized zirconia $8Y_2O_3$-ZrO_2 is not stable above the 1250°C and can be unstabilized quite fast at 1400°C [10]. Also the strain tolerance of the coating can be reduced rapidly by sintering effects, if too high surface temperatures are allowed [11]. For these reasons several cooling techniques of the gas turbine component are used to control the surface temperatures of the TBCs.

There have been several attempts to enhance the properties of the plasma sprayed TTBCs by various sealing and modification processes. Sealing treatments have been used mainly for improving the hot corrosion properties and erosion resistance of the coatings by closing the open pores on the coating surface. The modification of the open porosity in TBCs has been approached by liquid metal impregnation [12], laser-glazing [13-17], hybrid spray processing [18], solar furnace heat treatment [19], hot isostatic pressing (HIP) [20,21], sol-gel processing [22-24], phosphate impregnation [25-27] or by thin CVD overlay coatings [28]. Organic sealants are mainly used for corrosion protection at lower temperatures [29]. The other modification processes are mainly focused to increase the strain tolerance of TTBCs by lowering the stiffness of the coating. Lots of studies have been related to reducing Young's modulus and residual stresses of the thick TBCs [30-33]. In practice these can be achieved by controlling the spray parameters, but also controlling the substrate and coating temperature during the coating deposition. If the system heats too much in spraying, compressive stresses are formed into the ceramic coating. For that reason active substrate and surface cooling is normally used during spraying. Spray parameters can also be fixed to obtain desired level of porosity and microcracks. Vertical segmentation cracks, which can go through the whole coating, can be produced by introducing rather thick spray passes in coating deposition[30]. Segmentation cracks are very effective in lowering the Young's modulus of the TTBCs. For that reason they can increase the lifetime of coating in thermal cycling significantly[31]. In addition to strain tolerance, pores and especially the horizontal cracks are naturally advantageous in lowering the thermal conductivity of the coating. Extremely high porosity values (up to 25 vol-%) of TBCs have been obtained by spraying polymers together with zirconia[32]. However, when spraying very porous and thick coatings the deposition efficiency (DE) decreases, but also mechanical properties, such as erosion resistance, decreases. When modifying the TBC structures one should remember that the coating primary functions, such as thermal insulation and strain tolerance, should not be deteriorated.

5.2 OBJECTIVES

The aim of the project was to improve the properties of the Thick Thermal Barrier Coatings (TTBC) by modifying their structure by post treatments such as laser-glazing, phosphate sealing treatment and sol-gel impregnation. The work included coating manufacturing, optimizing and performing the modification procedures, coating characterization, determination of the coating mechanical and thermal properties, as well as high temperature testing of the coatings.

The goal of our project was to compare different TTBC modifications and finally find methods to produce thermally more resistant and mechanically more durable TTBCs without losing the beneficial properties of the coating such low thermal conductivity and strain tolerance.

5.3 RESULTS AND ACHIEVEMENTS

5.3.1 Scientific and technological results and their applicability

Results presented in this report are collected from the publications prepared in TUKEVA Programme. Results are divided in four chapters: Microstructural characterization, mechanical properties, thermal properties and high temperature testing.

Microstructural characterization

The optimal thickness of the melted layer in laser glazed TTBCs was 50-150 µm. In all cases the melted zone was significantly densified and vertical macrocrack network was introduced. In the laser-glazed $8Y_2O_3$-ZrO_2 coating the vertical cracks were nearly perpendicular to the surface, but in other coatings the cracks had tendency to branch and turn from the vertical direction below the melted layer. Due to the denser microstructure, the microhardness of surface layer in laser-glazed coatings was increased up to 1119-1240 $HV_{0.3}$. The t'-ZrO_2 was a dominating phase of the laser-glazed $8Y_2O_3$-ZrO_2 and $25CeO_2$-$2.5Y_2O_3$-ZrO_2 coatings whereas the phase structure of the magnesia stabilized zirconia changed from c-ZrO_2 + t'ZrO_2 to the mixture of rhombohedral $Mg_2Zr_5O_{12}$ and c-ZrO_2. Texture analysis showed a strong preferred crystal orientation in direction [002] of the t'-ZrO_2 phase in laser-glazed $25CeO_2$-$2.5Y_2O_3$-ZrO_2 coating.

In phosphate sealed coatings the penetration depth of the sealant was approximately 300-400 µm and microhardness at the range of 825-882 $HV_{0.3}$. The open porosity of the phosphate sealed coatings was reduced by 24-48 % depending on the coating material. TEM studies and EDS analysis showed the phosphate phases in coating structural defects and revealed their amorphous microstructure. Adhesive binding was defined as strengthening mechanisms of the aluminum phosphate sealed $8Y_2O_3$-ZrO_2 coating.

Mechanical properties

Erosion and abrasion resistance of the TTBCs was drastically increased due to the phosphate sealing. The average improvement of erosion resistance was 65-70% and at low particle impact angles even higher. The abrasion resistance was enhanced in the same proportion and the weight losses were 70-80% lower when compared to the as-sprayed coatings.

Erosion and abrasion resistance of the $8Y_2O_3$-ZrO_2 coating was improved also by the laser-glazing. The average improvement in erosion resistance was 35% and over 80% in abrasion resistance. In the case of 22MgO-ZrO_2 coating the effect of laser-glazing was insignificant or even negative. The orientation and the shape of the segmentation cracks in 22ML coating were not advantageous for coating wear properties. The accelerated material removal was caused by the crack branching and coalescing within and below the melted layer.

Four point bending test showed extremely high strength and stiffness of the aluminium phosphate sealed $8Y_2O_3$-ZrO_2 coating. Modulus of rupture in bending (R_B) was more than doubled and bending modulus (E) even seven times higher when compared to as-sprayed coating.

In laser-glazed $8Y_2O_3$-ZrO_2 coating the modulus of rupture in bending (R_B) was 75% lower and bending modulus (E) 80-90% lower than that of as-sprayed coating. Low strength and stiffness was consequence of the vertical segmentation cracks in the coating structure.

Heat treatment increased strength and stiffness of as-sprayed and laser-glazed $8Y_2O_3$-ZrO_2 coating, but had negligible affect on aluminium phosphate sealed coating.

Thermal properties

It was shown that the high temperature exposure up to 1300^oC increased the thermal conductivity of all TTBCs. In yttria and ceria stabilised coatings this was mainly caused by the sintering based phenomena in which the lamellae contact was improved at splat boundaries. In magnesia stabilised coatings thermal conductivity was increased significantly by precipitation of MgO, which led to unstabilization of c/t-ZrO_2 zirconia and formation of m-ZrO_2.

Laser glazing had only slight effect on thermal conductivity of TTBCs. Thermal conductivity was increased in some degree if the segmentation cracks were oriented vertically like in the case of laser-glazed $8Y_2O_3$-ZrO_2 coating. But if the orientation of the segmentation cracks differed from the vertical direction or if the cracks were branched, thermal conductivity was decreased. This was observed in the case of laser-glazed $25CeO_2$-$2.5Y_2O_3$-ZrO_2 and 22MgO-ZrO_2 coatings.

Phosphate based sealing treatments increased significantly thermal conductivity of TTBCs by reducing the porosity and filling the cracks and interlamellar spacings. High temperature stability of the TTBCs was also decreased by phosphate sealing.

High temperature testing

Thermal cycling resistance of all segmentation cracked coatings was superior if compared to the reference coating. Segmentation cracks reduced the modulus of laser-glazed coating and probably also the critical tensile stresses of the coating at maximum temperature and for that reason improved the strain tolerance of the coating.

Aluminium phosphate and sol-gel sealing treatments reduced thermal cycling resistance of segmentation cracked coatings. The decreasing effect of aluminium phosphate sealing was rather high, whereas in sol-gel sealing it was moderated.

As-sprayed reference coatings passed the diesel engine test without any damage. In phosphate sealed coatings some vertical microcracks were built up during the test run. However, no spallation was observed in any case.

Critical phase changes and corrosion reactions were observed in yttria stabilized zirconia coatings after the hot corrosion test. The amount of the m-ZrO_2 increased greatly and YVO_4 formed in all cases. The laser-glazed coating performed best in hot corrosion test.

Magnesia stabilized zircoania coatings were slightly more resistant to Na_2SO_4 - V_2O_5 than yttria stabilized coatings, if considering coating color changes and cracking. Coatings suffered also undesired zirconia phase changes, but in laser-glazed coating the $Mg_2Zr_5O_{12}$ phase seemed to be more resistant against hot corrosion as c-ZrO_2.

5.3.2 Researcher training

Samppa Ahmaniemi spent a one-year period (08/2001-08/2002) as an exchange researcher in University Trento (Trento, Italy). In there the knowledge of structural characterisation of the coatings by x-ray diffractometry was deepened. The work in the University of Trento was mainly carried out in Microstructure and Metallurgy Laboratory (Department of materials engineering).

5.4 FUTURE ACTIVITIES

The results of this study will be summarised more detailed in doctoral thesis of Samppa Ahmaniemi. That will be realised within couple of months. Later it is purposed to continue the research in this field using the partner network created during the TUKEVA Programme.

5.5 PARTNERS

In EVE project co-operation was mainly made with HUT/ICE as a form of discussion of the requirement of the combustion chamber components in extreme value engine.

International co-operation was mainly carried out in COST 522 Program (COST 522 'Ultra Efficient, Low Emission Power Plant' Gas Turbine Group, WP2 Protective systems, SP3 New Coatings/Processes). In COST 522 Program close research work was realised with CESI (Segrate, Italy) in form of determination of thermal properties of modified TTBCs. Close collaboration was made also with Ansaldo Richerche (Genoa, Italy) in studying TTBC structures and testing their thermal cycling behaviour.

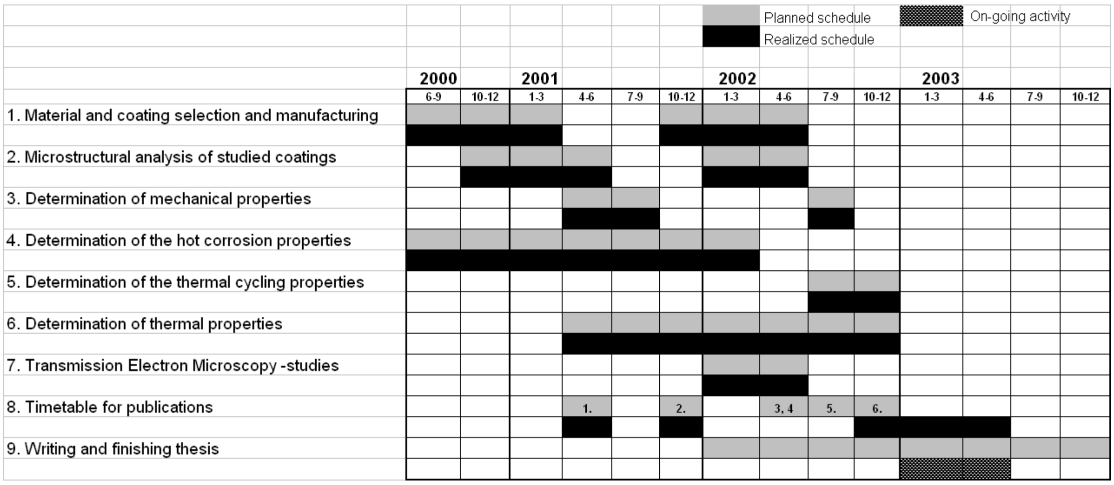
5.6 BUDGET AND SCHEDULE

The project was funded by Finnish Academy funding for the period 1.6.2000 – 31.12.2003. The budget for each year is listed in table below:

Year	Budget [k€]
2000	20
2001	39,7
2002	38,8
2003	20,2

Planned and realized project schedule for the years 2000-2003 is presented in Table 1. As can be seen from the Fig. 1 the project plan was followed and the schedule realized.

Figure 1. Planned and realized project schedule for the years 2000-2003.



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5.8 PUBLICATIONS

In refereed journals

1. S. Ahmaniemi J. Tuominen, P. Vuoristo and T. Mäntylä: Sealing Procedures for Thick Thermal Barrier Coatings, Journal of Thermal Spray Technology, 11 (3), 2002, p. 320-332.

2. S. Ahmaniemi, P. Vuoristo and T. Mäntylä: Improved Sealing Treatments for Thick Thermal Barrier Coatings, Surface & Coatings Technology, 151-152, 2002, p. 412-417.

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4. S. Ahmaniemi, P. Vuoristo, T. Mäntylä, F. Cernuschi, L. Lorenzoni, Modified Thick Thermal Barrier Coatings, Part II: Thermophysical Characterization, accepted to the Journal of European Ceramic Society, in print.

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7. S. Ahmaniemi, P. Vuoristo, T. Mäntylä, C. Gualco, A. Bonadei, R. Di Maggio, Thermal Cycling Resistance of Modified Thick Thermal Barrier Coatings, submitted to Surface & Coatings Technology.

Conference papers

1. S. Ahmaniemi, J. Tuominen, M. Vippola, P. Vuoristo, T. Mäntylä, F. Cernuschi, C. Gualco, A. Bonadei, R. Di Maggio, Characterization of Modified Thick Thermal Barrier Coatings, in Thermal Spray 2003: Advancing the Science & Applying the Technology, (Ed.) C. Moreau and B. Marple, Published by ASM International, Materials Park, Ohio, USA, 2003, pp. 1477-1486.

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6 THE EFFECT OF PARAMETER UNCERTAINTY ON THE REALIBILITY OF VIRTUAL TESTING OF FLUID POWER SYSTEMS

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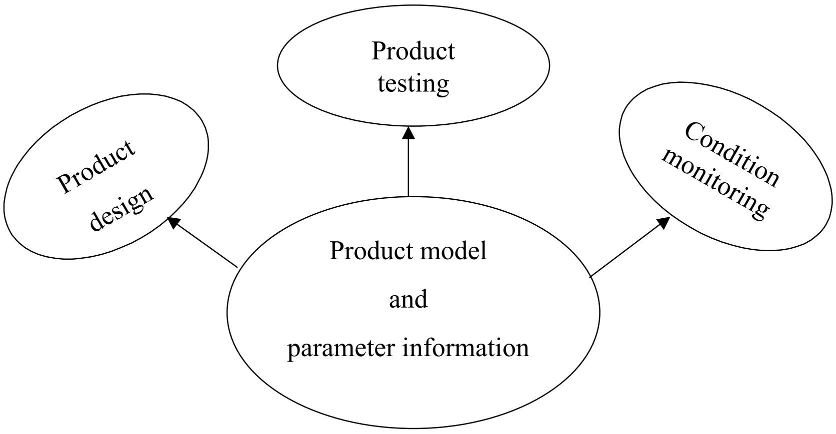
ABSTRACT : The main objectives of this research have been: evaluating the effect of parameter inaccuracy on the results of virtual testing of fluid power systems, evaluating the effect of varying operational conditions in the case of some of the most important fluid power components and applying knowledge on parameter uncertainty on condition monitoring of a hydraulic component and performance of passive vibration control.

6.1 INTODUCTION

Mathematical product model together with parameter information form the core of the theoretical knowledge that can be utilized in three stages of product life cycle: design, manufacture and use. At design stage virtual prototypes based on simulation models can be used for optimal product design. At manufacturing stage hardware-on-the-loop-simulation can be used for, e.g., product inspecting of the electronic control system. During the normal use models based on condition monitoring methods can be used for monitoring the service need.



Usefulness of theoretical approach is highly dependent on the reliability of the results of experimental and theoretical approach. In the experimental approach uncertainty depends on transducers, construction of the measurement system, data acquisition system and analysis methods. In theoretical approach uncertainty depends on the simplifications made in the modeling, the algorithms used and the component and system parameters.

The parameter inaccuracy can be divided into three classes:

- The accuracy of the parameter information
- Statistical dispersion between similar components
- The change of parameter values during the course of time.

6.2 OBJECTIVES

The main objectives of this research were:

- To evaluate the effect of parameter inaccuracy on the results of virtual testing
- To evaluate the effect of varying operational conditions in the case of some of the most important fluid power components
- To apply knowledge on parameter uncertainty on condition monitoring of a hydraulic valve and performance of passive vibration control.

Components to be tested were: a variable displacement axial piston pump with a constant pressure controller, a pressure compensated mobile proportional valve and an accumulator. As a source of disturbance fluid type, fluid temperature, ambient temperature, deviation between similar components and assembly type were used. Besides these also the effects of operational parameters, such as pressure, rotational speed, flow rate, flow frequency and pump displacement were studied.

Selected components are closely related to the top technology research areas of IHA (mobile hydraulics) and HUT (paper machine hydraulics).

Thorough measuring of all the originally selected components including deviation study between similar components proved to be too demanding in respect to financial resources of this project. Therefore cylinder and motor were left out of the study for ensuring sufficient resources for the other selected components.

6.3 RESULTS AND ACHIEVEMENTS

- The project had three main scientific results in fluid power. First of all it paid attention to the importance of the effect of parameter variation on performance of a final product. Secondly it considered the uncertainty associated with simulated results, which may be significant. The uncertainty was studied with componentwise models that were developed in this project. Finally it produced a good amount of well-documented measurement results, which will be available for fluid power researchers in the Web-pages of the project.
- Technological knowledge achieved in this project was applied to condition monitoring of fluid power components as well as on the reliability of vibration control methods.
- The project gave researcher training for two post-graduate students and two post-doctor students. Heikki Kauranne made his licentiate's thesis on determination of static and dynamic characteristics of pressure-controlled variable displacement pump. His doctoral thesis entitled 'Pump Models – Estimation of Uncertainty and Parameter Sensitivity' is expected to be completed in 2004. His research plan is enclosed in Appendix 2. Terho Nykänen's doctoral thesis is entitled 'The influence of parameter uncertainty on cylinder drive performance in mobile machines' and is expected to be completed in 2005. His research plan is enclosed in Appendix 1. Doctors Timo Koivula, Jaakko Myllykylä and Jyrki Kajaste have been participating in the project as post-doctor members.

6.4 FUTURE ACTIVITIES

This same research consortium has started a large 3,5 yearlong project entitled "Model based condition control" in the Masina-program funded by TEKES (National Technology Agency of Finland), Metso Paper and Plustech/John Deere. HUT/Machine Design has also applied for a Finnish Academy project to do research on cylinder seal friction in a small amplitude reciprocating motion. A new project on vibration control methods will be applied by HUT/Machine Design in 2003.

6.5 PARTNERS

The project was accomplished between two research institutes: IHA/Tampere University of Technology and Machine Design/Helsinki University of Technology. Despite of the basic research nature of this project two companies: Metso Paper and Plustech/John Deere (mobile machinery) were interested in the results of this project.

6.6 BUDGET AND SCHEDULE

	2000	2001	2002	2003	Totally
IHA/TUT	111 000	425 000	445 000	231 000	1 211 000 FIM
HUT	258 000	437 000	512 000	285 000	1 492 000 FIM
Total	369 000	862 000	957 000	516 000	2 703 000 FIM
Total in €					454 000 EUR

6.7 CONTACT ADRESS

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7 THE EFFECT OF PARAMETER UNCERTAINTY ON THE RESPONSE OF A PRESSURE COMPENSATED MOBILE VALVE

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ABSTRACT**:** A mobile valve is a complex entity consisting of several integrated valve functions. Due to manufacturing tolerances, there are slight differences in the inner parts of the valve. Also the operating conditions such as temperature and oil type affect the performance of the valve. Therefore similar valves do not have identical responses, especially in different operating conditions.

In this study the sensitivity of a pressure compensated mobile valve is studied. Several similar springs are measured in order to define parametric deviation of the springs. An analytical mobile valve model is used to evaluate the effect of the uncertainty of the spring parameters on performance of the mobile valve. The model is verified with measurements. The effect of operating conditions is studied by measuring the valve performance at three different temperatures.

The effect of spring constant changes on the valve output was clear. Also the effect of the compensator spool was studied and found to be quite small. The effect of temperature on the valve output was the most significant factor.

KEYWORDS**:** Parameter uncertainty, mobile valve, simulation

7.1 INTRODUCTION

A mobile valve is a complex component having several integrated valve functions. The primary function is a directional control valve function. Additional integrated functions are for example pressure relief, pressure compensation, flow sharing, load sensing and anticavitation valve functions. Due to the integrated functions, the valve has several parameters affecting its performance. Some of these can be defined quite accurately but some must be estimated. Due to manufacturing tolerances there are slight differences in the inner parts. Also the operating conditions such as temperature affect the performance of the valve. Therefore similar valves do not have identical responses.

Mobile hydraulics is an important sector when considering different hydraulic applications and lately the development in this area has been strong. According to Harms [1] and Backé [2] some of the most important development trends have been: reducing the building costs, raising the power and efficiency, reducing the environmental load, raising the user comfort and making maintenance simpler. Some of these trends can be realised by installing more electronics in hydraulic systems. Most of the actions are realised by using mobile proportional valves.

The mobile valve is an important component of a mobile machine especially concerning usability of the working hydraulics. The speed and position accuracy of a hydraulic cylinder is dependent on valve performance especially when a flexible boom is operated. Breeden [3] introduced the development of a high-pressure load-sensing valve. In this paper this type of load sensing valve was found to be very effective. The valve was pilot operated, it provided an optimum match for various load types and improved cavitation protection. Patel [4] introduced a pressure compensated electro-hydraulic proportional flow control valve. Low power consumption, contamination insensitivity, built-in position feedback and manual operation in the case of an emergency were the primary design criteria. The advantages of utilising these concepts in typical mobile hydraulic circuits were discussed. Lantto et al [5] studied the theories describing the steady state and dynamic characteristics of load-sensing systems with two kinds of pressure compensated valves and a variable pump. They stated that it is possible to use theoretical analysis to obtain a fairly good description of the mechanism that stabilise or destabilise a load-sensing system. Also simulation is another significant tool for analysing the dynamic properties of the load-sensing system. When these tools are available, the traditional trial-and-error method is no longer appropriate. Petro [6] studied a mobile load-sensing valve with individual section compensators, used in conjunction with a variable displacement pump. The paper also discussed the advantages of using individual section compensator. The advantages using individually compensated sections is apparent when metering more than one operating function. Since each section has its own compensator spool, the metering curve of the spool stroke versus work port flow will remain constant. Also it is independent of the working pressure of other functions being metered at the same time.

Käppi [7] has previously studied the modelling of a proportional mobile valve. He presented methods for modelling multifunctional mobile valves. The model was numerically efficient and problems due to numerical stiffness were overcome by ignoring small internal volumes of the valve. The model was semi-empirical and allowed easy parameterisation by using the manufacturer's catalogues. Handroos [8] studied hydraulic flow control valves and introduced a semi-empirical model for a proportional two-way flow control valve and for a three-way flow control valve.

In this paper the effect of pressure compensator on a mobile valve response is studied. The load acting at the cylinder is an external factor directly affecting the cylinder pressure. Load pressure also affects the compensator spool via the load sensing line. The pressure compensator tries to maintain a constant pressure difference and constant flow rate over the valve main spool. If the compensator spool springs have deviations due to manufacturing tolerances, the designed pressure difference is not achieved and thus the flow rate through the main spool changes from the designed value. A number of similar springs were measured in order to determine the deviation of the spring parameters. The mobile valve was tested with three compensator springs in order to find out their affect on valve response. Furthermore, the fluid temperature was altered and measurements undertaken at three temperature levels. An analytical model of the valve model is then used to generalise the measurement results of the mobile valve.

NOMENCLATURE

a	= acceleration of compensator spool
A_1	= flow cross area of a compensator spool
A_2	= main spool flow cross area

C_q = flow coefficient
C_r = clearance of compensator spool
D_C = diameter of compensator spool
m_{sc} = mass of the compensator spool
F_A = load pressure force on compensator spool
F_{pC} = pressure force on compensator spool
F_{flow} = flow force on compensator spool
F_{spC} = compensator spring force
F_{visc} = viscous friction force on compensator spool
p_A = pressure in load-sensing line
p_s = pressure in supply line
p_C = pressure after compensator
Q_{in} = flow rate into the compensator
Q_{out} = flow rate out from main spool
v_C = velocity of compensator spool
x_C = position of compensator spool
x_{Cpre} = pre set of compensator spool spring
k_{spC} = spring constant of compensator spool spring
ν = kinematic viscosity
θ = jet angle
ρ = density of fluid

7.2 SIMULATION MODEL

As previously stated Käppi [7] and Handroos [8] have developed semi-empirical valve models. However, a semi-empirical model was not suitable for studying the effect of parameter variations and an analytical model for the pressure compensator of the mobile valve was developed. The main spool is basically an adjustable orifice, which is controlled by a pilot spool. As the analytical equations for hydraulic control valves are discussed in [9] these are not included here.

Figure 1 shows the idealised model developed for the compensator valve.

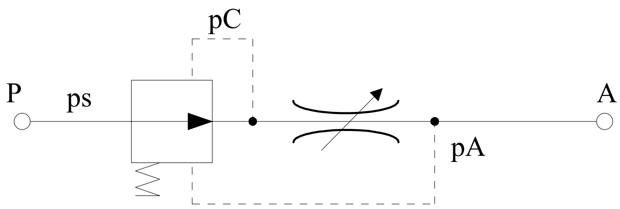

Figure 1. The idealised compensator valve.

The equations of motion for the compensator spool is introduced below:

$$a = \frac{F_{pC} - F_{pLS} - F_{flow} - F_{spC} - F_{visc}}{m_{sC}} \qquad (1)$$

where

$$F_A = \frac{\pi}{4} D_C{}^2 \cdot p_A$$

$$F_{pC} = \frac{\pi}{4} D_C^{\ 2} \cdot p_C$$
$$F_{spC} = k_{spC}\left(x_C + x_{Cpre}\right)$$
$$F_{flow} = 2 \cdot Cq \cdot \pi \cdot D_C \cdot x_C \cdot \left(p_s - p_C\right) \cdot \cos\theta$$
$$F_{visc} = \frac{\pi \cdot D_C \cdot \upsilon \cdot \rho}{C_r} \cdot v_C$$

Flow through the compensator spool is given by

$$Q_{in} = Cq \cdot x_C \cdot \pi \cdot D_C \sqrt{\frac{2\left(p_s - p_C\right)}{\rho}} \tag{2}$$

Flow through the main spool is given by

$$Q_{out} = Cq \cdot A_2 \sqrt{\frac{2\left(p_C - p_A\right)}{\rho}} \tag{3}$$

Using the simulation model the effect of parameter variations on component response is studied. Also the measurement results can be generalised using the model.

7.3 MOBILE VALVE MEASUREMENTS

The test installation consists of three flowmeter, six pressure sensors and one temperature sensor. Flowmeters are located as follows: one in the inlet line, (Q_{inlet},) one in the working line A, (Q_A) and one in the working line B, (Q_B.) Pressures to be measured are inlet pressure, (p_{inlet},) load-sensing pressure, (p_{LS},) pilot pressures A, (p_{pilotA}) and B, (p_{pilotB}) and working pressures A, (p_A) and B, (p_B.) The temperature is measured in the inlet line. The load is created by using a bridge connection with a proportional pressure relief valve. One valve block having the spool area ratio of 1:1 is studied. Each block has an individual pressure compensator. The measured valve block and related instrumentation is shown in the figure 2.

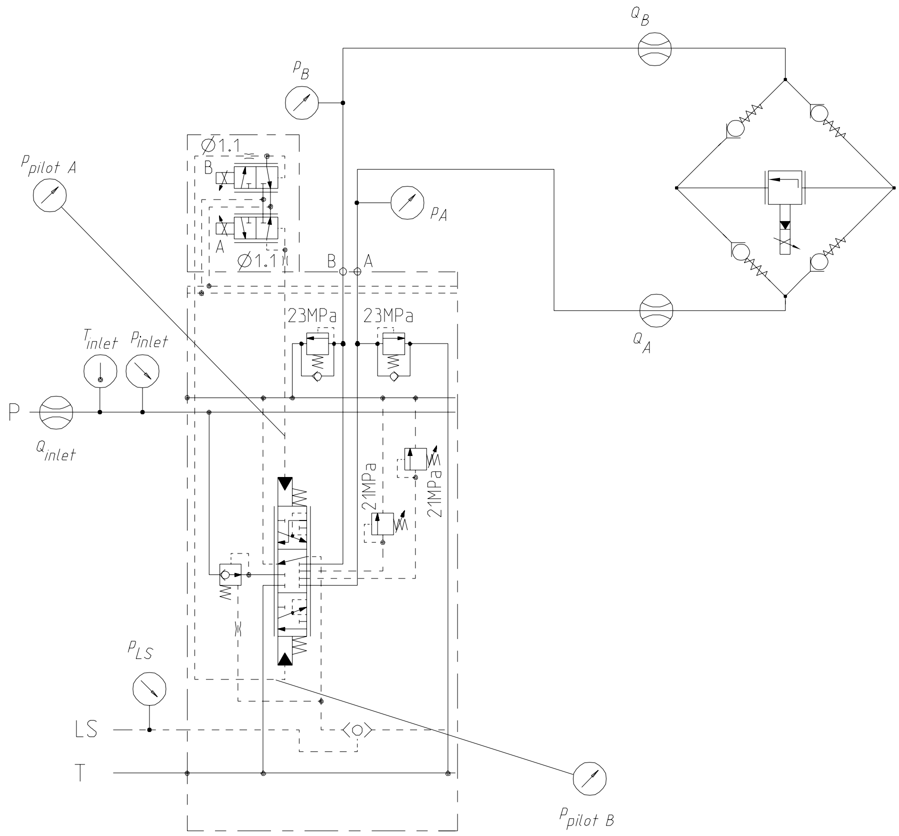

Figure 2. The test installation for valve measurements.

As the valve is a new component, the effect of wear rate is not included. The compensator nominal flow is 130 l/min, having a maximum pressure of 230 bar. The valve spool control and data collection during measurement is done using a dSpace© data acquisition system.

In these measurements both the steady-state characteristic curve and dynamic properties of the mobile valve are determined. The effect of spring, compensator spool and temperature is studied. In all cases full opening of main spool and constant load is used.

- Case 1: one spool, constant temperature, spring is altered
- Case 2: mean value spring, constant temperature, spool is altered
- Case 3: mean value spring, one spool, temperature is altered.

According to Kauranne [10] and Koivula [11] the effect of the oil type will be relatively small on the characteristic of the orifices and the clearances. Therefore in this study the measurements were carried out using a single type of oil.

7.4 RESULTS

Fourteen compensator springs were measured in order to find out the parameter uncertainty related to the spring parameters. Using a confidence level of 95.4% for a normally distributed variable, the coverage factor k is 2. The results obtained for the spring constant measurements are shown in table 1.

Table 1. Measured spring constant and standard deviation.

Spring (average)	47366±1033 [N/m]	$\mu \pm 2\sigma$
Spring (stiffest)	48399 [N/m]	$\mu + 2\sigma$
Spring (weakest)	46333 [N/m]	$\mu - 2\sigma$

The spring constant deviation of springs used in the commercial mobile valve was found to be small (4%). However, in engineering practice, it has been noticed that spring constants can vary considerable. Typically, a spring manufacturer gives a tolerance of ±10% for their spring constants. Therefore in the measurements, the stiffest and the weakest spring constant had about 10% difference compared to average spring constant of the measured spring set.

Table 2. Spring constants used in measurement and simulation.

Spring (average)	c1	47466±1033 [N/m]
Spring (stiffest)	c2	52583±970 [N/m]
Spring (weakest)	c3	43488±972 [N/m]

Table 2 above shows the used spring constants with standard deviation at 95.4% confidence level. The used average spring was the spring having a spring constant closest to the measured set average.

Table 3. Viscosity and density of oil at measurement temperatures.

Temperature	ν[cSt]	ρ [kg/m^3]
T1 = 25°C	85.2	843
T2 = 60°C	23.6	823
T3 = 75°C	15.7	815

The steady state characteristic curves obtained for the valve are shown in figures 3, 4 and 5. The measured results in figure 3 show that the differences in the main valve output between the springs are significant. The flow rate difference at 80 bar pressure drop is approximately 8.5%. Simulation results show a higher flow difference, as the weakest spring in the measurement is at the upper uncertainty limit. In figure 4, the results show that the differences between the spools are quite small, and at 80 bar pressure drop it is approximately 3%. The effect of temperature in figure 5 is much larger especially when considering low temperature. The flow difference at 80 bar pressure drop is approximately 12%. The simulation results show an almost equal flow difference, although the flow rate level is lower. The flow rate at the highest temperature level is higher in the measurements than in the simulation, probably due to leakage. Also it is noticed that the rate of increase in flow rate is significantly slower in the simulation at the lowest temperature level. The temperatures and oil properties are shown in table 2.

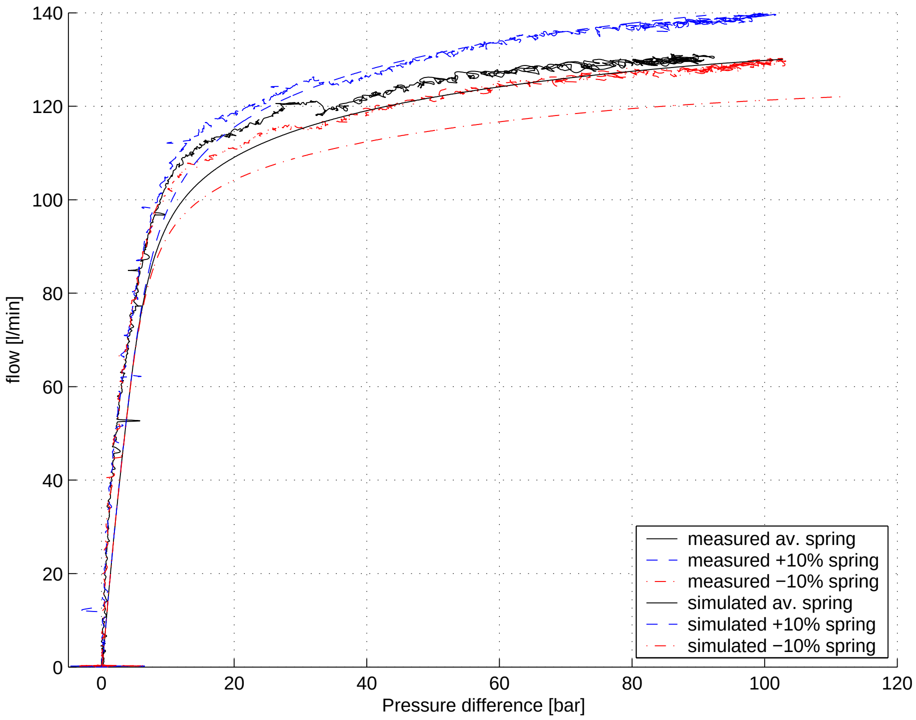

Figure 3. Effect of spring parameter on valve characteristic curve.

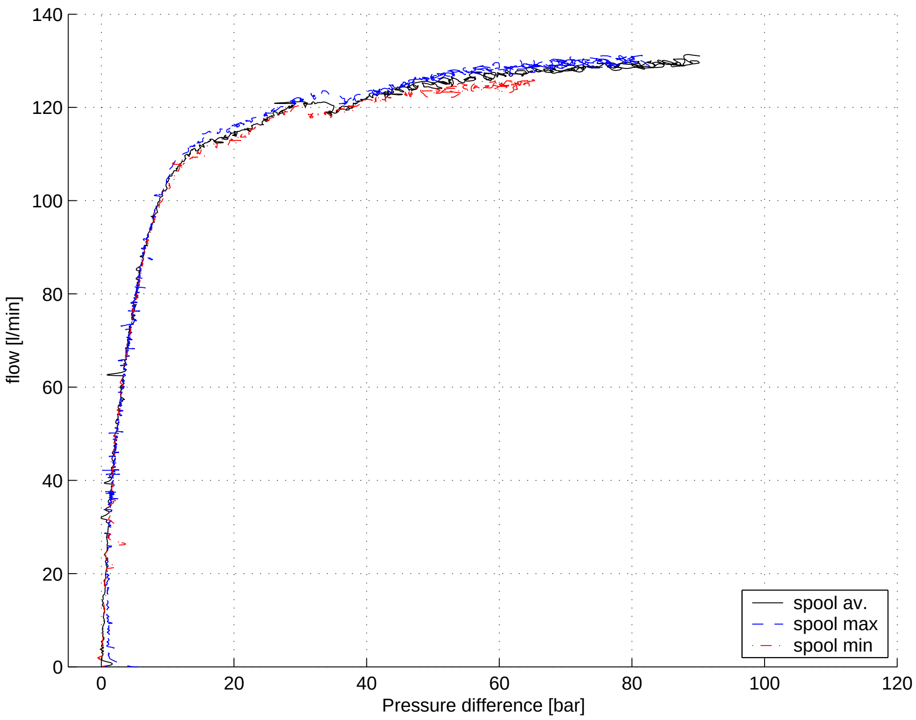

Figure 4. Effect of spool on valve characteristic curve.

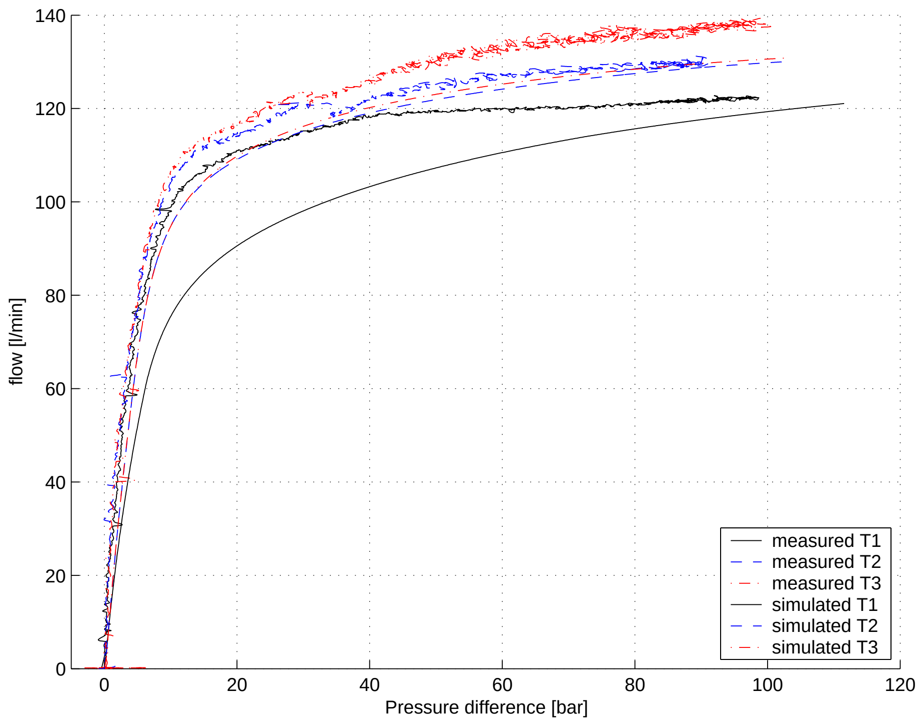

Figure 5. Effect of temperature on valve characteristic curve.

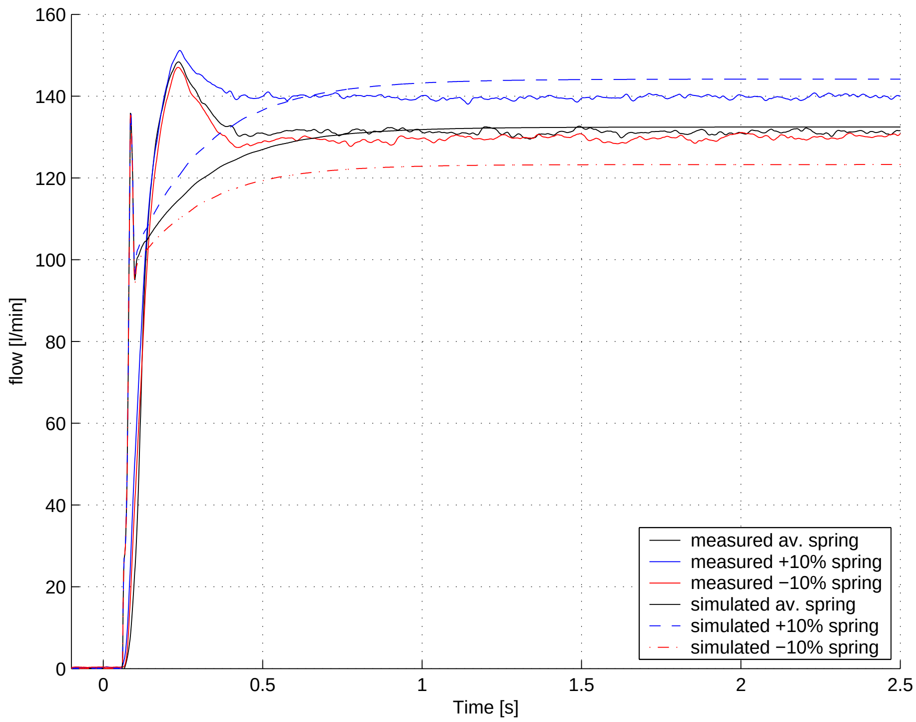

Figure 6. Effect of spring parameter on valve dynamic.

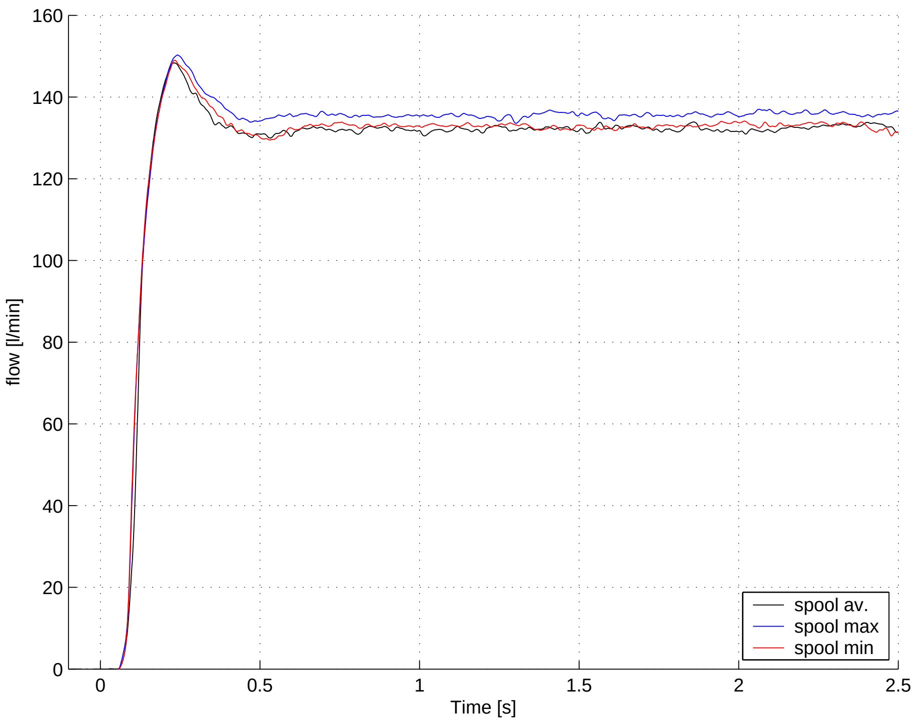

Figure 7. Effect of spool on valve dynamic.

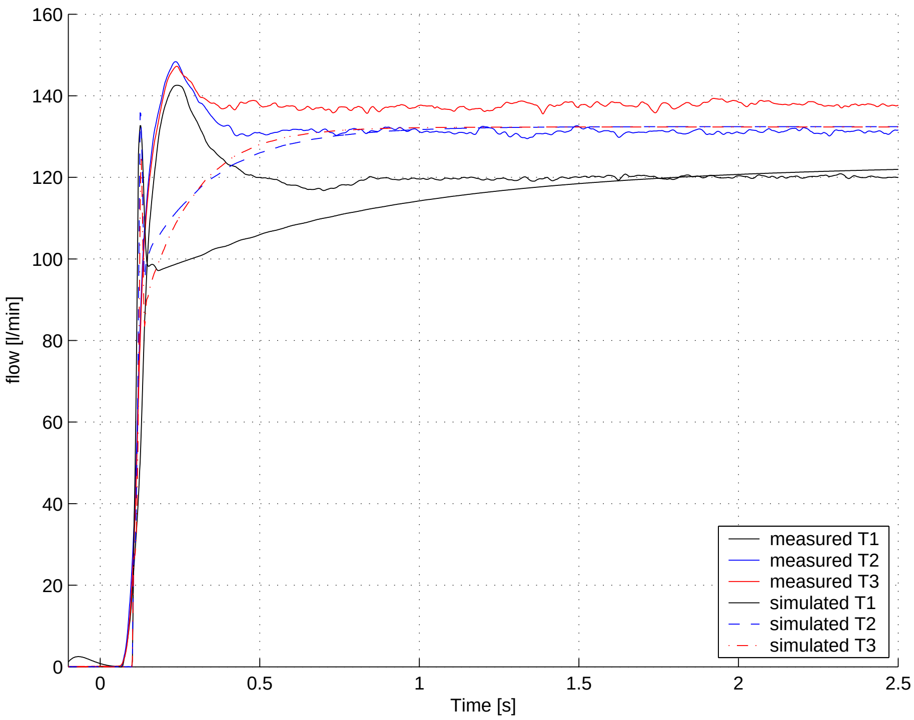

Figure 8. Effect of temperature on valve dynamic.

The dynamic behaviour of the valve was also studied. A flow rate step was supplied into the valve. In figure 6 the spring constant affects mostly the flow rate peak, resulting in the highest peak with the stiffest spring. The peak value difference is approximately 3%. The differences in settling times are relative small at only a few tenth of a second. The simulation results seem to have lower peak values and also the drop in the flow rate after the peak is faster. The settling time is also longer. In figure 7, the spool effect on valve dynamics is introduced. The only difference is on the peak values and it has no significance in practice, and the settling times are almost equal. Figure 8 shows the temperature effect on dynamic behaviour. The flow rate peak is lowest at the lowest temperature and the total flow rate difference is approximately 4%. The settling time difference is largest at the lowest temperature level. In the simulation results immediately following the step flowchange, the flow rate rise is faster. At the highest temperature level the flow rate drops more than at the other temperature levels and rises fastest. However the differences at the end of the time region is similar to the steady state case. The flow rate peak value is lower compared to the measured values and also the model dynamics is faster.

Figure 9 shows a comparison of the effects of the measured parameters on the flow rate.

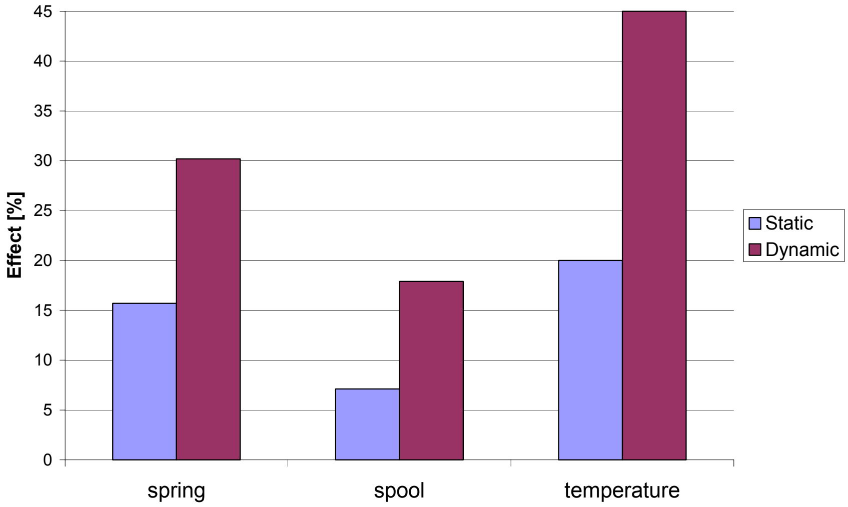

Figure 9. Effect of operation parameters on variation of flow rate.

In steady state, the comparison criterion was the flow rate difference between two points. Point one was the flow rate at the pressure difference where the compensator spool starts to move and point two was the flow rate at the maximum pressure difference. This flow rate difference was compared to the maximum flow rate. In the dynamic case, the comparison criterion was the difference in settling time. The percentage values in figure 9 are the difference between the minimum and maximum values.

7.5 CONCLUSIONS

In this paper the effect of internal and external parameters on a mobile valve response was studied. The internal parameters were the compensator spring and spool. The external parameter was temperature. The uncertainty of the compensator spring and spool are discussed. A number of springs were measured in order to find out the parameter uncertainty related to the spring parameters. The mobile valve simulation results were verified by measuring the mobile valve performance.

Simulation results show that the effect of the compensator spring on flow rate was more significant in steady state than in dynamic behaviour. The temperature effect was more significant especially at low temperature. However as the oil temperature rises fast during operation, the effect is significant only when using a system with cold oil. When simulation results were compared to the measured results they were found to differ, especially regarding valve dynamics. The analytical simulation model seems to be very parameter sensitive and to obtain good results requires accurate measures of the valve construction and inner volumes. To get accurate measures the valve should taken to pieces, which was not possible in this case. This will be possibly realised later and to improve the model accuracy.

According to the measurement results the deviation of the spring constant had an effect on the valve output in steady state and dynamic cases. In steady state case it affected the flow rate and pressure drop and in the dynamic case it affected flow rate and settling time. The compensator spool also affected the flow rate in the steady state and dynamic cases, but the effect on settling time was negligible in practice. The temperature effect was largest in both cases. In steady state, the effect on flow rate was significantly larger compared to the spring and spool effects, and in the dynamic case the effect was larger on settling time than the flow rate.

The deviation of main components of the pressure compensator had clear effects on the valve output. Also the simulation results were similar to the measured results though the model and parameter accuracy should be improve. In the future, the effect of output variation on a hydraulic actuator will be studied.

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8 INTELLIGENT LASER SURFACE ENGINEERING

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ABSTRACT: Surface hardening was one of the first laser-based fabrication methods to be commercialised, in the early 1970’s. However, its industrial application has been limited, in comparison with other laser-based processes such as cutting, welding and marking. A number of reasons can be identified:

- the limited amount of information available concerning the principles and practice of laser hardening, and its technical and economic benefits
- the large number of more familiar conventional surface hardening processes that are available
- perceived difficulties in implementing the process in production
- the implications for product design and performance in relation to existing codes.

Since the mid 1990's, major developments have taken place in laser sources, beam delivery optics, CAD/CAE software, process modelling, and process monitoring and control systems. Automated laser hardening systems are now becoming available, suitable for treating components of widely varying size and shape. Laser hardening can now be viewed more favourably against competing processes. Products can be designed with the intention that laser hardening is an integral part of the manufacturing process. This contrasts with the traditional approach of considering laser hardening as merely a replacement for an existing process, with no thought being given to new product design possibilities.

Experimental testing has shown that hardness requirements can be met, and in many cases exceeded, in a range of steels and cast irons. However, the implications of such high hardness values for the depth of hardening required are yet to be established. Further work is therefore needed to establish codes and practices specifically for laser-hardened components, in order to expand industrial application of the process.

This article describes the project ILSE (Intelligent Laser Surface Engineering), which is a collaboration between the Technological Universities of Lappeenranta and Tampere, and is funded by the Academy of Finnish. The project aims to solve many of the factors outlined above, in order to widen industrial application.

8.1 INTRODUCTION

Laser surface hardening or laser transformation hardening is a technique for producing a hard, wear-resistant surface on components. The surface is heated rapidly to the γ-phase by scanning a high intensity laser beam across the hardened area. Efficient conduction of heat to the surrounding material induces the surface to quench very quickly to temperatures below the M_s-temperature, forming a martensitic layer to the surface, or in high alloy steels a martensitic structure with portions of retained austenite and undissolved carbides. Due to the high cooling rates, $T_{8/5}<1$ s, the hardness of martensite reaches higher values than in components hardened with conventional methods.

When a component is hardened with a laser, the laser beam interacts with the substrate, heating it very rapidly. The amount of heat transferred to the material is defined by the absorptivity of the material. The absorptivity is the ratio between the energy absorbed by the work piece and the laser energy on the surface. Absorptivity is also often referred to as the coupling rate and it is a dimensionless number between zero and unity. After the energy is absorbed to a very thin surface layer, it is transferred into the surrounding material by thermal conduction. The principle of laser transformation hardening and the conduction of heat are presented in Figure 1.

If the laser beam-material interaction is rapid or the traverse rate is high, the absorbed energy has only little time to conduct to the surrounding material. This results in high surface temperatures. On the contrary, if the process is slow, the surface will not reach as high temperatures, even though the laser energy is equal in both cases.

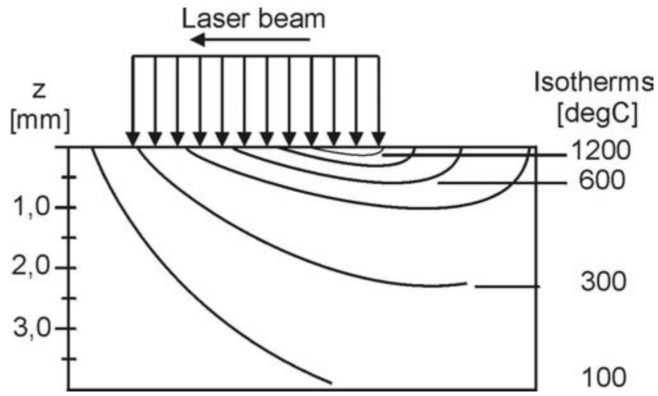

Fig 1. Principle of laser transformation hardening and the conduction of heat

The absorptivity, and therefore the process efficiency can be increased by applying an absorptive coating on the surface and by allowing surface oxidation during processing. Other affecting factors are the surface quality, the angle of incidence, the wavelength and the temperature of the material.

The phase transformations are affected by the chemical composition and the microstructure of the material. Especially the distribution of carbon in the microstructure has a great effect on hardening. Carbon is the most important and influential alloying element in steel. It is a pronounced extender of the gamma phase and considerably increases the hardness of martensite.

In hypoeutectoid and low alloy steels carbon is often distributed in the microstructure unevenly. The initial microstructure consists of high carbon content pearlite surrounded by proeutectoid ferrite. On heating, pearlite transforms to austenite by dissolution of the cementite lamellae, followed by growth of the austenite transformation front into regions of low carbon concentration, at a rate controlled by carbon diffusion between the lamellae. Ferrite transforms by nucleation and growth of austenite at internal ferrite grain boundaries, at a rate controlled by carbon diffusion over greater distances, associated with the size of the ferrite colonies. If the heating and quenching is very rapid, the pearlitic regions transform to martensite during quenching but the ferrite regions remain mainly ferritic. Therefore the hardened region is not uniformly hard.

Medium alloy steels such as heat treatable steels are often delivered in quenched and tempered condition. The austenitization of these finer microstructures is not controlled by the rate of carbon diffusion and therefore more rapid heating and quenching patterns can be used.

The microstructure of low-alloyed steels consists mainly of martensite, bainite, ferrite and pearlite. The volume fractions depend on the composition and the heating and cooling rates. The hardness and volume fractions of separate phases can be calculated with different formulae. Hardened regions of medium and high alloy steels can contain retained austenite that has not transformed to martensite. Austenite is much softer than martensite and therefore even small amounts of austenite can have an effect on the surface hardness.

In high alloy steels with a high carbon content, such as tool steels, the microstructure consist of mainly of martensite with portions of retained austenite. However in the original microstructure carbon and metallic elements form carbides. Some of these carbides are left undissolved during hardening, increasing the wear resistance in the hardened microstructure.

High alloy steels with low carbon content, such as martensitic stainless steels, are transformed only partly into austenite during heating, leaving δ-ferrite in the austenitized microstructure. The δ-ferrite regions are not transformed into martensite during cooling like austenite, therefore causing a decrease in the hardness. These materials are hardenable, but the hardness is relatively poor in comparison to other high alloy steels.

Establishing a formula for calculating the amount and hardness of different phases is an essential part of modelling the hardening. The amount of retained austenite depends on the martensitic start and finish temperatures, which are affected by alloy elements. These temperatures are raised by ferrite formers, such as Ti, Nb, V and W. Addition of these alloy elements decrease the amount of retained austenite. The austenite formers, such as C, Mn and Ni have an opposite effect. In order to predict the hardness of the hardened surface, it is crucial to define the quantitative effect of major alloy elements on the hardness of martensite and the martensitic start and finish temperatures.

The estimation of carbide dissolution to austenite is also important, altering the composition of austenite, thus changing the martensitic start temperature. Also the wear resistance properties are much affected by the amount of carbides in the microstructure.

Laser transformation hardening is beneficial process in many cases, where a hard wear resistant surface is needed on a component surface. The technique is exploited to it's full potential only if the components are designed for laser processing. In such cases the component geometries can be optimised for laser processing. In many cases the laser-hardened surfaces are harder than surfaces treated with conventional methods. The thickness of the hardened layer may present some problems in parts exposed to fatique. The failure mode may be different than in conventionally hardened machine elements.

Laser transformation hardening is mainly done with short wavelength lasers like Nd-YAG and HPDL's. Beam delivery with flexible optical fibers (Nd-YAG) and possibility to mount the whole laser unit (HPDL) to robot arm, enables robotized 3D processing. Flexible beam delivery is most beneficial in the case of hardening complex 3D shapes. However batch sizes of such work pieces are usually very small and required response times short, which adds pressure to the whole delivery cycle.

In the hardening process of such work pieces, most of the time is wasted on motion path programming. Manual programming with the robot arm itself, does not add value to the product, and should hence be minimized. Off-line programming (OLP) of laser robot cells is usually the only solution to meet these needs.

Using a virtual model of the entire robot work cell, motion path generation is done automatically by using the work piece's 3D model. To minimize the actual setup time in the laser cell, all laser controls and variables are not only added to the robot program, but also tested in the virtual environment. With the developed 'virtual pyrometer' system, all programs, downloaded to the actual hardening cell, are tested for correct motion path behaviour and laser parameters. Hence, the laser's utilization ratio can be maximised.

8.2 OBJECTIVES

The objectives of the undertaken work include research and development in the fields of mathematical modeling, machine component design and simulation, robotic off-line programming, and automatic process control. The main research area in mathematical modeling is to select an appropriate methodology for the modeling of laser transformation hardening and further develop the selected methodology in a way that it can be used for a wider range of materials from low to high alloy steels and it uses new established data of the laser-material interactions.

In design and manufacture a computer-based simulation model of a machine element is developed. The model uses the data from mathematical modeling as input data. Life cycles and failure modes of the studied elements are simulated. The aim is to deliver useable data of the advantages and limits of laser transformation hardening and to understand better the implications of laser-based fabrication for the design and manufacture of a common machine component.

In robotic off-line programming the objective is to develop an off-line programming system/methodology for surface hardening. The system takes into account the component geometry and the heat flow in the material. Results from mathematical modeling are as basis for processing parameter selection. An automatic monitoring and control system, using an optical pyrometer, is tested and for controlling the hardening process.

8.3 RESULTS AND ACHIEVEMENTS

The basis for the mathematical modeling is the calculation of the surface temperature, heat flow and cooling rates. There are several analytical and numerical methods for calculating the thermal properties during hardening and most of them give quite fitting results. However the laser-material interaction of a diode laser is unknown and no experimental data has been published. In the ILSE project many calorimetric experiments have been made to establish the absorptivity of a diode laser beam to a metal surface, or an oxidized metal surface. Measurements have also been made for graphite coated and aluminium oxide blasted surfaces. This data can be implemented to previous models of CO_2 and Nd:YAG hardening. Results show that HPDL hardening is an effective process even without absorptive coatings and challenges the more conventional laser types both in coupling rate values and wall plug efficiency. Figure 2 illustrates a summary of the measured absorptivity values (Pantsar) to the experimental data presented in literature (Stern). The experimental data of Stern presents the absorptivity values plotted against the temperature in which the tests were made. The data for HPD laser is plotted against the surface peak temperature during hardening.

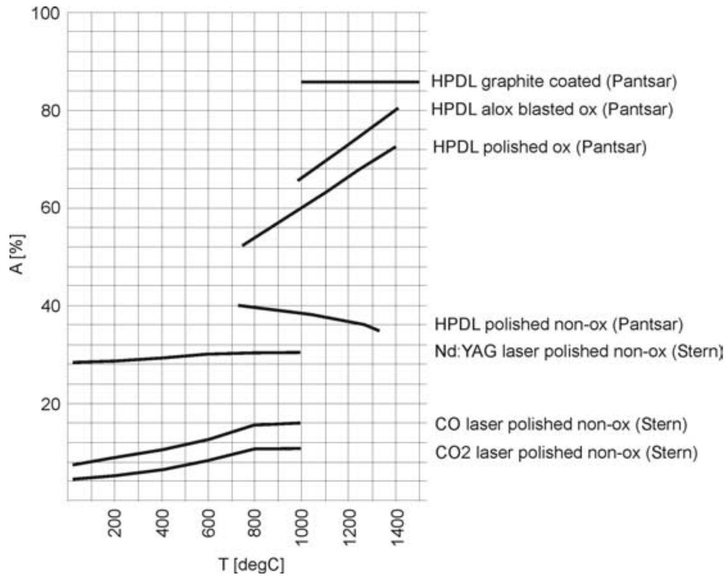

Fig 2. HPDL hardening compared to published experimental data for different laser types.

The heat flow in the material occurs as presented in Figure 1 and the effective laser power is determined by the absorptivity. The hardness of the resulting microstructure is dependant on the cooling rate, mostly affected by the traverse rate. A simplified rule for parameter selection is that harder surfaces are achieved with high laser power levels and high traverse rates, whereas deep case depths are induced by low power levels and slow traverse rates. The maximum depth for a given laser power is limited by surface melting. The effect of the cooling rate on the hardness of the hardened layer of 42CrMo4 is presented in figure 3 and the acquired case depths with different parameters are presented in figure 4.

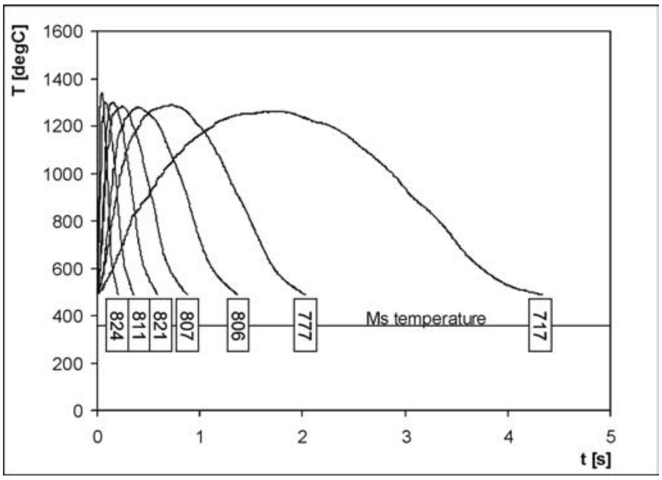

Fig 3. Heat cycles of surfaces hardened with various laser powers and traverse speeds. Average surfaces hardness, measured from the centerline of the hardened track, is shown for every sample, in HV5

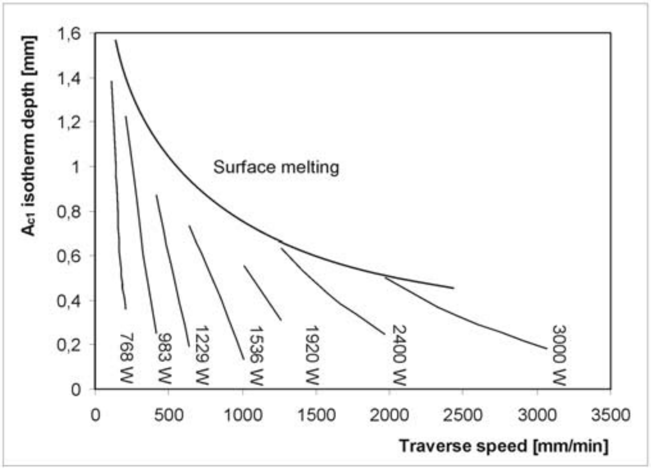

Fig 4. A_{c1} isotherm depths achieved with different nominal laser powers and traverse rates.

The heating and cooling rates together with the peak temperature determine which phase transformations take place during hardening for a given material. The equilibrium phases in different temperatures of each material have been calculated using a thermo-chemical software package together with a Scientific Data Group Europe –database at the University of Cambridge. Phase fractions and the chemical composition of presented phases can be calculated from the thermo-chemical properties of materials. From these calculated values, the austenitization temperature and the martensitic start temperature can be estimated. From this data the fraction of retained austenite in the hardened microstructure can be computed and the thermo-chemical calculations give also estimates for the carbide fractions in the material. All this data put together and using appropriate methodology for calculating the separate phase hardness, a model for calculating the uniform hardness of steels can be formed. This together with the formulae for calculating the thermal cycles during laser processing, using the new established data of absorptivity completes the task of simulating phase transformations in laser hardening.

For certain materials, in which a part of the carbon content is attached to carbides, the austenitization cannot be simulated using the equilibrium values of the thermo-chemical computation. In such cases the phase transformations are diffusion limited, and require calculations using the diffusivity values of carbon in austenite. With high traverse rates it is often not possible to attain a uniform hardened layer. Figure 5 illustrates the hardened regions of a hypoeutectoid steel S355 and medium alloyed heat treatable steel 42CrMo4. Same parameters were used in both cases. The steel S355 shows incomplete austenitization whereas the steel 42CrMo4 is uniformly transformed.

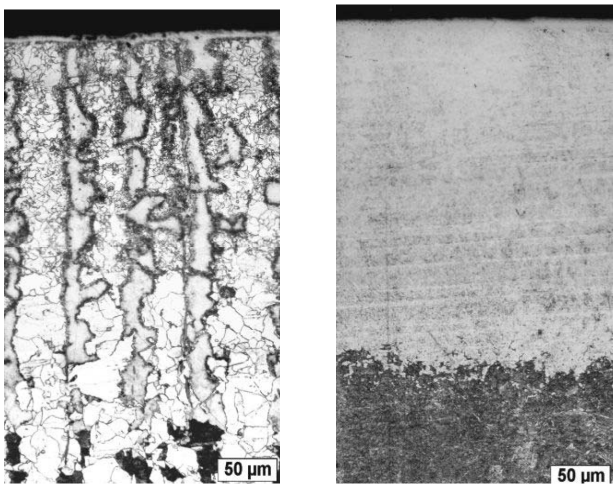

Fig. 5. Microstructures of two hardened steels hardened with equal parameters. Left: S355, Right: 42CrMo4.

A robot programming and simulation system for automated hardening path generation, illustrated in figure 6., has been completed. With programmed tools the user can generate optimal robot motion paths based on the 3D geometry of the work piece. All required parameters for hardening can be retrieved from a database or parameter file generated with the system developed in mathematical modeling. System functionality has been automated in order to get the user interface as simple as possible. The systems's ease of use decreases the need for the user's expertise in robotics. If changes in path generation or hardening parameters are however needed, the user can easily change them in any state of the programming and simulation.

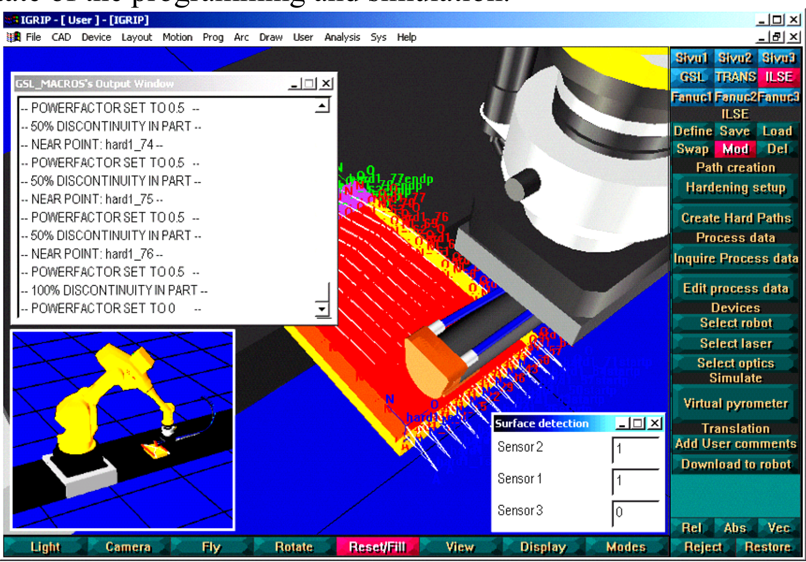

Fig 6. Laser hardening motion simulation with the virtual pyrometer.

Motion path and program generation in virtual environment is already standard practice in applications like spot- and arc welding as well as painting. What makes the developed system novel is the concept of the virtual pyrometer. Robot programs are still simulated to find possible robot limitations and collisions in created paths. The new feature of the system is the possibility to check the part geometry while simulating the robot motions. The virtual pyrometer works as a sensor detecting the part discontinuities while the robot moves, see figure 7.

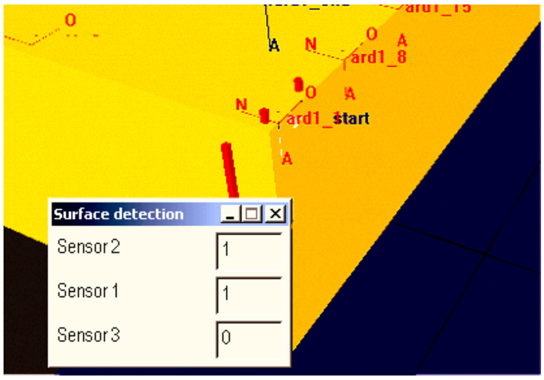

Fig 7. Virtual pyrometer sensors illustrated.

According to certain logic it will find features that can affect the hardening results. Holes, gaps and thin surfaces can cause melting and other unwanted effects on work piece. If such features are found, the system will automatically change the laser and motion parameters to avoid unwanted behaviour.

As the checking is done according to the robot model behaviour, all possible limitations of the actual motion system are checked simultaneously. Possible problems with robot performance and motion limitations in the real life work cell will hence be avoided.

When hardening paths are simulated and approved by the user, robot programs are automatically generated. The user does not need any deep knowledge in robot programming language as the needed program code is also generated automatically. Needed motion points, all required parameters and laser controls will be included in the program code. When the program is transferred to the robot controller it can be run without any further tasks of robot or laser programming.

The system for off-line programming of laser hardening has been built on a commercial robot simulation and programming software, Delmia IGRIP. The decision to start working on this platform was made based on previous experiences with robot OLP. The software has a vast selection of graphical robot models with correct controller and motion features. When virtually all broadly used robots in industry are already included in the software platform, efforts can be concentrated on automated program generation. All functionality of path generation and virtual pyrometer can be used with any robot model existing in the software libraries. It is even possible to generate own models for generic NC-machines and rare robot models. The selected approach enables flexible technology transfer to industrial applications. All parameters of laser hardening can be changed from a robot to another very easily, making for example comparison between different robots and their characteristics very easy.

8.4 FUTURE ACTIVITIES

The thermo-chemical calculations are implemented in a computer-based system for estimating the hardness of treated surfaces. X-ray diffraction measurements are made to verify the theoretical models. Hardness measurements for different processing parameters are made for 35 steels of industrial interest. One of each major steel category, low alloy steels, heat treatable steels, tool steels and martensitic stainless steels, is taken into more detailed study to observe the effect of processing parameters on the austenitization of the material. A map of processing parameter combinations together with hardness values can be established for the use of everyday practise and to help in component design and materials selection. The results may be used also in a computer program system, which consists of a mathematical software package, which uses thermo-chemical programs and databases as slaves. This way a computing method for calculating the material properties even further may be developed. Such system is however very expensive and needs to be tested in the part of diffusion calculations.

In the near future, activities in the field of robotic off-line programming will include testing and improvements on the virtual pyrometer concept. The accuracy of the actual robot and the simulation model will be investigated. Simplified samples have been made to check the pyrometer functionality in the cases of different kind of holes and variable surface thickness. Comparison of different hardening parameter setting will be tested. Tests will include manual laser power control, hardening with pyrometer and hardening with parameters from the virtual pyrometer.

When the basic level functionality of the system is established further work will involve development of new features and more accurate control. The first version of the virtual pyrometer works at pre-programmed steps. For example the part geometry can be checked every 1 mm, but such a small step makes simulation very slow. If the pyrometer functionality would be an independent real time software, the control cycle could be much faster and hence more sensitive to feature changes in the work piece geometry. An independent software module could also include more intelligence to react more accurately in more complex discontinuities than wholes or gaps.
System intelligence and usability could possibly be taken even further by including a mathematical 3D model of heat transfer in simulation. Such systems have been researched in Fraunhofer Institut Werkstoff- und Strahltechnik, in Dresden Germany. Co-operation with IWS in the future would definitively be a very interesting possibility to look into.

8.5 PARTNERS

Extensive metallurgical assistance and instruction has been received from the phase transformations and complex properties research group of the University of Cambridge. The contribution of Professor Bhadeshia to the work done in Lappeenranta is gratefully acknowledged. Some of the work has been done in non-commercial co-operation with Imatra Steel and Uddeholm Finland. A major robot manufacturer R/D department has shown interest in achieved results. Possibility to do collaboration in the near future in developing user interfaces and parameter control at the robot controller has been discussed preliminarily.

8.6 BUDGET AND SCHEDULE

The original project schedule has been followed well throughout the project. Slight delays have been caused due to the changes in the researcher group. The project has been kept well within the proposed budget.

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9 USER INTERFACE OF ROBOTICS MACHINES BASED ON PERCEPTION AND COGNITION

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ABSTRACT : In the project a new philosorhy of making the user interface for mobile robotic machines was studied and a demonstration prototype was developed and tested. The interface is based on utilising interactively the senses of both the the human and machine entities; the human when commanding the machine and the machine when perceiving objects or interacting with the working environment. The user commands the machine using communication natural to humans, such as speech and gestures. The syntax of the communication language utilises the objects and work targets currently existing in the presence (working environment). The prototype interface was constructed for the WorkPartner robot, which is a human like service robot developed for tasks in outdoor environment. The interface includes new interaction devices developed during the project. The whole interface is wereable and can be used simultaneously when the user works with the robot.

9.1 INTRODUCTION

Starting point and motivation of the research was stated as follows (direct citing from the research plan):

"Development of mechatronic machines has been fast on the level of automation of machine functions, but relative slow in the area of user interfaces. Little of those possibilities provided by today's computer and multimedia software technology have been utilized. Under-development of the user interfaces means that all potential benefits of mechatronisation cannot be utilized because the human operator is not able to fully use his strong cognitive abilities like understanding the environment, the work problem and planning related operations. Instead, he has more or less to concentrate on steering the machine. User interfaces are constructed still on the traditional idea of commanding and monitoring single operations rather than controlling task execution. Improvements are made mainly in ergonomics.

New computer-controlled machines are coming, however, more and more robotic like (development e.g. in modern construction or agriculture machines) and the user should be able to move to a more comprehensive level of planning and monitoring tasks (supervisory control). In this level his brains and senses are utilised most effectively in the human-machine process. This doesn't mean that the direct basic level controls are not needed or used at all, but the user can be freed from those operations if and when the machine knows how to proceed with the task. In practice such needs are already coming up when teleoperation is presently being taking use e.g. in mining machines. The machines are not teleoperated through the whole work cycles, but run in automatic or semi-automatic modes as much as possible. This improves the work environment and one operator may control several machines, which in turn improves efficiency.

The current digital multimedia technology offers versatile environment to develop new type of user interfaces for robotic machines. Machines can also be equipped with more sensors and senses, which give information concerning behaviour of the machine and the task environment. This gives possibility for the user to guide the work by "talking" with the machine (in a cognition level) by using concepts and symbols, which are perceived and understood by both parties. Research on this kind of new user interfaces is topical especially in robotics, but the results are beneficial and can be applied also in more traditional work machines. Up to now the relative high prices of multimedia technology has limited its use in practice, but there has been a rapid change in this situation when PC-technology can now provide cheap and powerful means to almost all applications."

During the project the original motivation and starting point of the research remained unchanged.

9.2 OBJECTIVES

Objectives was stated as follows (direct citing from the research plan):

"The main goal is to study, develop and test new methods and tools for a new type of user interface to robotic machines based on shared perceived information, interactive task analysis and multimedia communication. The target is a prototype user interface, which demonstrates new possibilities in human –machine interaction, like commanding tasks by analysing and advising operations rather than controlling individual motions or sequences. The interface also supports machine learning under operator supervision during working. The test platform is a service robot design for interactive working with humans in outdoor environment".

During the project there were no changes in the main objectives of the project.

9.3 RESULTS AND ACHIEVEMENTS

9.3.1 *Scientific results*

The research project advanced mostly according to the original research plan. The plan includes the following tasks:

Task 1. Analysis and Structuring
Task 2. Cognitive model
Task 3. Prototype user interface
Task 4. Integration tests

Task 1 was completed during the first year of the research. Needs and structures of user interfaces intended to interactive control of mobile robotic machines were analyzed from a new point of view, which takes into account the cognitive features of the presence, where the user and the machine operate. As the result a prototype model of the cognitive user interface was defined and an interactive experimental system for testing it was design. The system includes hardware and software for communication with the robot by using both speech and gestures. The prototype undergone several modifications during task 3 and is integrating to its final version during the spring 2003 when task 4 is completed. The prototype is explaned in more detail in the Appendix.

Scientifically the most important output is the cognitive model of the interface made in task 2. It is based on a high level communication and command language between the human and the robot, which utilises both speech and gestures as part of the syntax. The important part is the presence model, which describes the current surrounding world for both the human and the robot. It is a virtual environmet model, which includes both geometrical features and an object database. The cognition of the human user and the machine are unified trough this model. The robot control software has an planner, which iterpretes the high level command language, plans the actions its content requires and convert it to a sequence of intermediate language, which in turn commands the subsystems of the robot to execute the task related operations.

The cognitive user interface was integrated to the upper level management software of the WorkPartner robot, which was used as the test platform in the research. As the result, the human-robot interface (HRI) can be demonstrated using a limited version of the communication and command language developed during the research to perform non-trivial tasks for the robot. The following short example illustrates how the cognitive HRI works. The WorkPartner robot is a mobile service robot with a human-like two hand manipulator. Its perception system includes a color camera and two laser range finder units trough which it can "see" the surrounding world. It can also navigate autonomously using several different sensors. The user, which is identified from the special color jacket, can command the robot by voice and gestures using a wereable wireless user interface. He/she can e.g. make a command "bring box", which includes action "bring" and object "box". This tells to the robot to go to the box, grasp it and bring it to the user like a trained dog. The action "bring" is planned as a feching task to find the way to the object, recognize and localize it for grasping, take it and carry it back to the user (which might move during the operation). The object "box" is an object in the presence with certain features. If the object is recognized uniquely, but all necessary data, e.g. its location, is not available the robot's planner it asks that from the user. The user might show the location in the presence model at the screen of the interface PDA or directly from the real world using a laser pointer. When knowing all details the robot can plan the rest of the actions and go near the place where the box is. Next it has to find the box by using senses, because otherwise grasping cannot be done. The planner controls a proper perception process for this purpose. If the box is found the robot knows trough the database parameters what the box is like and how to grasp it. In the case the box is not found the robot again asks more information and the user reply e.g. "look under the table", which quides the searching area defined by the aid of another object in the presence model.

The most important result of the research, the model of the cognitive human- robot interface, is a fully new type of user interface for intelligent mobile machines. Its basic feature is that it can utilize the presence where the operator and the machine operate trough the sensor information and cogniniton of both entities. The machine also uses its "understanding" about the presence and the task, In classical user interfaces oly the user senses and his/her understanding are normally utilized. High level interactive commanding, which is based on the machine's capability to make autonomous operations, cannot be performed. The key element is the presence model which makes communication and interpretation of commands possible. The results of the research are generic and can be applied widely in the field of mobile machines. The obtained results are, however, only the first trial to work with the new paradigm. Most of the research results are still on theoretical basis without sufficient experimental verification. Human-machine interfaces typically includes lot of small details, whose rationality can only be studied trough extensive experimental tests. The research project was too short for such experimentation. Also the resources didn't allow extensive programming and construction of several versions of the haptic interface. The prototype HRI was integrated, programmed and tested only in the case of an relatively elementary vocabulary of the interaction commanding language and tests were done with few example tasks only. The presence model was implemented in a more general form, but its structure needs also more experimental testing to become functional in details. Fortunately, the prototype and its software were succeeded to be implemented in a generic form, which allows to develop its functions without problems in the future.

The prototype HRI is introduced in more detail in Appendix. The presentation is a conference paper given IFAC World Conference in Barcelona in July 2002.

9.3.2 *Technological results and applicability*

The nature of the project was basic research. There were no direct application target except to implement it in the test platform. The cognitive HRI concept offers, however, several possibilities to continue application development in the fields of service robot and work machines. The prototype HRI includes some technological innovations, which may have future as a stand alone application. The wearable system is one of them. It can be applied to communicate high level commands to a machine or teleoperate it off-board. It can be also used as a general interactive device like the "data clove", but copying the arm rather than the hand movements. The virtual representation of the presence, where both the machine and the operator exist, is another innovation , which has generic meaning. The laser range finding scanner technique and related SLAM methods by the aid of which the presence is created, is applicable e.g. to forming accurate maps from limited forest areas (more closely, see Pekka Forsman's doctor thesis). Trees are in their right positions and the associate trunk volumes can be roughly estimated. The most important innovation is, however, the HRI concept itself. It is applicable in several different forms to operator interfaces of intelligent machines. The operator can sit in the cockpit, be off-board or teleoperate the machine remotely. The interactive cognitive part is the same in each case. Naturally, gestures can be used only when the operator is off-board near the machine.

9.3.3 *Researcher training*

The researcher team included senior researchers, doctor students and master students. During the project, related to its problem area, one Doctor thesis (Pekka Forsman), one Licentiate thesis (Jussi Suomela) and one Diploma thesis (Jouni Sievilä) was completed, and one recently started Diploma thesis (Minna Väyrynen) is still under progress. In addition several students were working for study project related to details of the prototype HRI. Research results were reported in several international workshops and conferences by doctor students.

9.4 FUTURE ACTIVITIES

The research is continuing with another project providing more resources for experimental testing. The project is financed by TEKES and two companies. Also a European Community project called PeLoTe (Building Presence through Localization for Hybrid Telematic Systems) has been activated in autumn 2002 and within it the study of virtual presence modelling can be continued. The WorkPartner project also continues and the prototype HRI will be gradually adopted as a natural part of the human - robot communication system of the robot.

9.5 PARTNERS

The research team had no official partnership with other research institutes or companies, but it worked closely with the WorkPartner -project team, which in turn had following active partners.

- research institutes: VTT (robot languages)
  University of Lapland (art design)
- companies: Scientific Rover Company (St Petersburg, mechanics subcontrats)
  Tamrock (case study)
  Plustech (active follower of the project)
- CLAWAR thematic network (EU consortium including 42 members, active follower of the project)

9.6 BUDGET AND SCHEDULE

The total budget of the project was 229 408 EUR. It was financed by Academy of Finland (162 132 EUR) and the Finnish Work Environment Fund (67 275 EUR). The project started 1.7.200 and ended 30.6.2003.

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10 ANALYSIS AND CONTROL OF VIBRATIONS IN ELECTRICALLY DRIVEN MACHINE SYSTEMS

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ABSTRACT: In the project methods, computational models, algorithms and knowledge for solving the vibration problems caused by the interaction between the mechanism and the electric drive are developed. These areas have previously been studied separately. Insufficient computational capacity has made it difficult to combine the models with the precision needed, and thus, the final functionality is known only after testing the machinery or its prototype. This leads easily to oversizing or uncontrolled dynamical behaviour of the machinery. Inverter drives bring their own characteristics to mechanical systems. Feedback loop and semiconductor control create additional excitations which are transformed through the electric actuator to the mechanism. These combined with mechanical resonance may cause noise and vibration problems and thus impair usability and the lifetime of the equipment. Almost all new paper machines, elevators and cranes are fed by inverters.

10.1 INTRODUCTION

Nowadays fast dynamic servomotors are becoming general in several machine automation areas. This sets new demands on mechanisms connected to motors, because it can easily lead to vibration problems due to fast dynamics. On the other hand, the non-linear effects caused by motor and machine mechanism frequently reduce servo stability, which diminishes the controller's ability to predict and maintain speed. As a result, the examination of vibrations that form in a motor as well as of the mechanism's natural frequencies, has become important.

Physical prototypes have traditionally been used for studying the interaction between a motor and the mechanical system connected to it. Physical prototyping is, however, slow and expensive. The development of computers and software has made feasible the simulation of the behavior of mechanical systems as well as the 3D visualization of such systems, i.e. virtual prototyping or virtual testing. The aim of virtual prototyping is to enable the designer to test the behavior of a device without using a physical prototype, which requires the virtual model to incorporate the properties of the real application with sufficient accuracy. The traditional approach to dynamic analysis of mechanism and machines is based on the assumption that systems are composed of rigid bodies. However, when mechanism operates in a high-speed condition, the rigid-body assumption is no longer valid and the load should be considered flexible. In this study, virtual prototyping is used as a tool for the dynamic analysis and control system development of an electrical motor coupled to a flexible mechanical system.

Simulation models developed in the project are used for control algorithm development. In traditional control methods of electromechanical systems the feed back of the controller is taken from the motor. In that case the vibrations of the tool mechanism, reel, gripper or any apparatus connected to motor is not taken into account. This might reduce capability of machine system to carry out its assignment. Active vibration control methods for vibration suppression of mechanics have been receiving increasing interest in recent years.

10.2 OBJECTIVES

The objective of project is to generate methods, models and knowledge for solving the coupled dynamics problems in electrically driven machine systems. The dynamic interactions between the subsystems i.e mechanics, actuators and control systems are highlighted. One goal is to create methods and tools for designers to analyze coupled dynamics of these systems. The main challenges are mathematical and software problems while including physical phenomena occurring in different time –levels.

10.3 RESULTS AND ACHIEVEMENTS

Coupled simulation methods of electrically driven machines

In this study the simulation methods and control algorithms for electromechanical systems have been developed. First of all appropriate simulation environment was chosen. One simulation possibility was to model motor and mechanics in MatLab/Simulink environment. For mechanics modeling we tested add-on software called SimMechanics. Simulink and SimMechanics are good environments for simulation of simple rigid body mechanisms but these software applications were found too limited for the simulation of complex and flexible mechanics. Nevertheless, from an engineer's point of view, it is much more convenient to model the different subsystems directly in their original simulation environment. This simulation method, where two different programs trade parameters with each other at a preset time step, is known as coupled simulation.

For mechanics simulation we have used a commercial multi body dynamics program called ADAMS. ADAMS enables building and testing of virtual prototypes i.e. the simulation of the behaviour of mechanical systems as well as the 3D visualization. The advantage of ADAMS vs. for example MatLab is that mechanical dynamical systems are described geometrically. This means in ADAMS mechanics can be defined by building model with ADAMS's own library of parts or CAD geometry can be used to lay out the system, so the deriving of complex equations of motion is eliminated.

In the project we have used two coupled simulation methods. The first method is implemented in such a way that the electromagnetic phenomena were calculated in MatLab/Simulink® due to the complex differential equations involved, while the dynamics of mechanical system were calculated in the mechanical system simulation software called ADAMS/Controls. ADAMS/Controls is add-on product for ADAMS software family and it enables the exchange of data between these two programs. In this method the integrators in both software applications run parallel. They exchange data as specified by the step-size. Generally MatLab/Simulink® is used to model those parts of the system that it does best, the controllers which drive the dynamic of the system based on sensor feedback, while ADAMS is used to model the mechanical parts of the system that are influenced by the geometric layout. The first simulation models of the rotating- and linear motors were implemented by this method (Teppo 2000), (Teppo et al. 2001), (Hirvonen 2001), (Hirvonen et al. 2002), (Hirvonen et al. 2002).

In the second method drive and motor model are implemented in Simulink and compiled for a C-code using Real-Time Workshop (Fig. 1). Derived code is manually edited to run as a subroutine inside ADAMS. In this method user interface is in ADAMS and the motor system model is fully parameterised. The simulation with the control system then runs entirely within ADAMS using the

ADAMS integrators. With this simulation model we have examined the dynamics of the cardan joint application driven by a frequency converter and a rotating permanent magnet synchronous motor (PMSM). Studied double cardan joint driveline is also modelled analytically in Simulink and coupled electrical-mechanical simulations are performed both in ADAMS and Simulink. A good agreement was found between the simulation results obtained using different programs. The double cardan joint driveline is a good example of a mechanical system that may cause vibrations. It was found with the simulation models that the control system of the electric motor might try to compensate the cardan driveline transmission error, and thus, cause unnecessary dynamics loads. As the control algorithm, the frequency converter uses the direct torque control –method (DTC). DTC is a very fast responding control method, where control decisions are made in every 25 μs (Saren et al. 2001), (Saren et al. 2002). In the (Hammarberg et al. 2002) is more about this method and three papers are in preparation of the coupled simulation of cardan mechanism and rotating electrical motor (Sopanen et al. 2003). In these papers, resonance vibration and control strategies of a coupled system are studied.

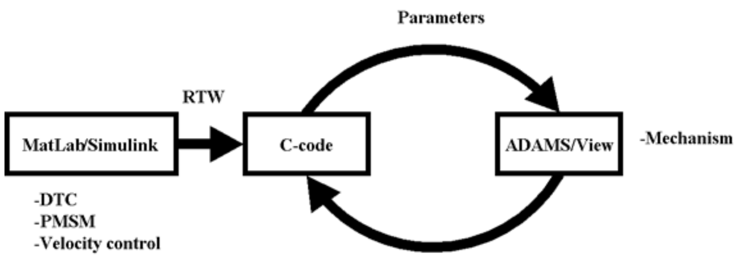


Figure 1. Principle of coupled simulation.

Coupled simulation models introduced above can be used for analysing the effects of the non-idealities of the system components on torque and speed vibrations. For example, the models of the frequency converter and PMSM can include non-idealities, which may cause mechanical vibrations at low frequencies. Current measurement errors and cogging torque of the motor are typical sources of vibrations (Hirvonen, 2001), (Hirvonen et al. 2002), (Laurila et al. 2001), (Laurila et al. 2002), (Laurila et al. 2003), (Salminen et al. 2000, 2001, 2002, 2003). The non-idealities of the system can be analysed separately or all together. In the latter case full advantage of the coupled model is taken. In general, the developed method of coupling the simulation models of the electromechanical system components allows testing different control algorithms, motor types and load models.

The servomotor application was obtained for model verifications and control system testing in the laboratory of mechatronics and virtual engineering. The motor is a linear permanent magnet synchronous motor (PMLSM). These kinds of linear motors are now playing a key role in advanced precision linear positioning. Linear motor is an ideal for control system development eliminating the non-linearities caused by backlash, friction, and compliance caused by mechanical transducer. The linear motor is an old invention but it is only recently that, as a result of the development of permanent magnets and their decreased costs, permanent magnet linear motors have become a viable alternative to rotating motors fitted with linear transmission. Linear motors are used in lifts, CNC –machines, conveyers and everywhere else, where fast dynamics, accurate positioning and linear movement are needed.

Control strategies for vibration suppression

In this study new control strategies for suppressing vibrations in an electromechanical system was developed. This development work was done using linear motor application. Whole simulation environment was carried out on Simulink due to simple mechanics. In control system design the mechanism can be usually simplified for a 2-dof system, when only first fundamental natural mode can be taken into account. In a physical application a mass-spring system acts as a tool-mechanism. Figure 2 clarify this in frequency domain and in pole/zero plot.

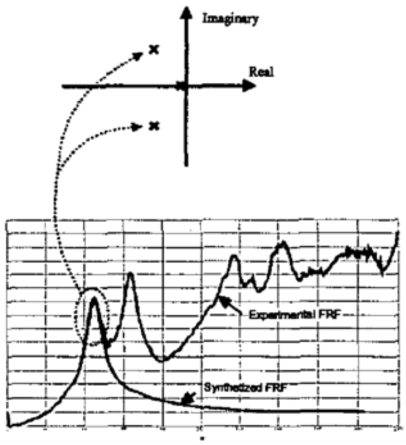
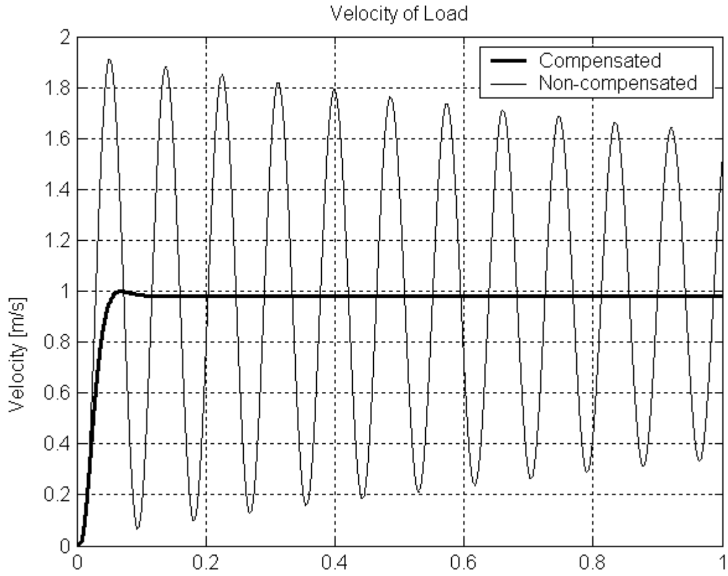


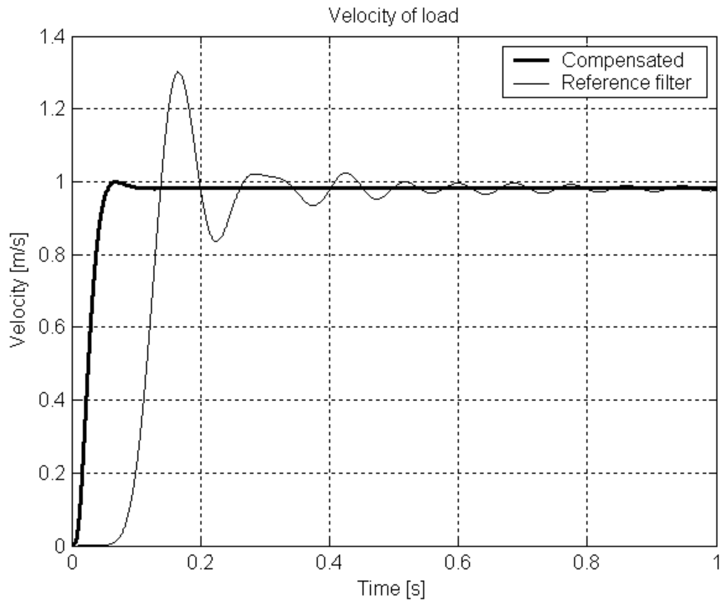
Figure 2. Simplification of mechanism for control system design.

There are two complementary methods to improve the dynamic behaviour of the machine system. The first is to make mechanism more rigid, but this method makes response slower. The second is to take the dynamic behaviour of the mechanism into account in a control strategy. This latter method is our subject of interest. Motion control technologies have been widely used in industrial applications. Due to the fact that good technologies allow for high productivity and products of high quality, the study of motion control is a significant topic.

One of the most traditional methods to suppress resonance in the electromechanical system is to allow only small and slow chances of a reference command. However, this method reduces dynamical properties of a servo system. In figure 3 (b) is an example of this kind of method, where the speed set point is filtered to remove fast movements. As we can see the dynamics is more incompetent compared to compensated system. More promising method is to use acceleration compensation to suppress load vibration. In this method the motor is controlled by simple PI – controller and load acceleration can be measured or estimated and to use as a compensation feedback. The weakness of using acceleration feedback is that the signal is usually very noisy. Often it is not possible to achieve acceptable performance using only those state variables that can be measured. If the system is observable, it is possible to estimate those state variables that are not directly accessible to measurement using the measurement data from those state variables that are accessible. And by use of these state-variable estimates rather than their measured values one can usually achieve acceptable performance. State-variable estimates may in some circumstances be even preferable to direct measurements, because the errors introduced by the instruments that provide these measurements may be larger than the errors in estimating these variables. In this study two different estimators have been tested and compared: Luenberger estimator and Kalman filter. In fig. 3 (a) are compared non-compensated and compensated velocities of load. In both cases the reference has been a unit step function.



(a)



(b)

Figure 3. Comparison of load velocities of linear motor using (a) acceleration compensation and (b) low pass filter as a reference filter.

During the project new knowledge of vibration sources of electrically driven machine systems has been obtained by using interactive models. Amount of papers done in the project shows that the issue interests several parties and the area is partly unexplored. The study carries on in the area of control system development and the aim is to develop new, more sophisticated methods in addition to traditional ones. Control methods and simulation models developed in the project can be utilized widely in machine automation applications and product development. Several papers are to be written about the topics presented.

10.4 FUTURE ACTIVITIES

In the reported project efficient tools for carrying out sophisticated simulator based analyses have been created. These models and software are going to be used in developing dynamics of paper machine roll drive systems in specialized R&D-projects going to be carried out in the future. They also are going to be used in developing direct driven motors for various purposes. The future trend in mechanical engineering seems to be the increasing popularity of integrated drive-mechanics systems that do not use gears. This increases the importance of understanding the coupled dynamics and electromechanical drive systems. There also will be academic activities in developing the vibration suppression methods for electromechanical drive systems.

10.5 PARTNERS

The work is mainly carried out with the Department of Electrical Engineering at Lappeenranta University of Technology. Their main task was to develop inverter models and non-ideal rotating permanent magnet synchronous motor (PMSM) models in Simulink incorporated into mechanics model in ADAMS. Also induction motor modeling and current measurement errors have been studied in this project. The co-operation with other consortium in TUKEVA has also been done. This co-operation has mostly been exchange of thoughts in the area of simulation methods. Laboratory of Machine Design, Helsinki University of Technology has carried out measurements with AC-motor, inverter and flexible rotor. This data is going to be used in verifying corresponding dynamic model in LUT.

10.6 BUDGET AND SCHEDULE

Budget: 272 296 €

Schedule: 1.6.2000-31.5.2003

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11 CONDITION MONITORING OF HIGH TEMPERATURE POWER PLANT COMPONENTS USING METAL EMBEDDED FIBRE OPTICAL BRAGG GRATINGS. FINAL REPORT, PART 1

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ABSTRACT: The aim of this project was to develop reliable manufacturing methods for metal embedded optical fibres and demonstrate the functionality of these The outcome of this project was intended to form a scientific basis for future product development projects. The project is still ongoing, therefore the final complete depiction is not yet available. The detailed achievements will be described in several scientific papers (see chapter 8). The development work and the main part of the experimental evaluation have been completed, but some important evaluation results are missing and will be reported in part 2 of the final report. From the available results, it is however evident, that the that the new type of in-fibre Bragg gratings can be metal embedded using vacuum brazing at temperatures up to 950ºC - 1050ºC and that the embedded gratings can serve as sensors in harsh environments at high temperatures. Optical fibres having a length of up to 30 cm have been embedded in metal alloys successfully. It should be relatively easy to extend the length of the embedded fibres if a larger brazing furnace was available. This report briefly discusses the main results of the different tasks in the project.

11.1 INTRODUCTION

A large amount of research have been conducted world-wide in the field of embedding optical fibres for sensing purposes in different kinds of non-metallic composites and concrete to monitor structural integrity of aerospace structures, vessels, bridges and dams just to mention some examples. In these cases the most frequently used fibre optic sensors seems to be in-fibre Bragg gratings, Fabry-Perot sensors and the distributed temperature sensing (DTS) technique. Very little seems to have been reported on embedding optical fibres in metallic alloys in the open literature. The aim of this project is to fill this gap by developing and demonstrating a method for embedding optical fibres in high melting point refractory nickel alloys. Embedding of optical fibres (with or without Bragg gratings) in nickel alloys will open up new applications in condition monitoring as the embedded fibres can operate at high temperatures and in other ways harsh environments. The Bragg grating used in this project has been developed and delivered by Acreo in Sweden. The experiences gained in this project will be utilised later for building fibre optic sensing networks, mainly for monitoring power plant components.

11.2 OBJECTIVES

The objectives of the project is to develop and demonstrate a method based on vacuum brazing for embedding optical fibres in a nickel alloy. To achieve this the following subtasks had to be solved:

- Development of a method for applying a nickel coating to optical fibres to improve wetting of the fibre surface (during brazing) and to protect the fibre.
- The choice of brazing alloy and choice of metallic coating for the fibres.
- Development of a method for pre-fixing the fibre before brazing.
- Development of an integrated fibre optical connector on the specimen in which the fibre is embedded in order to eliminate the weak points where the fibre enters or leaves the metallic alloy.
- Selection of brazing parameters by iterative brazing runs followed by microscopic and SEM-investigations of cross-sections of the embedded fibre.
- High temperature exposure tests of the embedded fibres

The results of the project are intended to form the scientific base for future application and commercialisation of fibre optical monitoring techniques in condition monitoring of future engineering constructions, mainly in energy production.

11.3 RESULTS AND ACHIEVEMENTS

In this part the main scientific results are described. Some aspects on the technological applicability are also included and finally a short overview of the researcher training imposed by the project is given.

11.3.1 *Scientific results*

In this section the results are presented mainly in a consecutive order i.e. later results are usually based on earlier results.

11.3.1.1 Nickel coating of optical fibres

The in-fibre Bragg gratings are delivered uncoated and they need a metallic coating in order to be successfully metal embedded using vacuum brazing. During planning of the project it was assumed that metal coating of optical fibres should be available as a commercial service. No such service was available so the coating technique had to be developed. This development work was therefore added to the project as an extra task by the steering committee. Unfortunately this task showed to be much more difficult than expected and therefore it took a considerable amount of effort. The solution adopted (patent pending) was to make the fibre electrically conducting first, by applying a thin layer (about 1 μm) of silver to it. After that an about 20 μm thick layer of nickel can be applied using electroplating technique. In Fig. 1 a cross-section of a nickel coated multimode fibre is shown. The fibre is embedded in conductive epoxy for eventual further SEM-investigations.

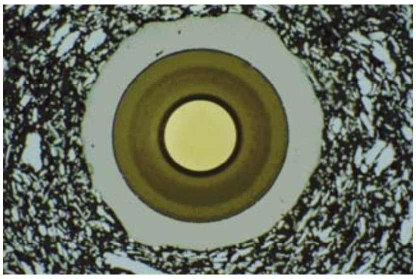


Figure 1. The coating technique has been developed to produce good nickel coatings (the grey ring) on optical fibres. The coated fibre is embedded in conductive epoxy and light is coming out from the core (the yellow colour) due to a light source placed behind the specimen. The diameter of the fibre is 125 µm.

11.3.1.2 Choice of brazing material and fibre coatings

Two commercial high temperature brazing alloys have been selected. For lower temperature applications up to about 500ºC the silver-based active brazing alloy Cusin-1 ABA (Wesgo Inc., USA) seems to be suitable. In many plant applications the temperature will be close to 600ºC and for these applications the nickel based brazing alloy MBF-35 (Metglas, Honeywell, USA) was chosen. Using the silver brazing alloy the fibres were brazed for 15 minutes at 950ºC. In Fig. 2 examples of bad and good brazing results are presented. A criterion of a good brazing result is that the brazing alloy should have an even distribution around the fibre and that the fibre coating should have dissolved almost completely.

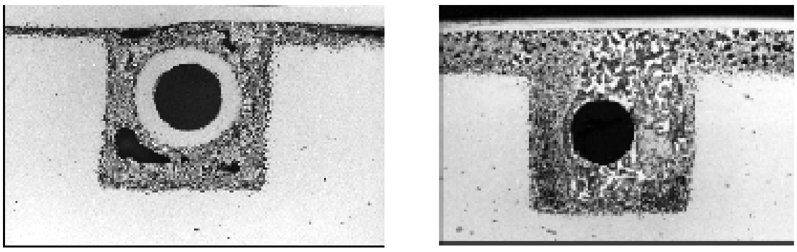


Figure 2. Examples of bad (left) and good (right) results in vacuum brazing of nickel coated fibres. In the right picture the nickel coating has dissolved into the silver based brazing alloy. The brazing parameters were adjusted until the result on the right was achieved.

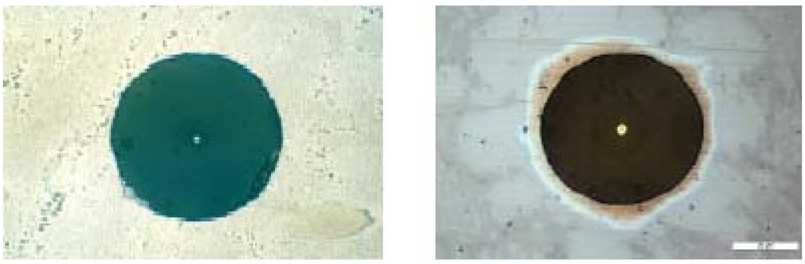


Figure 3. A nickel coated fibre (left) and a copper coated fibre (right) embedded using the nickel based brazing alloy MBF-35. The left result is excellent. The copper coated fibre is also well embedded, but the mixing of the coating and the brazing alloy is not as good as in the case of a nickel coated fibre.

In using the nickel based brazing alloy the quality criterion was the same as above. In Fig. 3 we see examples of brazing results using the nickel based brazing alloy MBF-35.

Optical fibres with copper, gold, tin and aluminium coatings are commercially available. These coatings are applied during the fibre drawing process and therefore existing fibres cannot be coated using these equipments. Bragg gratings are not written into the fibre in connection with the fibre manufacturing process so a method for coating the gratings needed to be developed separately as mentioned above. However, to simplify the coating process, it was suggested to splice the fibre gratings to pigtails of commercially available metal coated fibres, because in doing so, only the short grating area (5 - 7 cm) needed to be nickel coated. A suitable commercial metal coated fibre needed to be selected for this purpose. The low melting point coatings, such as tin or aluminium, were rejected based on the aimed service conditions for the fibres. Gold and copper coated fibres were tested. Gold behaved as well as nickel coating in the brazing process, but these fibres had to be rejected because of their otherwise low mechanical quality. Commercially copper coated fibres were chosen as pigtail fibres.

11.3.1.3 Test specimens, fibre pre-fixing, an integrated connector and brazing results

Several kinds of specimens were used in developing the brazing process. In Fig. 4 we see an Inconel (a nickel alloy) specimen in which a fibre grating (#5) was embedded. The nickel coated fibre grating was placed in a small nickel tube (outer diameter 0.35 mm and wall thickness 0.025 mm). The tube with the fibre was placed in a small groove machined into the lower part of the specimen. The nickel tube is useful for pre-fixing the fibre and for centring it in the groove. The groove was covered with brazing foils (MBF-35) and then the upper narrower part was fixed in position with two spot welded narrow bands of Inconel. This specimen was also equipped with an integrated fibre optical connector in the form of a zirconia ferrule with a stainless steel flange. The idea with this is to eliminate the fibre ingress/egress points where the fibre is very prone to breakage. Using the zirconia ferrule the fibre goes directly from the metal to the ferrule and light can be coupled to the embedded fibre using a normal fibre connector. However, this integrated connector part (the zirconia ferrule and the stainless steel flange) has to survive the brazing process (15 minutes at 1050ºC). In Fig. 4 the specimen has been connected to an optical cable using the ferrule and an optical connector. The manufacturing of specimens with an integrated fibre optical connector part is unfortunately rather difficult and had a low yield rate so in many cases measurements had to be made by coupling light to the embedded fibre through a polished end surface instead (free space coupling). Later the integrated connector was cut off and both ends of the specimen was polished in order to investigate the quality of fibre embedding. As can be seen from Fig. 5 both ends of the specimen show an excellent embedding.

Using the cut out connector part shown in the upper part of Fig. 4 it was verified that light is transmitted from the end of the zirconia ferrule and emerges from the embedded fibre at the other end of the piece. This indicates that the fibre is mechanically intact at the critical point were it crosses the interface between the ferrule and the embedding alloy. Inspections showed also that the zirconia ferrule and the stainless steel flange had survived the brazing process at 1050ºC under a high vacuum well.

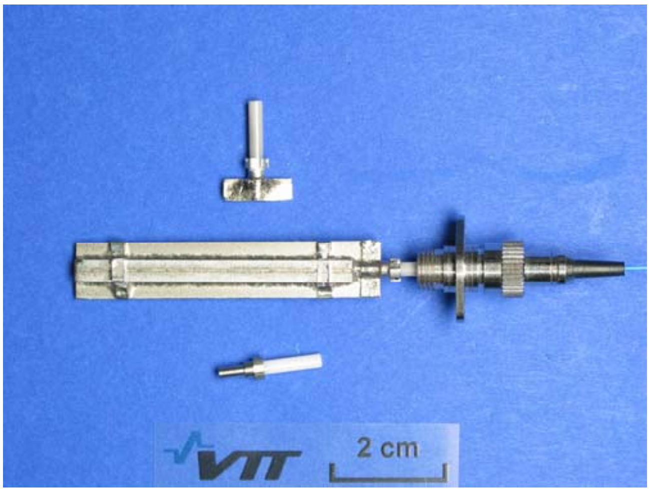


Figure 4. Test specimen with an embedded in-fibre Bragg grating (#5). In this case a fibre optical connector part has been integrated into the specimen to eliminate fibre ingress/egress points. In this picture the specimen is connected to an optical cable using the ferrule and the connector to the right. The zirconia ferrule with a stainless steel flange integrated into the specimen is shown in the lower part of the picture. The upper part of the picture show a connector part cut away from a similar specimen.

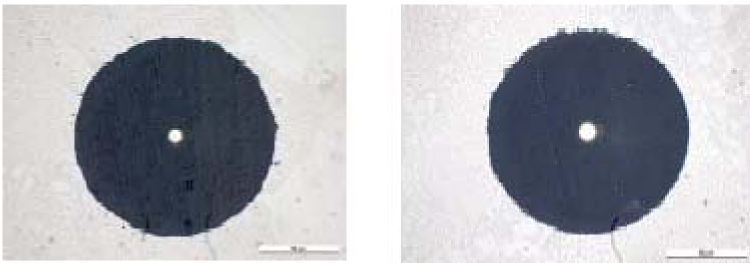


Figure 5. The ends of the specimen shown in Fig. 4 after cutting off the connector part and polishing the surfaces. Both ends show an excellent embedding. Light is coming out from the single mode fibre core. The right picture corresponds to the end where the integrated connector was. Both the small nickel tube containing the fibre and the nickel coating on the fibre has dissolved into the brazing alloy.

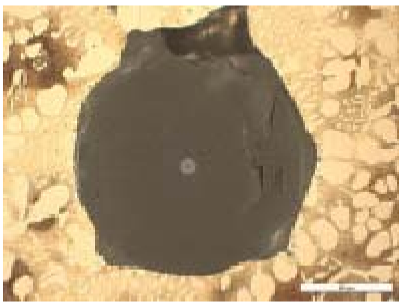


Figure 6. A bare fibre embedded in the same way as the fibre in picture 5. The embedding is poor with an uneven distribution of metal around the fibre.

For the sake of completeness a brazing test using a bare fibre was also performed. In Fig. 6 we see a cross-section of an embedded bare fibre. This fibre was embedded in the same way as the fibre shown in Fig. 5. The quality of embedding is poor in this case and the brazing alloy is unevenly distributed around the fibre. The uneven distribution of the brazing alloy around the fibre causes fibre damage. On the other hand, attempts to embed bare fibres are not recommended because of the risk of causing surface damage to the fibre and because of difficulties to handle a bare fibre.

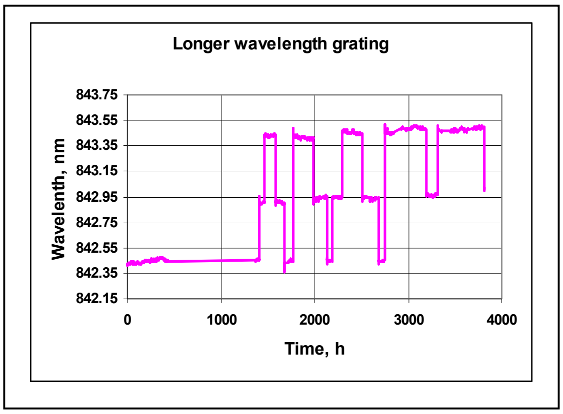
11.3.1.4 Brazing of long fibres

For testing brazing of long fibres copper coated fibres where used. Fig. 7 shows a 30 cm long piece of Inconel into which a copper coated multimode fibre has been embedded. This specimen was used for attenuation measurements.

Figure 7. A specimen used for developing the brazing technique for long fibres, in this case a 30 cm long multimode copper coated fibre was embedded. The cross-section of the specimen is about 4×4 mm and the fibre is placed in the middle.

11.3.1.5 Thermal cycling tests of embedded in-fibre Bragg gratings

The registered measurements of a long term elevated temperature test of two metal embedded optical fibre Bragg gratings are shown in Fig. 8. This test lasted for over five months and the embedded gratings were cycled between the temperatures 502ºC, 527ºC and 552ºC in air atmosphere. The wavelength response of the grating is stable and repeatable during the test. No reports of similar long term elevated temperature tests are available. These results are very encouraging with respect to future applications.



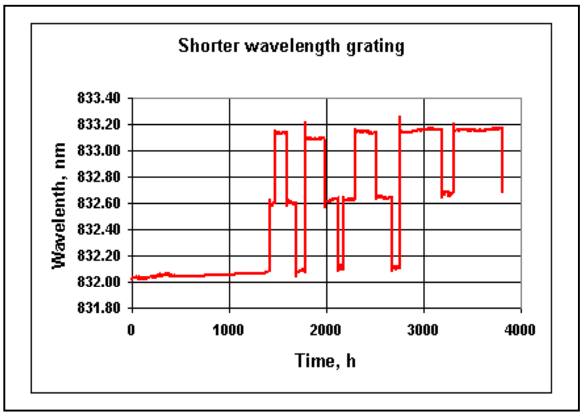


Figure 8. Thermal cycling of two metal embedded in-fibre Bragg gratings for over five months. The Figure shows the wavelength response of the gratings when they are cycled between 502ºC, 527ºC and 552ºC. These test results demonstrates that metal embedded fibre optical Bragg gratings can operate reliably at the aimed high temperatures.

These gratings where embedded in a piece of the Ni-based alloy Inconel using a silver based brazing alloy. A similar test on gratings embedded using the nickel based brazing alloy MBF-35 remains to be done. The nickel based brazing alloy is expected to give metal embedded gratings that can be used at even higher temperatures. Also, the gratings used with the MBF-35 alloy will have wavelengths in the more commonly used 1550 nm area.

11.3.1.6 Light guiding properties of metal embedded fibres

The long term elevated temperature results shown in Fig.8 demonstrate that the light guiding properties of a metal embedded single mode fibre is good enough to preserve the function of the embedded gratings i.e. the signal reflected from the gratings are strong enough and the reflected Bragg-peaks have preserved their (narrow) clock shape. In these tests the specimens in which the fibres were embedded had a length of a few centimetres. A spectrum of two metal embedded gratings recorded at 537ºC is shown in Fig. 9. The spectrum also contains the peak reflected from a reference grating. No peak splitting was observed. The intensity differences of the gratings (1 and 2) are mainly due to the light source, an ELED with maximum intensity at about 855 nm.

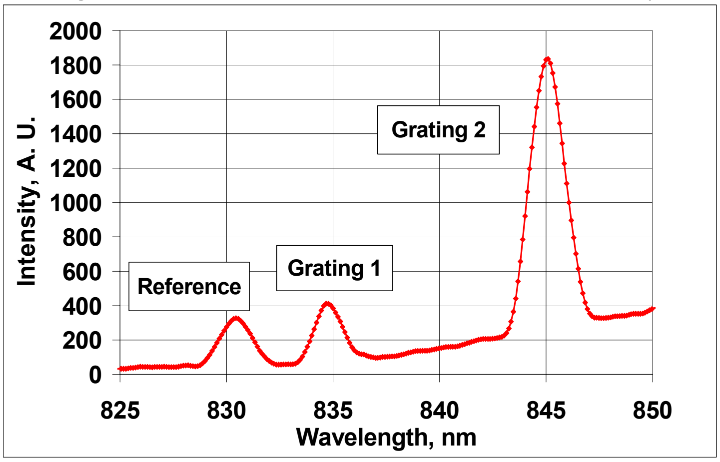


Figure 9. The spectrum of two metal embedded Bragg grating at 537ºC. A reference grating peak is also seen to the left. These gratings had about 2 nm longer wavelengths than those tested in Fig. 8. These gratings also survived a 68 hours test at 600ºC.

The attenuation of the guided light in an embedded multimode fibre was evaluated at room temperature using the 30 cm long specimen shown in Fig. 7. Multimode fibres are mainly used in distributed temperature (DTS) monitoring and it is therefore interesting to evaluate if many meters of metal embedded optical fibres can be used together with the DTS technique. This possibility would open many new possibilities for condition monitoring. Microbending caused by uneven distribution of the brazing material around the fibre is expected to cause larger attenuation in a multimode fibre than in a singlemode fibre because of the larger core diameter in the multimode fibre. Another cause of increased attenuation may be devitrification. Before attenuation measurement the specimen shown in Fig. 8 was heat treated at 650ºC for three hours. Then the specimen was cut into a 20 cm (left part of the specimen in Fig. 7) and a 10 cm piece for attenuation measurement. The attenuation measurements were made using a white light source (halogen lamp) and an optical spectrum analyser (Ando AQ-6315A). A halogen lamp was coupled to a multimode fibre (core diameter 50 µm) with lenses. This multimode fibre was coupled to the metal embedded multimode fibre (core diameter 50 µm) using a micromanipulator. The output of metal embedded fibre was coupled to optical spectrum analyser with a multimode fibre (core diameter 62.5 µm). The results are shown in Fig. 10. As can be seen the shorter specimen has a much higher attenuation. However, the attenuation in both specimens is high as compared to free multimode fibre, which have a typical attenuation of 2.4 dB/km at 850 nm. Normal single mode telecommunication fibres typically have attenuation around 0.2 dB/km at 1550 nm. The attenuation measurements need to be repeated at high temperatures with both singlemode and multimode fibres.

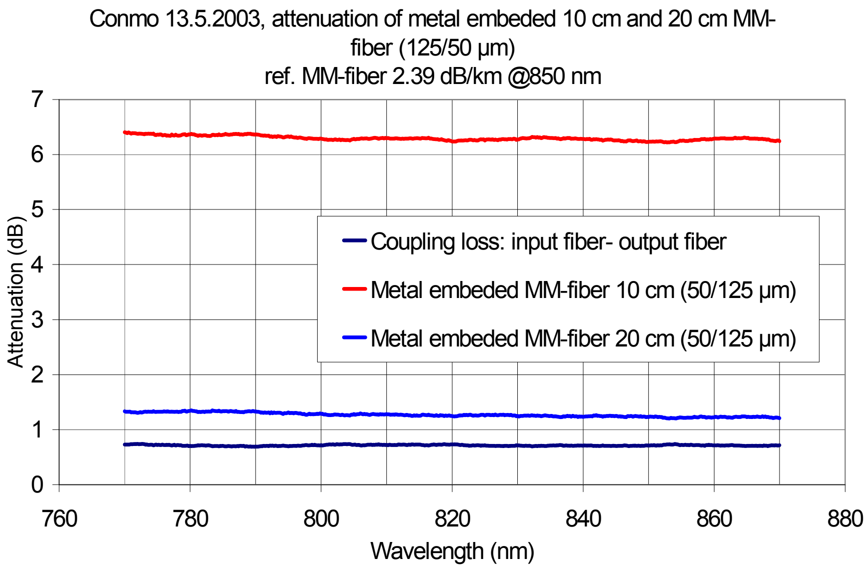


Figure 10. Attenuation measurement results at room temperature of the specimen shows in Fig. 8 after the specimen has been cut in two pieces. The shorter one has the higher attenuation.

11.3.1.7 Merging of VTT and Acreo processes

The Swedish Acreo AB, who manufactured the gratings used in this project, use a heat treatment step to make the gratings thermally stable. One project task was to investigate if the heat treatment used by Acreo could be replaced by the heat treatment used in the vacuum brazing process for embedding. A successful merging of these two processes would eliminate one process step in manufacturing metal embedded Bragg gratings. To investigate this possibility a couple of gratings lacking the heat treatment at Acreo were metal embedded.

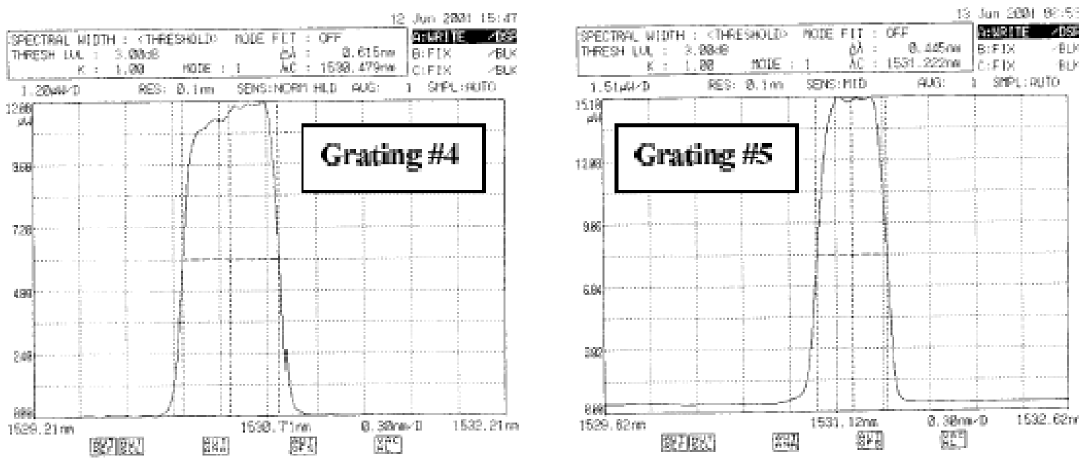


Figure 11. The reflected peaks from two Bragg grating (#4 and #5) before heat treatment and embedding. The centre wavelengths are 1530.479 nm and 1531.222 nm.

In Fig. 11 we see the peak reflected from two Bragg grating (#4 and #5) before the heat treatment and before embedding. The centre wavelengths of these grating are 1530.479 nm and 1531.222 nm. The centre wavelengths will be several nm lower after embedding.

Two initial trials to merge the two processes failed, as no Bragg grating signal was observed neither in reflection nor in transmission. These tests need to be repeated.

The metal embedded gratings were tested with the measurement setup shown schematically in Fig. 12. A Broad band light source (HP 83437A at 1550 nm) was coupled to an optical fibre circulator (O-Net Communications, 1520-1580 nm). The optical fibre circulator was connected to the embedded fibre grating with a micromanipulator (free space coupling). Back-scattered light was measured with an optical spectrum analyser (Ando AQ-6315A). The smallest measurement resolution of optical spectrum analyser was 0.05 nm. The resolution is the wavelength window of spectrum analyser grating, which sweeps the desired wavelength band.

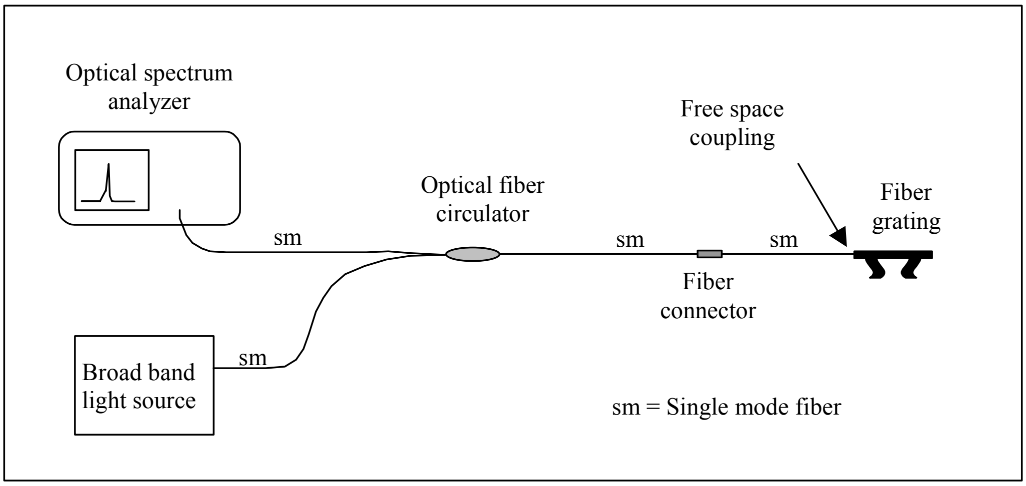


Figure 12. Measurement setup for the embedded fibre grating.

11.3.2 *Technological achievements and applicability*

The main technological achievements of the project is the development of a new method for embedding of optical fibres in refractory nickel alloys, the microscopic verification of the quality of the embedding and the presented measurement results on elevated temperature thermal cycling of metal embedded in-fibre Bragg gratings. No similar result seems to have been published anywhere. The project also produced three notifications of invention (see chapter 8).

As the method of embedding optical fibres in nickel alloys is new, it will also open up new methods for condition monitoring of engineering structures. An embedded fibre can sense the real conditions inside the wall of a component (temperature, strain, acoustic emission, radiation etc) better than surface mounted sensors. Furthermore, an embedded fibre is well protected against mechanical and chemical damage and can therefore function in very harsh environments, eg. combustion gases in energy production. Several project proposals for applying and further development of the developed technology have been prepared.

11.3.3 *Researcher training*

The scientific papers (see chapter 8) produced in the project are intended to form the base for a doctoral thesis for the project manager (Stefan Sandlin). The papers produced and the measurement methods developed will also provide material for licentiate studies for Ari Hokkanen. Besides these purely academic merits the project has deepened the insights in opto-electronics, fibre optics, materials science, joining technology, coating technology and monitoring technology of many of people involved in the project.

11.4 FUTURE ACTIVITIES

The future activities will be concentrated on national and international co-operation for developing applications for the developed technology. Some proposals including this technology have been sent to the sixth framework of the EU. Co-operation with a university in USA in also included in the plans.

11.5 PARTNERS

Two VTT departments, a university and a Swedish research institute participated in the project:

- VTT Industrial Systems
- VTT Information Technology
- University of Oulu
- Acreo AB (a Swedish research institute)

VTT Industrial Systems had the main responsibility for the project, while VTT Information Technology has assisted in solving optical measurement problems. They also had a representative in the steering committee. University of Oulu assisted in developing a method for nickel coating of in-fibre Bragg gratings. Acreo delivered the high temperature stable Bragg gratings used in the project. Acreo also provided valuable scientific advice. They participated through their own funding.

11.6 BUDGET AND SCHEDULES

In Fig. 13 budgeted costs and realised costs of the funding received from the Academy of Finland are shown. The realised costs are counted until May 2003. The remaining funds are used for the ongoing evaluation and for writing part 2 of this report.

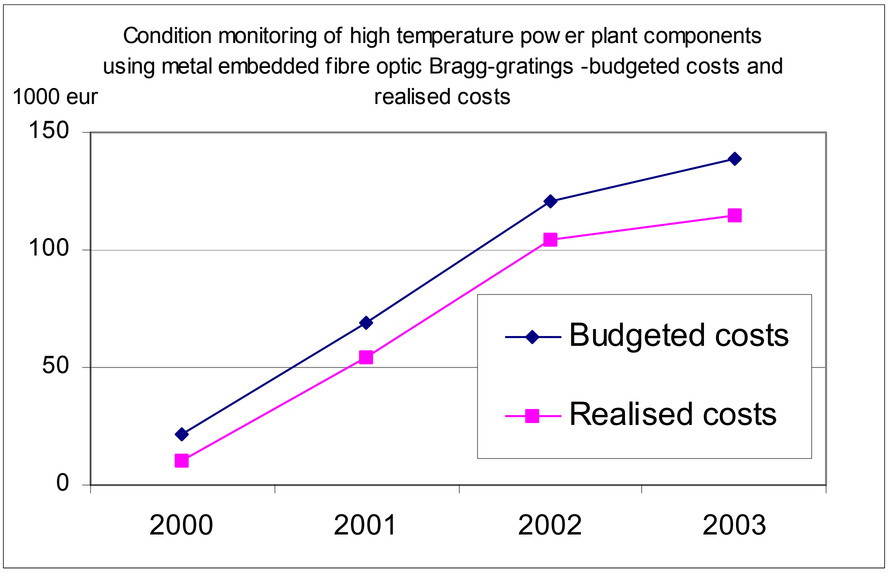


Figure 13. Use of the funding received from the Academy of Finland. The realised costs curve shows the situation until May 2003. The remaining funds will be used for the ongoing evaluation and for writing part 2 of this report.

The project schedule was mainly influenced by the task of developing a method for nickel coating of optical fibres. This task had to be added to the project in order to be able to coat the in-fibre Bragg gratings. This task delayed most tests involving coated Bragg grating with about 7 months. For funding this coating task a task involving software development was cancelled and the measurement method was reviewed in order to make the software development unnecessary. Also the brazing of fibres up to 2 m in length was cancelled as a larger brazing furnace would have been needed and the new cost profile did not allow the use of more expensive equipment. These changes were discussed and accepted by the steering committee.

11.7 CONTACT ADDRESS

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11.8 PUBLICATIONS

The following papers have been published or are in preparation:

Sandlin, S. & Heikinheimo, L. 2001. Evaluation of a new method for metal embedding of optical fibres for high temperature sensing purposes. Baltica V Conference. Condition and Life Management for Power Plants. Vol. 2. Pp. 547 - 557.

Sandlin, S., Kinnunen, T. & Rämö, J, 2002. Proceedings of the TUKEVA Research programme On Future Mechanical Engineering. Pp. 155 - 164.

Sandlin, S. 2002. Nickel coating of optical fibres. Helsinki University of Technology. Laboratory of Corrosion and Material Chemistry. Seminar 26.11. 2002.

Sandlin, S. & Hokkanen, A., 2003. Reliability of metal embedded fibre optical Bragg gratings at elevated temperatures up to 600ºC. COST 270 Workshop at BAM/Berlin 28/2.

Sandlin, S. & Hokkanen, A, 2003. Embedding Optical Fibres in Metal Alloys. IEEE Instrumentation & Measurement Magazine. June issue. Pp. 31 -36.

Sandlin, S., Kinnunen, T., Rämö, J, & Sillanpää, M. 2003. A method for metal coating of optical fibres. To be published.

Sandlin, S., & Hokkanen, A., 2003. Optical Performance of Metal Embedded Optical Fibres and Fibre Gratings. In progress

Sandlin, S. & Heikinheimo, L. 2003. Joint formation and characteristics of vacuumbrazed optical fibre to metal assembly. In progress

The following patents or notifications of invention have been produced in the project:

Sandlin. S. 2001. Patent application FI 20010307. A method for embedding of optical fibres in solid metal. VTT Manufacturing Technology, Espoo.

Sandlin, S., Kinnunen, T. & Rämö, J. Notification of invention 10.10. 2001. A method for metal coating of optical fibres.

Sandlin, S. 2002. Notification of invention 7.10. 2002. Utilization of small nickel tubes and zirconia ferrules in metal embedding of optical fibres.

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12 NOVEL CERAMIC TECHNOLOGIES IN REALIZATION OF MINIATURE ACTUATORS AND MOTORS

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ABSTRACT: During the project manufacturing technology of new piezoelectric ceramic structures has been studied. First manufacturing methods for pre-stressed actuators were studied and tested. Secondly manufacturing of 3D tape cast ceramic structures were investigated. Modelling of conventional and pre-stressed actuators and motors were studied with ATILA program confirming good correspondence between modelling and measured results. Pre-stressed piezoelectric actuator structures have been optimised and studied to create basis for further exploitation of the actuators. Prototypes of the piezoelectric motors have been realised with different functioning principles. Within project new pre-stressing methods were developed and these actuators have been used for different prototypes to utilise accurate and fast movements.

12.1 INTRODUCTION

Piezoelectric actuators are transforming electrical energy to mechanical work, producing relatively high loads with high precision and within short transient times. Piezoelectric micro actuators and motors have unlimited applications in general, and in micro robotics and telecommunications in particular. For example, consequent on developments in the manufacturing technology, present markets for the piezo actuators have reached the level of 10 billion USD a year.

The properties of the piezoelectric actuators are superior for small, fast, light weight and accurate applications. Major drawback of these actuators is that they have been limited to small displacements. Displacement has been amplified via bending structures such as bimorph (similar structure with bimetal on thermostat) but in this case load bearing capabilities has decreased significantly. The prospect of generating relatively large movements and moderate loads with piezoelectric ceramic has been under extensive research for several years. One of the most promising actuator achieving this goal has been RAINBOW (Reduced And INternally Biased Oxide Wafer) actuator and later on THUNDER (THin layer composite UNimorph ferroelectric Driver and sEnsoR). These two actuators utilise different thermal expansion of the ceramic and other materials during cooling after manufacturing processes. Due to pre-stress actuator possess high displacement and moderate load bearing capabilities which makes them feasible for various applications. New actuators opens possibilities for new solutions in fine/micromechanics, telecommunication, medical technology, microfluidistics and instrumentation (e.g. devices for vibration control, control of active spiral and patch antennas, micro twisters, very accurate light weight and small tilt-tables, pumps, valves, linear movers, load-speakers, etc.).

12.2 OBJECTIVES

General goal of the project was to create internationally significant new knowledge and know-how concerning about piezoelectric ceramic manufacturing and material technology (pre-stressed RAINBOW structures and 3D ceramic structures). Another aspect of the project was to obtain new actuators and applications for the fine and micromechanics, active noise and vibration cancelling, telecommunication, medical technology and instrumentation. Objectives were also to maintain and form new national and international co-operation projects and to help in commercialisation of studied applications.

The overall technological goal of the research project was to investigate new kinds of piezoelectric actuators especially for the fine/micromechanical applications with the realistic prospect of generating relatively large movements (up to 10 mm) by combining bulk, thick-film and tape casting ceramic manufacturing technologies with novel RAINBOW piezo structures. RAINBOW is piezoceramic structure manufactured with high temperature reducing process from piezoceramic bulk discs. They possess high displacements (up to millimetres) and moderate load bearing capabilities. Several RAINBOW actuators can be combined to achieve even greater displacements up centimetre range. RAINBOW technique can be used for conventionally (bulk) or tape cast (HTCC and LTCC) made piezoelectric ceramics. Objective was to test functional properties of such actuators and their behaviour would be studied and modelled. After basic structures more complex structures would be constructed, tested and modelled. Combination of modelled and measured results will ensure optimised structures and expands theoretical and practical knowledge. Manufacturability of the actuators is under careful examination during whole project so that mass production of the actuators would be possible.

Tape cast LTCC/HTCC (Low/High Temperature Co-fired Ceramic) enables stacked and laminated ceramic structures even up to 100 layers. Unfired tape (green tape) with soft and elastic form can be used to form different kind of 3D ceramic structures for actuation or sensing purposes. Also low voltage piezoelectric multilayer actuators are manufactured by this method. The tape cast materials planned to be used were commercial HTCC and customised piezoceramics aiming for LTCC compatibility (sintering temperature <1000°C) so that combination of the passive and active LTCC materials would be possible.

12.3 RESULTS AND ACHIEVEMENTS

12.3.1 *Research of the manufacturing process of the pre-stressed actuator*

In early stage of the project manufacturing of the RAINBOW actuators was tested in larger scale. This led to conclusion that repeatable processing of the actuators is very hard task to fulfil in laboratory conditions (high variation in component properties). New method to manufacture similar type pre-stressed components was discovered after research. The process allowed repeatable manufacturing with lower variation between component performances. Manufacturing is easy and straightforward process feasible together with normal piezoceramic manufacturing process and with conventional and widely used equipments. Process has also other advantages (compared to RAINBOW or THUNDER processes) such as pre-stressed region manufacturing is possible for almost any shape. Comparison between corresponding actuators is still under work as well as optimisation of the actuator performances (mainly displacement and load bearing capability). Best actuators have been on the same level with THUNDER and RAINBOW. Research group is expecting that the actuator performances will be improved in the future. An investigation for commercialization was done by outside consultant with TULI funding of the TEKES. This study revealed wide interest of the different fields of industry (medical technology, mechanic and electronic industries). New method to create the pre-stressed actuators is under patent pending.

Research group is also currently investigating two new methods for pre-stressed actuator manufacturing. These methods can be used as an extension for previous one or separately. Both methods has own advantages and unique properties as well as feasibility for different applications. One of the investigated methods is aiming for integrated components for really low price components. Another method is aiming for larger size pre-stressed components with very high performance level. Both methods are mass producible and patenting of new methods is under investigation.

12.3.2 *The pre-stressed actuator structures*

Extensive studies about behaviour of pre-stressed actuators have been done considering individual components, components together with base structures and structures with several actuators.

Individual components have been optimised to obtain displacement (currently DC displacement up to 250 μm, with ∅25 mm actuator) and load bearing capability as large as possible. Optimisation has been carried out by using different processing parameters and piezoelectric material as well as modifying actuator shapes with the laser. Problem of the optimisation work has been measurement system that couldn't provide loads high enough for actuators so that maximum force could be determined. However, new updated measurement system has been constructed and it will enable sufficient loading conditions still maintaining very high displacement detection accuracy.

Research about actuators clamped with the base structure has been done to facilitate actuator feasibility for the industrial applications. Since actuators are shrinking, expanding and creating bending motion coupling with other mechanical construction have to be considered carefully to fully obtain actuator performance. In the same time electrical connection has to be reliable and easy. As a result practical ways to solve these issues has been found so that now actuators can be attached for instance with screws or glue from the clamping area. Attachment doesn't cause decrease of the actuator performance, but on the contrary it will increase performance (compared to freely moving actuator) when actuator is optimised for that purpose.

Structures with multiple actuators are following the same clamping principles as individual components. Stacked actuators have been done to certain units that can be connected together later on if required. Therefore research has concentrated on attaching two actuator to single unit that has doubled displacement (~0.5 mm). Stacking works also other way so that load bearing capability of the actuator structures can be increased. In this case group is waiting for completion of new measurement system so that load bearing capabilities can be fully characterised.

12.3.3 *Tape cast manufacturing*

3D tape cast structures has been manufactured by different methods. Flexible piezoelectric tape (typical thickness 20-200 μm) can be formed during lamination or/and sintering (Fig. 1.a)). Different shapes of the tapes are attached together in lamination process giving 3D form for the structure so that cavities and channels can be manufactured for e.g. pump or cooling applications (Fig. 1.b)). Lamination can also shape the tape with mould, which gives form for the structure. However, in some cases mould should be included in sintering process to maintain form of the created structure. In sintering process, laminated tape structure is formed by gravitational force (and mould) since non-sintered tape is flexible. Different kind of shapes and structures was manufactured from piezoelectric tape to get the limits for the shaping the ceramic, work is still going on.

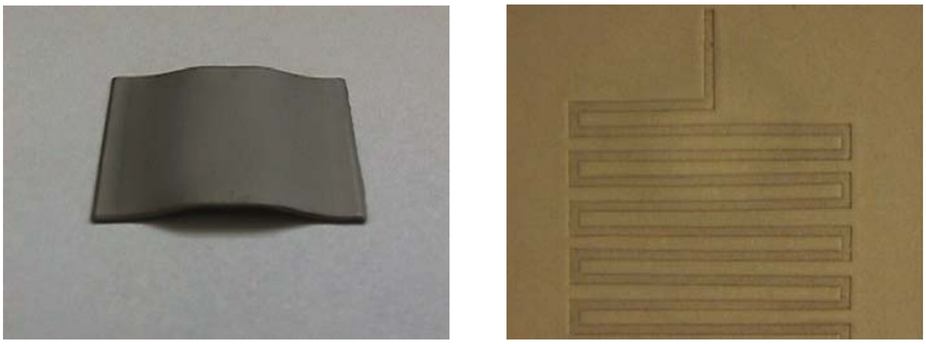

Fig. 1. a) PZT structure formed during sintering b) tape cast channel structure (channel width 150 μm, depth 40 μm)

Also thin multilayer actuators (total thickness ~200 μm) were manufactured for the investigations of low voltage pre-stressed actuators realised by new method. Measurements of the actuators are still under work.

12.3.4 *Motors*

Research group has constructed several different (with or without pre-stress) prototypes of the piezoelectric motors which are under measurements currently. Functionality of the motor constructed from pre-stressed actuator is already tested in practise, but characterisation and optimisation is still under work (Fig. 2.). Idea for using pre-stressed motor is to have rotating motion with low excitation frequency (well below ultrasonic frequency). In this case pre-stressed motor provides high displacement even without resonance of the structure that can be transformed to rotating motion. Aim is to get motor with reasonable torque, stable and continuous rotating movement with low heat generation and degrading of the piezoelectric material. Working principle of the motors realised by the group varies between travelling ultrasonic wave motor, d31 utilised motor and pre-stressed large displacement motor. Every motor needs four different channels that can be reduced down to two using opposite polarisation of the elements. In addition to motor constructions the group is currently investigating possibilities to reduce signal channels to one, so that structure itself could provide needed phase shift between the channels.

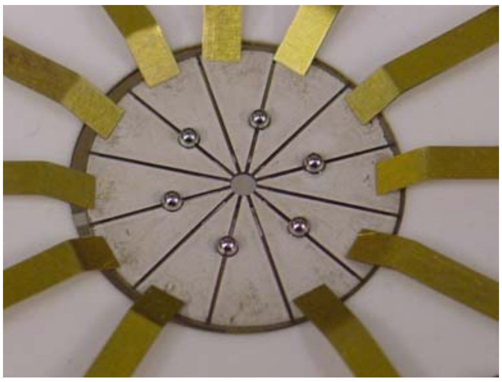

Figure 2. Prototype of the pre-stressed and curved piezoelectric stator (∅25 mm). 12 individual elements produce elliptical motion with the steel balls that are moving the rotor.

12.3.5 *Other applications of the pre-stressed actuators*

Application realised in project are selected so that they can utilise performance of the pre-stressed actuators such as fast response, precise movement, large displacement (in piezoelectric point of view) and moderate load bearing capabilities. Applications realised are piezoelectric pump, valve, tilting device and vibrator/linear transducer. Applications showed possibilities of the actuators pointing out key issues of designing of such devices in actuator point of view.

Currently new pump prototype is under designing with estimated flow rate from microliters per minutes up to decilitre per minute. Piezoelectric active valve construction was already tested as a part of the pump system, but also tests for individual valve construction will be finished during the project (Fig. 3.). Advantages for such valves are fast response time, large flow rate (because of the large displacement), high pressure range (can be improved by actuator stacking) and easiness for precise regulation. Piezoelectric vibrator is currently utilising high vibration level with mass on quite small frequency range (70-110 Hz). Future development will make frequency bandwidth of high vibration level wider and flatter which is required in this kind of applications. Final vibrator will be small, compact and is efficiently using resonance behaviour of active ceramic metallic spring.

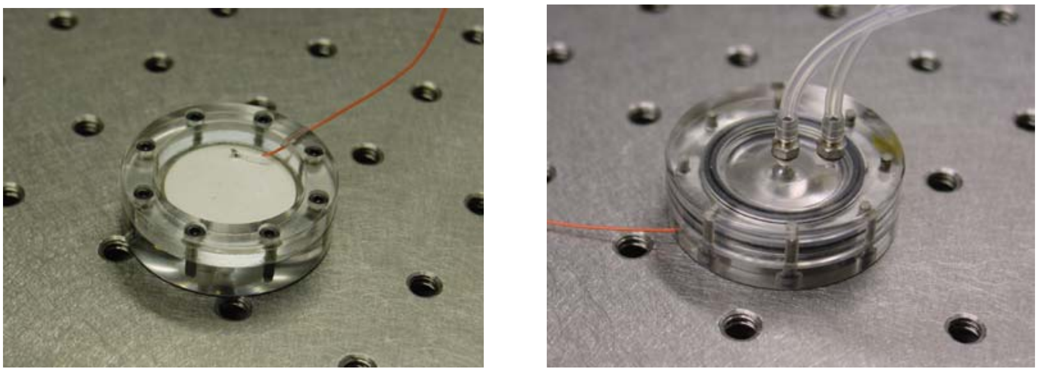

Figure 3. a) Piezoelectric valve from bottom (piezoelectric element in the middle ∅25 mm) b) from top

12.3.6 *Modelling of active structures*

Modelling task of the piezoelectric structures was started with well characterised basic actuator structures. Bulk, multilayer (Fig. 4.), unimorph, bimorph and RAINBOW actuators were modelled with the ATILA program (purchased for this project) and results had good correspondence between measured values. In the case of the RAINBOW actuators (Fig. 5.) modelling accuracy was tested also with laser cut actuators which revealed some differences compared to measured values. Accuracy is still under improvement by realisation of more detailed models and obtaining better modelling practice.

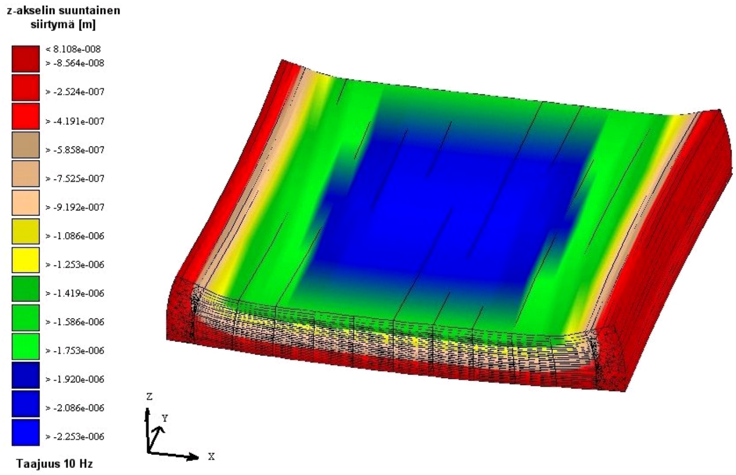

Fig. 4. Displacement distribution of modelled multilayer actuator (27 active layers, size 13,75x15,62x2,83 mm).

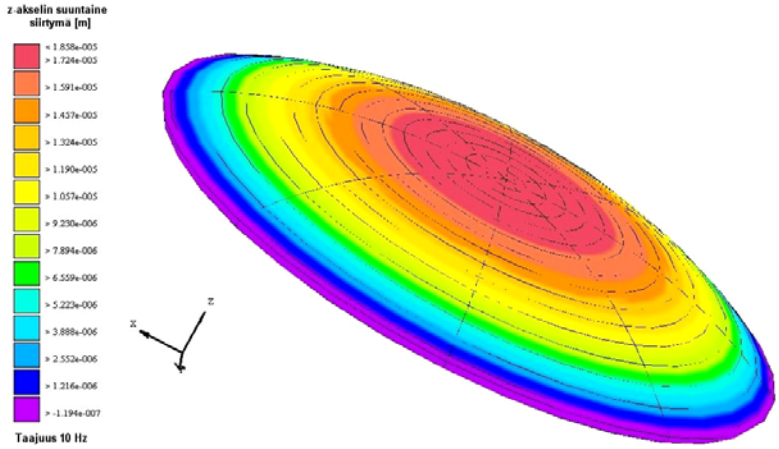

Fig. 5. Modelled RAINBOW actuator (∅25 mm, thickness 375 μm)

ATILA has been also used for more complex models e.g. piezoelectric motors to optimise their behaviour (Fig. 6.). Other structures such as 3D tape cast piezoelectric actuators and movement enhancement structures for pre-stressed actuators have been modelled. ATILA has given excellent tool for active structure modelling, optimisation and behaviour and performance estimation of the actuators and motors.

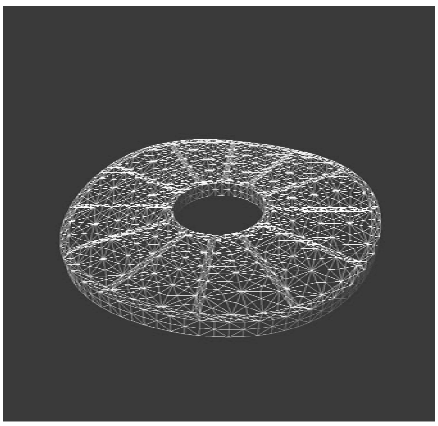

Fig. 6. Piezoelectric travelling wave ultrasonic motor in motion modelled with ATILA (∅25 mm, thickness 500 μm).

12.3.7 *Measurement facility*

During project measurement equipments has been updated to cover performance tests for actuators and motors. Four channels (individual with phase shifting option, purchased from PRESTO project of the TEKES) high voltage excitation system was purchased for the motor testing that enables even bulk motor prototype testing. Displacement measurement system has covered high and low voltage measurements (±4kV), displacement range of 0.005-150 μm, wide frequency range (up several tens of kilohertz with small displacement) and with low applied force. System is now updated to cover also high force (>100 N) measurements with displacement accuracy of ~5 nm.

12.3.8 *Co-operation*

Material development has been made in co-operation Professor Andrzej Lozinski (TU, Gdansk, Poland). Co-operation included LTCC compatible PLZT paste and tape was manufacturing and characterisation (later one is under optimisation). Work has been done under Thematic Network POLECER funded by EU.

Piezoelectric paste with low sintering temperature was manufactured with Dr. Somnuk Sirisoonthorn (MTEC, Bangkok, Thailand) for different substrates (alumina, silicon).

Integration of the LTCC and LTCC piezoelectric tape was studied with Professor Heiko Thust group (M.Sc. (Eng.) Torsten Thelemann, TU, Ilmenau, Germany). Work was done under DAAD (German Academic Exchange service).

12.3.9 *Researcher training*

During the project four diploma thesis were made or will be finished. Jari Juuti will finish his doctoral thesis within year after the project and two other doctoral thesis are in good progress (Esa Heinonen, Johanna Honkamo).

Active materials require wide knowledge basis about electricity, mechanics, materials and measurement systems. During the project researchers of the EMPART group (= Electronics Materials, Packaging and Reliability Techniques, research group of the Infotech Oulu) have had chance to work together. Skills of the different fields are combined (especially mechanical, electrical and material engineering) that has led to spreading of the knowledge and know-how further. People working in the project have expanded their knowledge basis to much higher level. This is due to information exchange between different fields as well as education during whole project time. As a result of the project people from different fields are continuing even tighter co-operation. This provides fertile atmosphere and knowledge basis for future research and development. Also co-operation between young and senior doctor researchers as well as foreign researchers has improved. This will (and already have) lead to improved scientific quality of the publications. Research and development as also education possibilities has improved as a result of better knowledge and realisation methods of the active structures. Since new structures are feasible and easily manufactured they will be a subject of many graduation and post-graduation works and studies. Improvements in measuring, modelling and manufacturing also leads to better scientific quality and industrial interest of the different fields.

12.4 FUTURE ACTIVITIES

Project is continuing to the end of the year 2003 together with project in PRESTO program of the TEKES. MELA (=MEMS in laminates) project in the ELMO (=Elektroniikan miniatyrisointi) program of the TEKES has started. This project utilises the actuator research work of the TUKEVA project. Project will concentrate on manufacturing e.g. large displacement piezoelectric actuators with several industrial partners. Some companies have also plans for mutual project involving piezo actuators.

12.5 PARTNERS

Project was funded by Academy of Finland. TEKES funded simultaneously project concentrating on same aspects.

Several possible industrial partners as well as research institutes have been informed about progression of the project, including: Nokia research center, Filtronic, Abloy, VTT Industrial Systems, Asperation, Aspocomp, Perlos, Machine Design Laboratory (university of Oulu), Metso Paper Machines, Oras, Planmeca, Orion-Pharma, Wallac.

Research group has also participated national and international conferences and seminars spreading information about project results.

12.6 BUDGET AND SCHEDULE

Length of project: 1.6.2000 - 31.12.2003
Man-years covered: 7 = 84 man months
Changes were made to originally proposed budget due to decrease of the total budget. Budget of the project was following:

	Budget of the project	Remaining budget
Salaries and additional costs	**215554**	**17734**
Travel expenses	**4500**	**896**
Consumables	**4000**	**2112**
Equipment and special software	**14000**	**83**
Other expenses	**7500**	**2334**
Sum	**245554 €**	**23159**

Remaining budget will cover expenses of the year 2003. Project schedule presented in research plan is valid since earlier appeared delay in schedule has been reached. Work currently going on will be finished at the end of year 2003. Publications and graduations will finished later on and they will be accordingly acknowledged.

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12.8 PUBLICATIONS

12.8.1 *Conferences and seminars:*

Juuti, J., Moilanen, H., Leppävuori, S., 2001 Manufacturing of Rainbow Actuators for Displacement Applications. Proc. 2nd Euspen Int. Conference Vol. 1: pp. 204-207, Torino, Italy.

Juuti, J., Leppävuori, S., 2002 Novel ceramic technologies in realization of miniature actuators and motors. "Mechanical Engineering Research New Possibilities by Co-operation" Proc. Academy of Finland, TUKEVA seminar: pp. 19-24, Tampere, Finland.

Juuti, J., Heinonen, E., Leppävuori S., 2002 Tape casting and RAINBOW ceramic technologies in realization of miniature actuators and motors. Program & Abstracts Piezoelectric Materials for the End User Conference, 24th-27th Feb 2002, Interlaken, Switzerland, Overview-14.

Juuti, J., Heinonen, E., Leppävuori S., 2002 Effect of the laser processing in RAINBOW actuators. Electroceramics VIII, 25th-28th August 2002, Rome, Italy

Łoziński, A., Juuti, J., Leppavuori, S., 2002 Compatible with LTCC the PLZT thick-films for piezoelectric devices. Eurosensors XVI conference, 15th-18th September 2002, Prague,Czech Republic.

Juuti, J., Heinonen E., Leppävuori, S., 2003 Keraamisten toimilaitteiden ja moottoreiden uudet toteutusteknologiat. PRESTO Tulevaisuuden tuotteet – lisäarvoa tarkkuusteknologioilla Tulosseminaari, 8th January 2003, Espoo, Finland

Juuti, J., Heinonen, E., Leppävuori S., 2002 RAINBOW and tape casting ceramic technologies in realisation of miniature actuators and motors. 11th congress in Mechanism and Machine Science (IFToMM), April 1-4 2004 Tianjin, China.

12.8.2 *Full manuscript accepted:*

Juuti, J., Heinonen, E., V.-P. Moilanen, Leppävuori S., 2002 Displacement, stiffness and load behaviour of laser-cut RAINBOW actuators., Journal of European Ceramic Society

Juuti, J., Heinonen, E., Leppävuori S., 2002 RAINBOW and tape casting ceramic technologies in realisation of miniature actuators and motors. 11th congress in Mechanism and Machine Science (IFToMM), Tianjin, China, April 1-4 2004

12.8.3 *Full manuscript currently in reviewing:*

Łoziński, A., Juuti, J., Leppavuori, S., Compatible with LTCC the PLZT thick-films for piezoelectric devices. Eurosensors XVI conference, Czech Republic, 15-18 September 2002.

12.8.4 *Abstracts approved for presentation, manuscript under writing:*

Łoziński, A., Juuti, J., Honkamo, J., Leppavuori, S., Ferroelectric LTCC Tape for Piezoelectric Applications. Eurosensors XVII conference, Guimarães, Portugal, 21-24 September 2003.

12.8.5 *Diploma thesis:*

Lonnakko, R., Pre-stressed piezoelectric ceramic structures in pump application.

Heinonen, E., Characterisation and modelling of the piezoelectric ceramic structures with ATILA program.

Leinonen, M., Tuneable piezoelectric loudspeaker. (under work)

Moilanen, P., Manufacturing and characterisation of the pre-stressed actuator integrated into LTCC substrate. (under work)

12.8.6 *Doctoral thesis:*

Juuti, J., Development and fabrication of pre-stressed piezoelectric actuators for micro and fine mechanical applications (under work).

Heinonen, E., Development and modelling of 3D piezoelectric actuator structures (under work).

12.8.7 *Papers under preparation:*

Single Axis Piezoceramic Deflector

Poling Characteristics of the Pre-stressed Actuators

New Manufacturing Method for Pre-stressed Actuators

Properties of the High Displacement Pre-stressed Stack Actuator

12.8.8 *Topics of the papers will be published in near future:*

Pre-stressed piezoelectric shutter

LTCC integrated pre-stressed actuators

Characterisation of the pre-stressed piezoelectric valve

Properties of the high force pre-stressed stack actuator

Pre-stressed multilayer piezoelectric actuator manufacturing and testing

Actuation analysis of the pre-stressed actuator

Piezoelectric motor based on pre-stressed actuator

Functional properties of the pre-stressed piezoelectric pump

Clamping effect of the pre-stressed actuators

Tuneable piezoelectric loudspeaker

13 COHERENCE MICROSCOPY IN INDUSTRIAL MANUFACTURE, ROBOTICS AND IMAGING

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ABSTRACT: Our objective in the project was to design a white light interference microscope to meet the demands of mechanical and electrical industry. The experiments were started with a horizontal setup based on some off-the-shelf optical components and after gaining some experience with the setup a more professional vertical setup based on commercial interferometric microscope objectives was realized. We have built three working prototypes. The repeatability of the system is now below 100 nm. The device is used in real measurements to gain more experience in the functionality of the instrument and the developed software.

13.1 INTRODUCTION

Topographical information of various components is invaluable for many types on industries: mechanical, electrical, and optical. It is desirable that the quality of the measuring device is superior to manufacturing techniques. This is the only way to have enough information to guarantee the properties and the repeatability of produced objects.

There are many methods available to monitor the quality of produced items using destructive and slow techniques. Usually this is achieved by picking samples from the production line and analyzing them in a laboratory environment. To maintain the quality it would be extremely important to increase the number of studied components to provide good statistical coverage. This demands for non-destructive, on-line measurements that are fast enough to be placed into the production line. Optical methods are non-contacting and therefore they provide a good candidate to solve the problem.

Generally there are two types of optical instruments that are used to make a 3D-image from a sample: confocal and coherence microscope. They have similarities in their construction but usually the main difference is the light source: in a confocal microscope it is a laser and in a coherence microscope it is a broadband light source e.g. halogen lamp. The other difference is that the confocal microscope produces the image with a point-by-point method; in the coherence microscope it is possible to use CCD camera to produce the image from a bigger area in a single scan. The development of the coherence microscope (i.e. scanning white-light interferometer) is presented in the following.

13.2 OBJECTIVES

Our objective in the project was to design a white light interference microscope to meet the demands of the mechanical and electrical industry. The feasibility of the method to different applications was one of the main elements of the study. In high resolution measurements vibration makes the procedure dubious. The effects of vibration were one part of the development task.

13.3 RESULTS AND ACHIEVEMENTS

The procedure of creating an image containing the topographical information of the measured object can be divided into two main parts: the scanning and the processing of the captured frames. The scanning needs to be performed in a controlled manner synchronously to the capture process of the frames. Obviously possible errors in the scanning (e.g. presence of vibration) deteriorate the final result. Mistakes made in the early stage of the process cannot be corrected entirely with processing algorithms. We started the experiments with sinusoidal signals applied to the scanning piezo actuator. In the next step we chose a new scanner with an inductive position feedback to improve the accuracy of the scanning procedure. The mechanical setup was also made more rigid and less sensitive to externally induced vibration. The final setup is presented in Fig. 1.

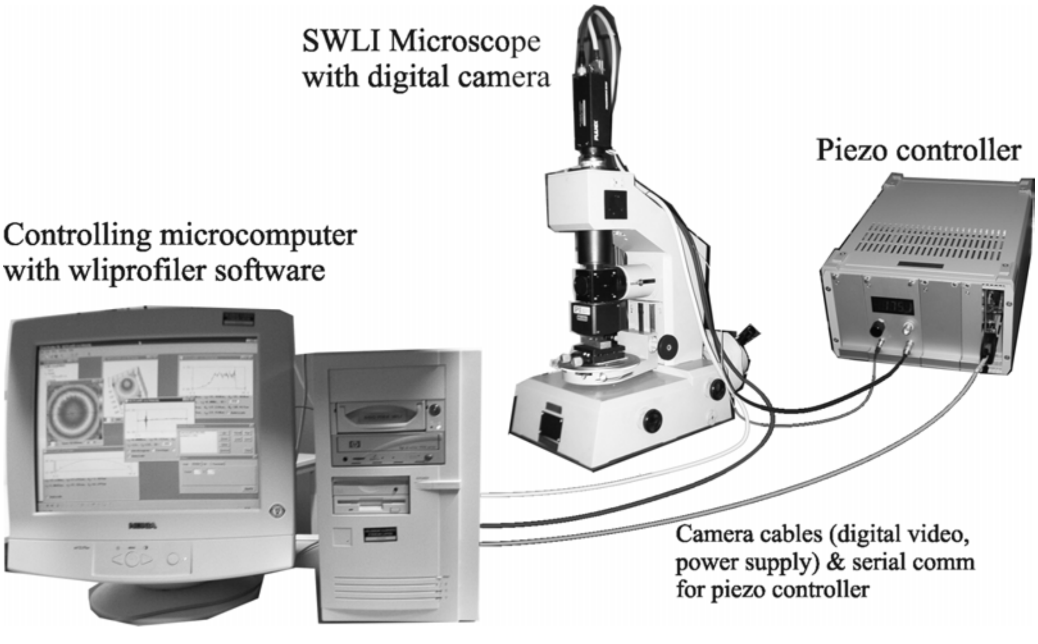

Figure 1. The microcomputer controlled profile measurement system. The microcomputer controls the piezo translator, captures the images, processes the images and displays the results. SWLI = Scanning White Light Interferometer.

There are many technical problems when the data rate exceeds the transfer rate of a hard drive. The image processing nature of the measurement made demands on the optimization of the procedure. By increasing physical memory (i.e. RAM) of the computer many problems were solved allowing us to concentrate on processing algorithms and not on the quirks of a personal computer. We tested different algorithms presented in the literature to extract the topographical information (i.e. z-positions of the object's surface) from the captured frames. Finally we chose a customized algorithm, which is a combination of three routines. In the first part of the processing the rough z-position of an individual point of the sample is searched for. Next an algorithm (Larkin 1996) is used to calculate the z-position with a resolution well below the wavelength of the light source. Finally phase-shift based routine (Harasaki et al. 2000) is used to get the best possible accuracy.

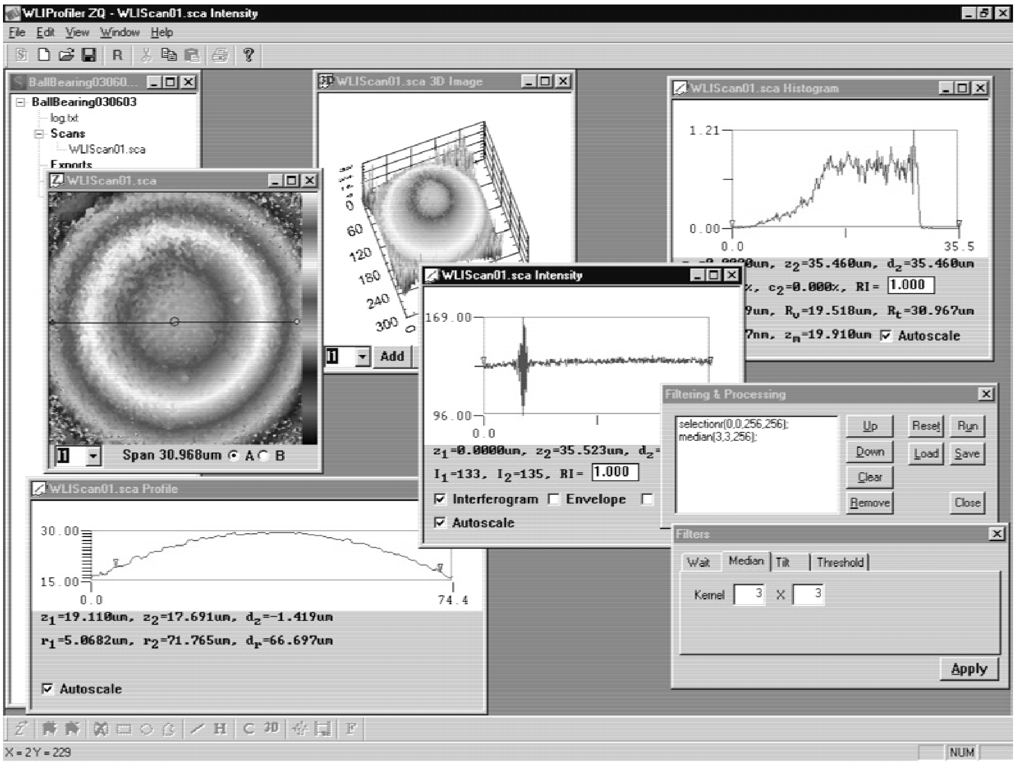

Figure 2. WLIProfiler software interface contains many features to extract the desired information from the raw data: profile, histogram, interferogram, 3D image etc.

We chose to develop the software (WLIProfiler) for the device (Fig. 2) ourselves. This allowed us to keep the interface as simple as possible and customize it to the requirement of a measurement application or a customer. The single software application controls scanning, image capture process, and displaying of topographical information with various types of graphs.

The functionality of the system was tested with various types of samples and applications. As an example of a mechanical application there is a 3D image of a ball bearing (Fig. 3). Depending on the inclination of the surface approximately, an area of 0.5 mm x 0.5 mm can be measured in a single scan (naturally the information from several scans can be combined to make a bigger image). Other examples of mechanical (and/or electrical) samples measured were micro acoustic sensors (provided by VTT Microelectronics). We made also some preliminary thermal expansions tests with electronic components (Nokia Research Center).

We made also some test measurements with biological samples by measuring the thickness of a bacteria growth (yeast, bacillus subtilis, pseudomonas fragi; samples provided by VTT Biotechnology). The system proved to be faster than the confocal microscope measurement used by VTT. However the interpretation of the results needs a lot of special work to be done.

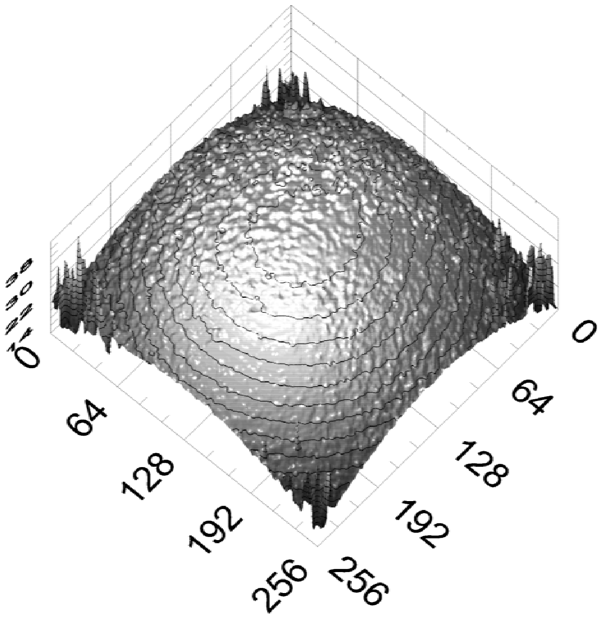

Figure 3. Profile of a ball bearing (diameter 2.5 mm) presented in a 3D image. The contour lines are 2 microns apart (z-axis). The x and y axes are in pixels (one pixel = 1.5 micron). The spikes in the corners of the image represent uncertain areas (i.e. beyond the reach of the measurement); with this magnification (6x) and inclination of surface it is possible to measure an area of ~ 400 µm x 400 µm.

The interference signal from polymer films (e.g. capacitor films) was more straightforward to interpret compared to the signal received from biological samples. Figure 4 presents a tomographic image (left) of a capacitor film. The thickness of the film can be calculated if the refractive index of the material is known. It is possible to find internal defects by inspecting the signal between the reflections from the top and the bottom interface. Both the information on the locations and the number of defects per unit volume can be extracted from the image.

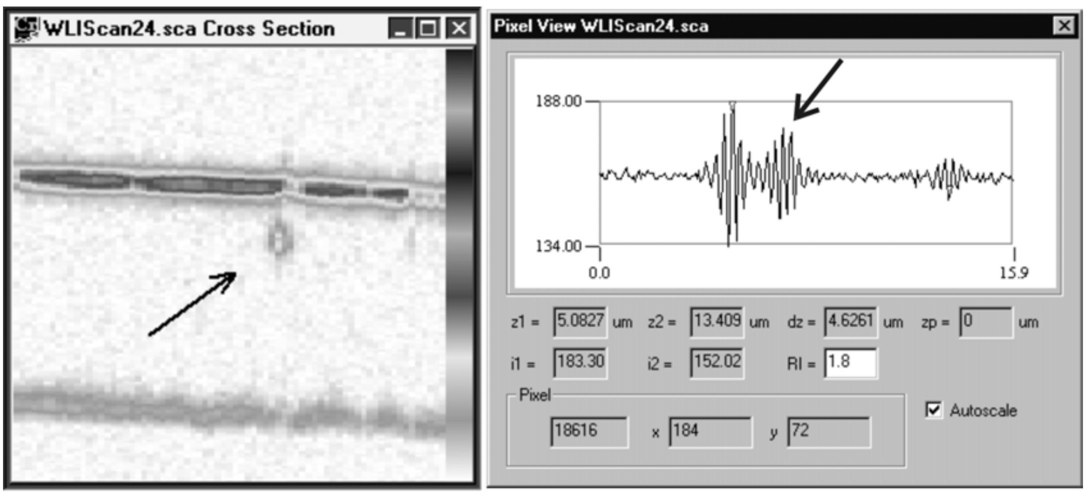

Figure 4. Cross section image of a capacitor film showing an internal defect. In the left image the top and bottom interfaces are seen clearly; the arrow points to the defect, which is seen as an extra interference signal in the right image.

The development of the algorithm was presented in the licentiate work (Aaltonen 2002). The doctoral thesis (Aaltonen) on applications of scanning white light interferometry based on the information gathered during the project is to be published as soon as possible. A number of master of science students were involved in the individual parts of the development and in the realization of the prototypes including the measurements made to test the device. During the research they gained the basic knowledge of interferometric techniques.

13.4 FUTURE ACTIVITIES

The method proved itself to be a valuable tool for measuring topography of different types of samples. There is a great request to develop the device further. We have already tried to apply for new funding (e.g. TEKES, ELMO). We try to find new applications all the time. The applications and the gathered information will be published as soon as possible. The new areas of application (i.e. thickness measurement of transparent layers) where the technique could be used after some modification will be studied. We are taking part in different applications (e.g. biotechnical) as information and measurement service providers.

13.5 PARTNERS

We contacted many companies and interested parties in search for new applications and partners. The main input of the involved partners was to provide us the samples to be measured. The types of the samples and the related partners are display in Table 1.

Table 1. Types of samples and the partner.

Type of samples	**Partner**
Biological: bacteria growth, seeds, contaminated building material	VTT Biotechnology
Silicon based acoustic sensors	VTT Microelectronics
Capacitor films	Evox-Rifa
Silicon membranes	VTI Technologies
Electrical components	Nokia Research Center

In addition to the partners listed above we made tests with various samples from different laboratories of our department.

13.6 BUDGET AND SCHEDULE

The project started in summer 2000 and ended for us in the beginning of summer 2002. The funding provided by TUKEVA is presented in Table 2.

Table 2. The financial management of the project.

Year 2000	Year 2001	Year 2002	Total (EUR)
38241.16	**92642.48**	**26540.25**	**157423.90**

According to the budget most of the activity occurred in year 2001 when we bought most of the needed mechanical and electrical components and equipment.

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13.8 PUBLICATIONS

Aaltonen, J., 2002. Envelope peak detection in scanning white light interferometry. Licentiate thesis, Unversity of Helsinki, Department of Physical Sciences.

Aaltonen J., Kassamakov, I., and Luukkala, M.: "The development of white-light interference microscope; first results", Proceedings Mechanical Engineering Research, New Possibilities by Co-operation, p. 165-174, (2002), TUKEVA seminar.

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Larkin, K.G. 1996. Efficient nonlinear algorithm for envelope detection in white light interferometry. *J. Opt. Soc.Am. A* 13(4):832-843.

Aaltonen, J., 2002. Envelope peak detection in scanning white light interferometry. Licentiate thesis, Unversity of Helsinki, Department of Physical Sciences.

14 AXIALLY MOVING MATERIALS AND COMPOSITES

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ABSTRACT: Numerical models for estimating the threedimensional flow field around the web satisfying the no-slip condition on the surface of the web have been developed. A new finite element containing flexural stiffness and avoiding shear locking has been developed. For an axially moving band, by using concepts of composites, we have developed an innovative fluid-structure model where results of boundary layer theory can be employed. An explicit exact dynamic stiffness matrix was derived for an axially moving string and tested with a system consisting of an axially moving string and a stationary spring-mass-damper. The elements developed are intended mainly for design purposes, but the new fluid-structure model could also be used in process control.

Computational procedures for cure induced residual stresses were developed for controlling the manufacturing process. In these procedures thermal expansion and chemical shrinkage as well as the viscoelastic material behaviour of the resin were taken into account.Fibre distances vary a lot although the fibre volume fraction is the same. It was found, for example, that the reduction of fibre distances increases the residual stresses in the resin.

Optical fibre measurement techniques have been developed and applied. A continuum damage mechanics based model for predicting fatigue behaviour of fibre reinforced composites under high load cycle number was also developed. Computational results were compared to the experimental ones. According to the comparison it seems that the damage model works reasonably, i.e. the results correlate fairly well. These results apply both into the design and maintenance .Also viscoelastic behaviour of composites was studied.

14.1 INTRODUCTION

The background for our effort in TUKEVA was our earlier research within dynamic behaviour of axially moving materials and within thermomechanics of composite materials and structures. The earlier research was financed by the Academy of Finland, TEKES, European union and industry.

The Academy of Finland has financed fundamental part of the research. The three other sponsors have financed applied research. However, in a research group it is sometimes difficult to make exact difference between fundamental research and applied research.

Axially moving materials and composites are a relevant combination in such nationally important systems as paper machines and printing presses. Moreover, most of the solid materials, e.g. wires, belts and paper in axially moving material problems are composites by their nature.

14.2 OBJECTIVES

In our research proposal we stated as objectives to achieve major breakthroughs in fundamental research on problems of axially moving materials and on composites in order to boost the future development of practically applicable knowledge and new modelling and measurement methods. The aim was also to continue the close link between the fundamental research and practice in order to contribute to the success of existing Finnish enterprises and to the creation of new ones.

Both theoretical and practical achievements of our work can be listed: scientific papers and the new composite roll factory of Metso Oyj here in Oulu. During the inauguration of the new factory CEO Bertel Carlstedt especially mentioned the contribution of our department in establishing the factory.

14.3 RESULTS AND ACHIEVEMENTS

14.3.1 *Vibration of axially moving materials*

We have developed numerical models capable of estimating the three-dimensional flow field around the web satisfying the no-slip condition at the surface. One especially important aspect is the cross flow in front of the leading roll, as experience and engineering intuition already suggest that this can cause flutter of the free edge, as in the case of a flag. In this fluid-structure interaction problem two fractional step algorithms are formulated which can solve unsteady incompressible viscous flows. The first algorithm is a three-step method and doesn't need any higher-order spatial derivative calculations and hence is very convenient to simulate non-linear multidimensional flows. The second algorithm is a conventional fractional step method added with artificial diffusion operators which adds diffusion to smooth regions and discontinuity capturing coefficients which adds diffusion to non-smooth regions of the flow. This algorithm is an improved balancing-tensor-diffusivity (BTD) method.

When finite element implementation (FEM) is used, both algorithms can be used with equal-order interpolation. This is an advantage because we can calculate pressure more accurately near the light paper web than using mixed interpolation method or penalty method. This has been verified using the ANSYS/FLOTRAN software.

Depending of the fluid area geometry around the axially moving paper web, the shape of the fluid boundaries can change very much. For this reason we have to update the fluid mesh used in the calculation. To do this the fluid flow calculation algorithms are formulated based on the arbitrary Lagrangian-Eulerian (ALE) formulation. The programming of these algorithms is going on.

Based on the extended Hamilton's principle an MITC4-type plate bending element is formulated using shear correction tricks to analyse an axially moving paper web. This element can take into account the small flexural stiffness of the paper and we can now analyse the paper movement at small velocities and also in zero tension situations. The shear correction tricks are needed to avoid locking in the case of thin plates. We have applied two shear correction techniques both in frequency analysis and transient dynamic analysis. The results are much more accurate with modifications than without them. Based on the results of the article (Laukkanen, 2002) more accurate versions of the plate bending element is developed. The first version uses the ideas of DKQM-element and the second one uses the ideas of ARS-Q12-element. The article of these two plate bending elements used to calculate axially moving paper web is under construction.

To study the long term behaviour of the axially moving web the generalized α-, Newmark, Hilber-Hughes-Taylor α- and θ time integration methods are used. The preliminary results show that the generalized α- method is the best one. The adaptive time-stepping versions of the Newmark and generalized α- methods are also implemented. The testing of these methods are going on.

The newly developed elements are extended to be used in the problems where the axial velocity is not constant. The testing of these extensions are going on with the test of the time integration methods.

When the axially moving member is light, surrounding fluid has a measurable effect on its dynamic behavior. Usually in these problems the surrounding fluid is considered as ideal, which means that the axial velocity of the band has no effect on the flow of fluid. Because viscosity of any fluid does not equal to zero in practice it has been taken into account here approximately. In the interface of the band and the surrounding fluid there is a zone, where the velocitygradient has a great value, in other words the velocity of the fluid is decreasing fast in perpendicular direction to the band. This area is called the boundary layer.

We make following assumptions. Firstly, axially moving material and surrounding fluid comprise a layered system,secondly every layer has same perpendicular translation. Moreover tension is naturally zero in a fluid. Taking sum over all layers and decreasing thickness of the layers, as a limit we get definite integral over the whole system. After taking the integral over the system in three pieces we get added mass to gyroscopic and centrifugal terms. These terms are proportional to displacement and momentum thickness in the boundary layer theory.

The equation of motion is derived using Hamilton's principle. The resulting partial differential equation is discretized by the finite element method. This FEM model is solved by using own program, which is ran in Matlab version6.5. It is necessary to use FEM, because the displacement and the momentum thicknesses are function of longitudinal coordinate.

The results of this study are that surrounding fluid decreases system eigenfrequencies. In practice laminar boundary layer has no effect on eigenfrequencies, but turbulent boundary layer has a significant effect.Difference between critical speed calculated in this study and earlier results where ideal fluid assumption was used is even 15%. Although we have made many assumptions this model is more accurate than earlier.

Optimal design of cantilevered fluid-conveying pipes was also studied as one example problem of the peculiar behaviour of axially moving moving systems. The aim was to maximize the critical flow speed of the fluid by using additional masses, supporting springs and dampers along the length of the pipe.

An optimization problem was formulated by modelling the pipe by FEM, using Euler-Bernoulli beam elements. Location of the additional masses, springs and dampers and the properties of these elements (mass, spring constant and damping constant) were chosen as design parameters. The maximization problem for the critical fluid speed was solved by using the sequential quadratic programming (SQP) technique.

In addition to the presentation of the optimal values obtained for the design parameters, some aspects of the sensitivities of the systems to the variation of these parameters and the robustness of the optimal designs with respect to the stability of the system were studied.

It was found that over 50% increase in the critical flow velocity of the fluid can be achieved in the example cases studied. On the other hand, a great sensitivity of the system with respect to the location and properties of the additional elements in the optimized designs was observed. Also, the margin with respect to the stability in the optimized designs seems to be relatively small in some of the cases considered.

The explicit exact dynamic stiffness matrix of an axially moving string under constant tension was derived based on the assumption that the material particles enter and leave the domain tangentially. The eigenvalues of an axially moving string in contact with a stationary spring-mass-damper system obtained by the present element were compared with the ones obtained by using the element based on the assumption that the material particles enter and leave the domain horizontally. Within wide range of parameters the results are very close to each other. However, in a forced vibration case the results differ considerably. This result demonstrates that assumptions concerning the inflow and the outflow can have dramatic effects on the contrary to earlier published results.

14.3.2 *Composites*

In the beginning of the TUKEVA-project the calculation procedure for residual stresses of composite laminates was freshly developed. The residual stresses were solved by using the finite element method in a computational procedure with the purpose of taking into account all changes in resin properties during the cure. The calculation procedure started with a thermal analysis containing a model for simulating chemical reactions and thermal conduction analysis. The thus obtained results were used as body forces in the subsequent structural analysis performed in two stages. In the first stage, the laminate was regarded as a global structure whose dimension changes were calculated using homogenised material properties for each lamina. In the second stage, these dimension changes were used as displacement boundary conditions to predict residual stresses at a local point in the laminate by a representative volume element of resin and reinforcing fibres. The structural analyses took account of thermal expansion and chemical shrinkage as well as of the linear viscoelastic material behaviour of the resin.

Computational procedure required to solve the residual stresses was rather complicated, and a simple model for the purpose was needed. Before this was possible, the evolution of residual stresses had to be well understood and the parameters closely related to the phenomenon identified. Also, it was advantageous to distinguish material properties of great significance requiring accurate measurements from the ones found safely in material handbooks. That is why, the computational procedure developed was applied to a sensitivity study, where the parameters connected to the problem were varied to discover their significance.

The calculation procedure was simplified by making good use of the study of sensitivity, where the significance of each material properties and analysis phases were perceived. Also, it was noticed that the residual stresses depend on the laminate dimension changes taking place during the cure, and, therefore, it is enough to model laminate with layers having correct stiffness ratios with each other. This means that a layer can be modelled by a local model of the laminate micro structure and the whole laminate by a number of local models building up structure having similar stiffness ratios in the laminate plane as there is in the whole laminate. The local model used earlier was diminished to its quarter. In addition, the change of the material properties during the thermal conduction analysis was noticed unnecessary and the temperature variation of a relatively thin laminate in thickness direction during the analysis was so small that during the structural analysis the temperature history for all elements can be similar, ie. taken from one location of the thermal model.

Using the calculation procedure average residual stresses are obtained, because the distance between reinforcing fibres is assumed constant. Then, with different stacking sequences the residual stresses in resin are almost identical, while in fibre stresses the influence of the stacking sequence is clearly seen. Taking into account that in practice the fibre distances vary a lot, different local models having similar fibre volume fraction but different fibre distances are used with a global model solution. Expectedly, it was found that the reduction of the fibre distance increases the residual stresses in resin. That is why, the residual stresses in resin are sensitive to the variation of the fibre distances and the residual stresses in fibres to the variation of the stacking sequence.

Optical fibre measurement techniques for fibre composite materials have been developed and applied together with Optoelectronics and Measurement Techniques Laboratory. Two types of techniques have been used; fibre Bragg gratings (FBG) measuring strain and temperature locally and time-of-light method (TOF), which is based on the measurement of light travelling time and which is measuring an average strain between two mirrors. Sensor networks can be constructed for the composite materials by using both of the sensor types. Also, electronics and software for the signal processing has been developed. In the near future, the research will concentrate to the possibility to measure both local and average strains from one sensor network and develop its process interface.

A continuum damage mechanics based model for predicting fatigue behavior of fiber reinforced composites under high load cycle numbers is developed in this project. The research was restricted to consider damage caused only by matrix cracking and delamination in laminates with various fiber orientations. A FORTRAN coded subroutine has been written for describing the material behavior. The subroutine is integrated into the finite element computation by applying UMAT user subroutine utility available in ABAQUS/Standard.

In lack of relevant material information the reduction coefficients for matrix cracking are applied also for describing degradation due to delamination cracking. Material property values for matrix cracking were found in the literature, but slightly lower strength values have been used in the test computations. There is a possible uncertainty because the material properties measured in cross ply laminates are applied to an arbitrarily oriented composite. The material model does not account for the frequency of the load nor possible effects of fiber breakage. The lacking values of delamination strength parameters have been assumed equal to the matrix cracking parameters.

A cylindrical carbon fiber / epoxy tube has been chosen as the test specimen. As the finite element model a thin sector formed slice of the tube was analyzed. Computational results are compared to the laboratory test results. 5 % loss in the stiffness of the composite material was considered as the characteristic damage state in the tests. In the computational model the constitutive materials are presumed linearly elastic. The reduction of stiffness in the damaging material makes the problem non-linear. The theoretical and experimental numbers of load cycles were of the same order in magnitude. The computational result can be achieved by selecting initial time increment suitably.

It seems that the damage model works reasonably. The stiffness of the structure is reduced as the damage parameters and the number of load cycles increase The model accounts for only two modes of damage. The real damage mechanism may be more complicated than the computational model represented in this paper. However, the computational and the laboratory test results correlate fairly well.

The prediction of the hygrothermal behavior of the materials is important in tailoring prescribed properties to composites which are to be used under hot and wet conditions. The finite element method has been found an applicable tool in predicting the effective transverse thermal conductivity of the fiber reinforced composite materials. The idea is expanded and applied to the determination of the effective coupled hygrothermal steady-state diffusion coefficients by employing the homogenisation technique together with finite elements. Onsager's reciprocal relation is utilized to reduce the number of the diffusivity coefficients of constitutive materials from four to two. The so called cross coupling diffusivities are expressed in terms of the thermal conductivity and the coefficient of diffusion.

The effect of coupling is most clearly noticed in the heat flux field of the finite element results. It may be predicted that the moist material warms up faster than the one as dry. The effect on temperature, moisture and moisture flux fields seems not to be so relevant. Naturally different material parameters can change the hygrothermal behavior, and every material should be investigated case by case.

The aim of the research work was also to study the edge effects of laminated composites. This part was done by studying tension bars by the finite element method. The purpose was to detect the stresses at the free edge of the tension bars and to define the SN-curves for matrix cracking and delamination. The material parameters for the failure criteria were also defined.

The modelling came off well. Singularities of the stresses showed up clearly in every model. The largest values of stresses was in the boundary of the laminate. The stresses decreased when going away from the free edge as assumed.

The SN-curves for the matrix cracking and delamination was succesfully determined. The dispersions of the failure criteria were small both in matrix cracking and in delamination. The dispersion was a little bit bigger in the case of matrix cracking. The material parameters were also studied. In matrix cracking the material parameters were almost same in different lay-ups. In delamination the separation of the parameter values between different lay-ups more general.

A continuum damage mechanics based model for predicting fatigue behavior of fiber reinforced composites under high load cycle numbers was developed. The model is restricted to consider damage caused only by matrix cracking and delamination in laminates with various fiber orientations.

A cylindrical carbon fiber / epoxy tube was chosen as the test specimen. As the finite element model a thin sector formed slice of the tube was analyzed. Computational results are compared to the laboratory test results. 5 % loss in the stiffness of the composite material was considered as the characteristic damage state in the tests. In the computational model the constitutive materials are presumed linearly elastic. The reduction of stiffness in the damaging material makes the problem non-linear. The theoretical and experimental numbers of load cycles were of the same order in magnitude. The computational result can be achieved by selecting initial time increment suitably.

It seems that the damage model works reasonably. The stiffness of the structure is reduces as the damage parameters and the number of load cycles increase The model accounts for only two modes of damage. The real damage mechanism may be more complicated than the computational model represented in this paper. However, the computational and the laboratory test results correlate fairly well.

In order to increase payloads in transportation it is important to lighten transportation vehicles by using light composite structures. However, long-term behaviour of polymer matrix composite material is difficult to foresee because polymer matrix material behaviour depends on time.

The purpose of this study was to research viscoelasticity and aging behaviour of material of polymer matrix composites. Behaviour of the material is limited to linear viscoelasticity, when time-temperature and time-aging time superposition are valid. The objective of this study was to find out how to predict the material aging properties from the creep test results by using ABAQUS program and how the obtained results can be applied to the program.

The study contained both short and long-term creep tests, where the test material was made from polymer matrix composite. Short-term creep tests were done with a method developed by Struik. However, the number of tests was statistically too small and, thus, the results give only a trend of material behaviour. Also, the test coupons were cut from the laminate and not from the lamina meaning that the results can be applied only to the same laminate lay-up. That is why, the focus of this work was mainly concentrated to figure out how to use test results.
ABAQUS and KaleidaGraph programs were used to fit the Prony series to every long-term creep curve. ABAQUS converts creep test data to relaxation curve, and after that Excel is used in search of time-temperature shift factor function from the creep and relaxation curves. Similarly, ABAQUS is used to fit the Prony series to every short-term creep curve and Excel in the search of time-aging time shift factor function. After examining the shift factor functions, it was considered how to combine them and then use in ABAQUS.

When the time-temperature shift factor function of the relaxation and creep curves were compared, it was noticed that the curve fitting of the relaxation Prony series work well in ABAQUS. With a small number of test coupons it is easy to use Excel but it needs a lot of handwork. Otherwise, it is worthwhile to develop a program to search for shift factors.

14.4 FUTURE ACTIVITIES

We will continue both fundamental and applied research. The reason for doing both is firstly the motivation of young researchers and secondly to support ongoing R&D work of industry.

In fundamental research the topics will be vibration and stability of axially moving materials and thermomechanical behaviour of composites. We have also started research work together with the Department of Anatomy, the Clinic of Surgery and the Department of Medical Engineering in order to develop new type of implants based on the use of shape memory alloys.

14.5 PARTNERS

In development of optical fibre measurement techniques we have done co-operation with Optoelectronic and Measurement Techniques Laboratory.

14.6 BUDGET AND SCHEDULE

The project started 1.1.2001 and will finish 31.6.2003 when the budgeted sum has been used.

	2001	2002	2003
Allocated	138755	116891	18669
Used	91912	132035	38002 (31.5.2003)

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15 SIMULATION OF MULTIPHASE FLOWS FOR INDUSTRIAL PROCESSES

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ABSTRACT: The dynamics of two-dimensional Couette flow of monodisperse liquid-particle suspensions was studied using direct numerical simulations by the lattice-Boltzmann method. The results display complex flow phenomena, *e.g.*, a nonlinear velocity profile, and layering and clustering of particles that appear due to the two-phase character of the fluid. The rheological behaviour of the suspension is dilatant. The mechanisms of momentum transfer and shear stress are studied in detail, and the results indicate that the observed shear thickening is related to mesoscopic phenomena such as clustering and layering of solid particles. Wall-solids interactions in fibre-suspension flows were studied by the lattice-Boltzmann method as well as conventional CFD-methods. Also, a special mean-filed approach was used to reproduce the results of the numerical methods for averaged hydrodynamic forces acting on the fibres. The results suggest that the origin of the drag reduction in such flows is the nonlinear hydrodynamic lift force, which causes fibres to be repelled by the pipe wall so as to form a lubrication layer of pure carrier fluid at the wall. Applications included also pipe flow of liquid-particle suspension with deposition of particles on the pipe walls, capillary rise dynamics, droplet spreading, permeability of porous materials, and the pressure drop induced by porous screens.

15.1 INTRODUCTION

Fluid mechanics has great importance in mechanical engineering where it can shorten the prototyping phase by providing a virtual tool for performance studies. The dynamics of one-phase Newtonian fluids is known adequately well for practical purposes, and the analysis of the flows of such fluids is based on the boundary layer theory and on a large set of carefully measured experimental data.

In industrial processes most of the fluids are, however, multiphase fluids. Their flow properties have not been understood as deeply as those of Newtonian fluids. Traditionally multiphase fluids have been modeled as single component fluids that have unusual flow properties, *e.g.* non-Newtonian viscosity. These properties are determined by using various rheological techniques. The theoretical predictions based on these rheological measurements are doubtful in cases where the real flow conditions differ considerably from those of rheological measurements. These uncertainties have been normally avoided by doing heavy overdimensioning, but they can still cause the design point to deviate form the optimal point. Moreover, the uncertainties can shorten the lifetime of the product due to uncontrolled phenomena, *e.g.* flow induced vibrations. It is thus evident that the multiphase nature of the fluids has to be considered when constructing more reliable models for flows of multiphase fluids.

15.2 OBJECTIVES

The objective of the project is to study the multi-phase features of flows of liquid-particle suspensions, and flow in porous media, by doing direct numerical simulations with the lattice-Boltzmann method. This method is based on discretized kinetic theory, and it can be used to simulate various transport phenomena. The development of lattice-Boltzmann methods has recently undergone significant improvements (Chen & Doolen 1998). The simulations are *ab initio* simulations, which include realistic mesoscopic (here ‘mesoscopic’ refers to the typical length and time scales of the particles) description of the system, *e.g.* (contact) interactions between the particles. These interactions include also realistic hydrodynamic 'lubrication' forces between the particles. All interaction forces inside each phase, and between different phases, are calculated on a mesoscopic level. These mesoscopic fluxes are averaged, depending on the approach, over time, volume or ensemble, and the operation is repeated for a range of macroscopic flow parameters. Dimensional analysis and analytical results found in literature are utilized when studying the numerical correlations and searching for the final multiphase closure relations.

15.3 RESULTS

15.3.1 *Liquid-particle suspension*

During the first period of the project the main emphasis was on the two-dimensional Couette flow of monodisperse liquid-particle suspensions. The target was to understand the mesoscopic mechanisms that contribute to the complex flow behaviour, *e.g.* shear thickening, of such complicated suspensions. The projected results are of great importance in the interpretation of rheometric measurements and in applying the results of these measurements in modeling.

15.3.1.1 *Apparent viscosity*

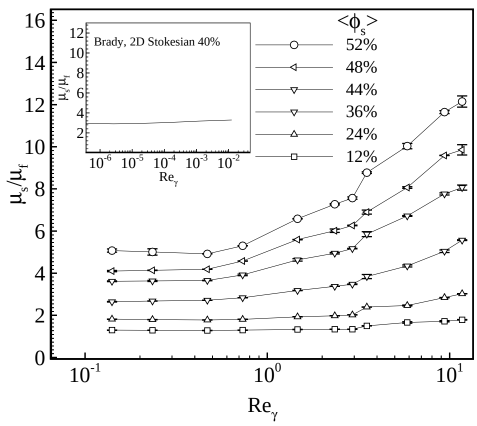

Figure 1. Relative viscosity μ_s/μ_f as a function of shear Reynolds number Re_γ for varying mean solid volume fraction $\langle\phi_s\rangle$. In the inset are shown the simulation results for very low Reynolds numbers (Brady & Bossis 1988).

In Fig. 1 we show the relative apparent viscosity μ_s/μ_f as a function of the shear Reynolds number $\mathrm{Re}_\gamma = \gamma d^2/\nu_f$ with γ the shear rate, d the particle diameter and ν_f the kinematic viscosity of the carrier fluid, for various solid volume fractions $\langle\phi_s\rangle$. Here μ_f is the viscosity of the carrier fluid and the apparent viscosity μ_s is defined as the ratio of the total shear stress on the moving walls and the mean shear rate given by the velocity difference and the distance between the two walls. It can bee seen that the suspension is shear thickening, *i.e.* the viscosity increases with increasing shear rate, which correlates with the experimental results of many concentrated suspensions, see *e.g.* (Hoffman 1998) and (Frith *et al.* 1996).

15.3.1.2 *Layering and clustering*

It has been found that clustering of the solid particles has a remarkable effect on the apparent viscosity of liquid-particle suspensions by enhancing the transport of momentum between the walls. In Fig. 2 we show a time series of snapshots from a simulation. It is evident that the system is strongly inhomogeneous and particles have formed clusters of different sizes. For the visualization purposes the particles in one of the clusters are marked with white disks. The cluster is formed in a certain orientation, then it is compressed while it rotates clockwise in the shear field, and finally it is destroyed by shear forces that tear the particles apart.

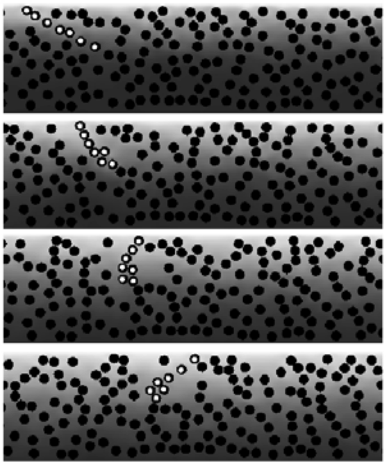

Figure 2. Time series of snapshots from a simulation of liquid-particle suspensions. Upper wall is moving with a constant velocity and the lower wall is stationary. Particles belonging to a selected cluster are marked with white disks.

We have developed a kinetic clustering model (KCM) in which large clusters are formed by merging two or several small clusters (including single particles) in a shear flow. The model predicts a power-law cluster-size distribution which agrees well with that of simulations. According to the model, combined with simulation results, the relative viscosity of the suspension can be written as

$$\frac{\mu_s}{\mu_f} = 1 + 0.5 m_0,$$

where m_0 is the characteristic cluster size. This typical cluster size depends on the particle concentration, and in terms of concentration ϕ we find that $m_0 = (\phi / \phi_c - \log(\phi / \phi_c) - 1)^{-1}$, where ϕ_c is the dense packing limit. This form for the relative viscosity is similar to the semi-empirical Krieger formula,

$$\frac{\mu_s}{\mu_f} = (1 - \frac{\phi}{\phi_c})^{-2},$$

for which we have thus given a theoretical background. This expression is valid in the viscous regime (the particle Reynolds number $\mathrm{Re}_p \leq 0.1$). In the transition regime ($\mathrm{Re}_p \approx 1$) typical cluster size grows considerably and layers of particles develop near the walls. In this regime both the relative viscosity of the suspension and the typical cluster size depend on the particle Reynolds number. In the inertial regime ($\mathrm{Re}_p \geq 10$) flow instabilities arise causing the wall layers to largely disappear and the typical cluster size to decrease. Due to these instabilities viscosity now increases strongly with the particle Reynolds number.

In Fig. 3 we show the average velocity U/u_w (u_w is the wall velocity) of the suspension, and the volume fraction of the particles ϕ_s, as functions of the position between the walls for two different mean solid volume fractions. For each position the averages are taken over a plane parallel to the walls, over a long period of time, and over an ensemble of macroscopically identical systems. It can bee seen from Fig. 3(a) that, in relatively dilute systems, the particles tend to migrate towards the center of the channel. Only weak layering can be observed near the walls, and the velocity profile is nearly linear. The apparent viscosity near the walls is decreased due to decreased solid volume fraction, which manifests itself as an increased local shear rate and a shallow S shape of the velocity profile. For a dense suspension, Fig. 3(b), layering of particles is pronounced near the walls, and some layering can bee seen even around the centerline of the channel. The layering phenomena have been observed in light-diffraction experiments (Hoffman 1998). The shear rate oscillates strongly near the walls, and its minima occur at the same positions as the maxima of the solid volume fraction. In the middle part of the channel, the shear rate is clearly reduced from the mean value (dashed line).

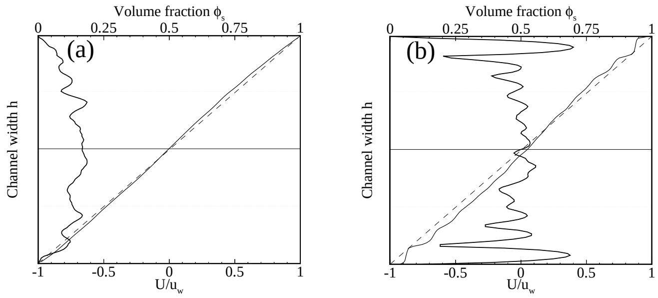

Figure 3. The volume fraction of solid particles, ϕ_s, and mean velocity profile, U/u_w, of the suspension across the channel for suspension with mean solid volume fractions $\langle\phi_s\rangle = 12\%$ (a) and $\langle\phi_s\rangle = 48\%$ (b). Thick lines give the volume fraction and thin solid lines give the suspension velocity U scaled with the velocity of the walls, u_w. Dashed line represents a linear velocity profile.

How exactly layering of particles near the walls affects the viscosity is still being analysed.

15.3.1.3 *Momentum transport and stress*

A schematic illustration of the simulation setup is shown in Fig. 4. The suspension is now placed between two moving solid walls.

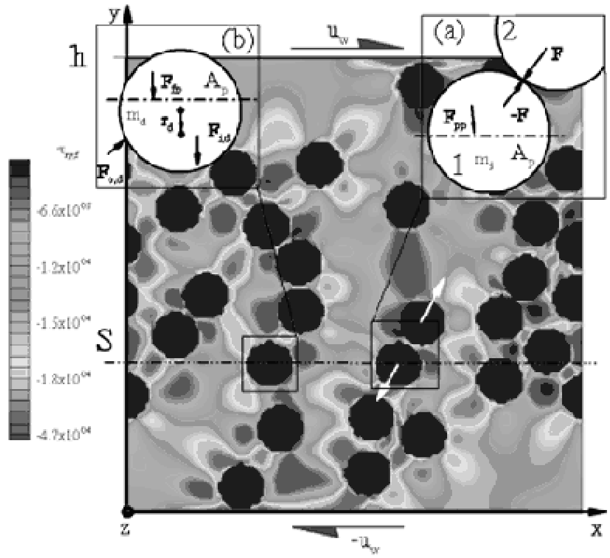

Figure 4. A snapshot of a two-dimensional Couette flow of liquid-particle suspension solved by the lattice-Boltzmann method. Colour coding indicates viscous shear stress in the fluid phase. The two insets show the forces used in calculating the internal particle stress due to collisions (a) and due to hydrodynamic forces (b).

To get a deeper understanding of the dynamics of the suspension the actual two-phase nature of the suspension was considered in detail. The transport of longitudinal momentum in the transverse direction, *i.e.* apparent viscosity, was decomposed into various mechanisms. The total shear stress, τ_T, acting on an any selected plane parallel to the walls was written as a sum of the convective stresses of the fluid (σ_f) and solid (σ_s) phases, the viscous stress of the fluid phase (τ_f) and the internal stress of particles (τ_s). In Fig. 5 we show the ratio of τ_f and τ_s to the total shear stress as a function of Re_γ. In Fig. 6 we show the same ratio as a function of the average solid volume fraction, $\langle \phi_s \rangle$, for a fixed $\mathrm{Re}_\gamma \approx 3$. It is evident that the contribution of the particles to the apparent viscosity increases with the solid volume fraction. For a solid volume fraction of 50% the particles carry almost 90% of the total shear stress. The relative shear stresses are nearly constant for low Re_γ, but begin to change for Re_γ above unity, which is also the point of the onset of shear thickening It is thus obvious that shear thickening is related to the enhanced solid stress for increasing mean shear rate. There is indication that this phenomenon is results from clustering and layering of the particles, but the actual mechanisms of this effect is still being investigated.

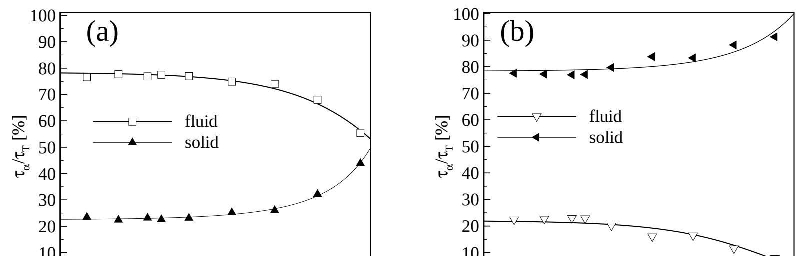

Figure 5. The ratio of viscous stress τ_f and of solid stress τ_s to the total shear stress τ_T as a function of the shear Reynolds number Re_γ for suspensions with mean solid volume fraction $\langle \phi_s \rangle = 12\%$ (a), and $\langle \phi_s \rangle = 48\%$ (b).

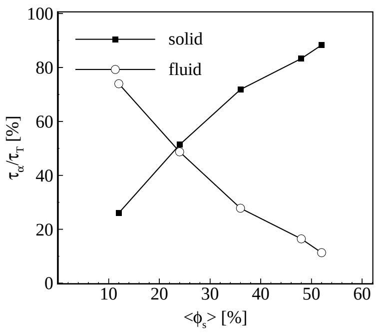

Figure 6. The ratio of viscous stress τ_f and of solid stress τ_s to the total shear stress τ_T as a function of the mean solid volume fraction $\langle \phi_s \rangle$ for $\mathrm{Re}_\gamma \approx 3$.

15.3.2 *Wall-solids interaction in fibre suspensions*

Flow of paper pulp often exhibits a regime where the pressure loss surprisingly decreases with increasing flow rate. This drag reducing phenomenon has been known for a long time, and it has typically been explained qualitatively by a thin lubrication layer of pure water developing at the pipe wall. There has been many explanations for the existence of such a layer, but our recent results indicate that the layer is caused by repulsive hydrodynamic forces applied by the carrier liquid on the fibres in the vicinity of the pipe wall.

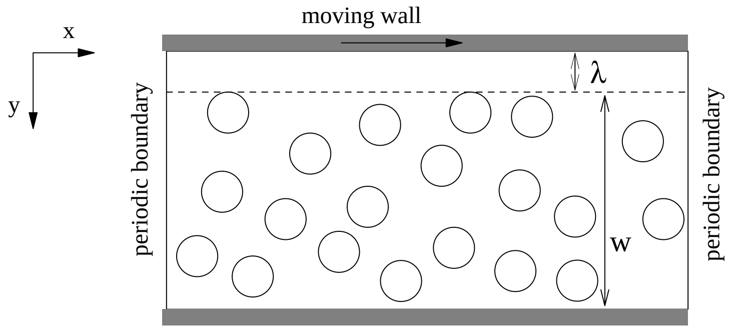

Figure 7. Random rigid matrix of cylinders suspended in a Newtonian flow between walls.

The interactions between the fibres and the carrier fluid have been studied extensively by the lattice-Boltzmann method. In Fig. 7 we show a schematic setup of 2D simulations. The fibre network is described as a random rigid matrix of disks of width *w* and next to the wall there is a lubrication layer of carried liquid of width *λ*.

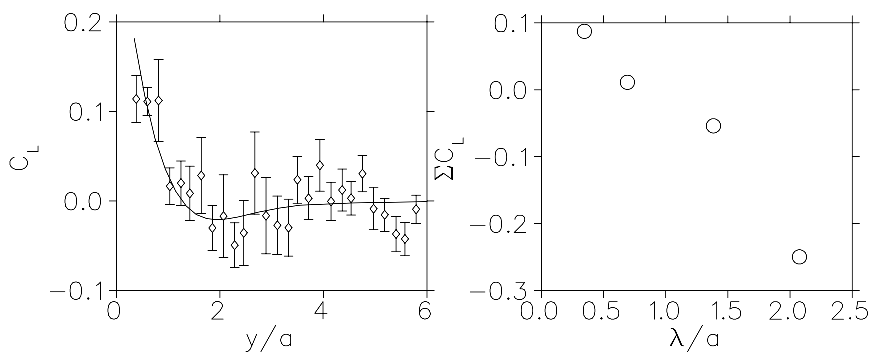

Figure 8. Left: Dimensionless lift force C_L acting on fibres as a function of dimensionless distance from the wall y/a. Here a is the radius of fibres and positive lift force means repulsion away from the wall. Open markers are the result of the lattice-Boltzmann simulations and solid line is given by a mean-field approach.

Lubrication layer width is $\lambda / a \approx 0.4$. Right: Total dimensionless lift force ΣC_L acting on fibre matrix as a function of dimensionless lubrication layer width λ / a.

The averaged dimensionless hydrodynamic lift forces acting on the fibres are shown in Fig. 8. In the left figure we show the local lift force C_L acting on the fibres as a function of dimensionless distance from the moving wall for a lubrication layer of width $\lambda / a \approx 0.4$. The lift force is strongly repulsive (positive) close to the wall and becomes attractive as the distance increases. For long distances the lift force approaches monotonically zero as the velocity difference between the fibres and the carrier liquid venishes. In the right figure we show the total lift force ΣC_L acting on fibre matrix as a function of dimensionless lubrication layer width λ / a. The total lift force is close to zero when λ is of the order of fibre radius a. This condition should be relevant for the plug flow regime of dense fibre suspensions in the presence of a drag reducing lubrication layer.

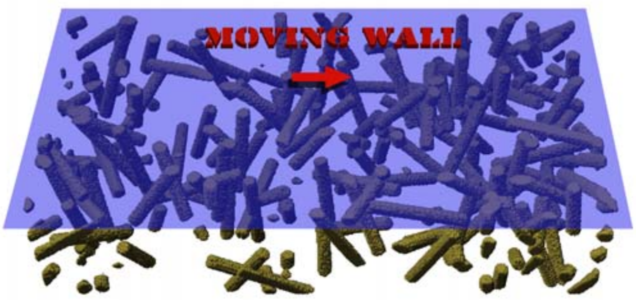

Figure 9. An example of three-dimensional wall-interaction simulation.

Fibre-wall interactions have been studied also in 3D. In Fig. 9 we show an example of simulations where the fibre network is described as a rigid matrix of long cylinders having random position and orientation. The results correlate well with those of the 2D study. Moreover, supporting single-particle simulations were carried out with finite-volume methods. A mean-field method was used to calculate the hydrodynamic properties, *e.g.*, permeability, of a random porous medium consisting of unconnected particles. In this method the flow field around a single particle is solved by modelling the remaining particles as a homogeneous background obeying Darcy's law. In the limit of vanishing inertial effects, the governing equation becomes the well-known Brinkman's equation. The method was applied in 2D to calculate the permeability of a rigid matrix of spherical disks suspended in a uniform flow. The calculated permeabilities agree well with the results of direct numerical simulations down to the porosity $\phi = 0.5$, *c.f.* Fig. 10. The mean-field results agree surprisingly well with the lattice-Boltzmann results.

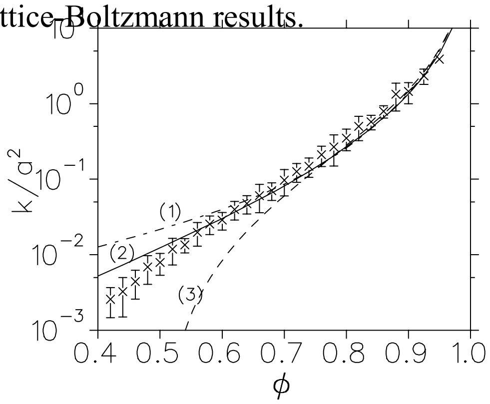

Figure 10. Dimensionless permeability k / a^2 vs. porosity ϕ for a rigid matrix of fully aligned cylinders. The discrete symbols are the results of direct numerical simulations (Ghaddar 1995), and the lines are the results of mean-field hydrodynamics with different flow-resistances in a narrow annulus around a cylinder: (1) zero resistance, (2) linear decay to zero resistance at the cylinder surface, and (3) constant resistance.

We have also studied the lubrication layer dynamics of paper pulp experimentally. We used a novel laser-optical method to measure the lubrication layer thickness in birch and pine pulp flows for mass concentrations 0.5% - 2.0%. The results indicate that a wall layer forms at the onset of drag reduction, and that the layer thickness increases with increasing flow rate. Maximum thickness corresponds to the local minimum in pressure loss, after which the wall layer is gradually destroyed by turbulent fluctuations, and the pressure loss increases with increasing flow rate. The observed maximum of the wall layer thickness is of the order of 500 μm at the concentration c=0.5%, and decreases with increasing concentration to a value about 10 μm at c=2.0%. This observed behaviour is very much as expected based on our numerical analyses.

15.3.3 *Fouling dynamics*

We studied particle suspensions flowing in a channel in which fouling layers were allowed to form on the channel wall. Fouling was modelled by attachment if a suspended particle collided with a wall or a deposited layer, and by detachment of deposited particles if they felt a large enough hydrodynamic drag force. The relevant parameters governing the dynamics are the solid volume fraction of the suspension and the detachment drag force threshold. Four different types of behaviour were found depending on the values of the two parameters, including full blocking of the channel. This model can be applied, *e.g.*, to the growth of the sediment at the pipe walls in hydraulic conveying.

15.3.4 *Capillary rise and droplet spreading*

Spreading of small droplets on smooth and rough surfaces was studied. For relatively flat initial drop shapes our results are consistent with Tanner's law $R = t^{1/10}$, while for more spherical initial shapes the value of the exponent increases. The surface roughness slows down the spreading, as expected. We also investigated capillary rise dynamics, and found a power-law correlation between the cosine of the dynamic contact angle and the rise velocity. Practical applications of these problems include, *e.g.*, ink-jet and offset printing as well as spray coating of paper.

15.3.5 *Flow in porous media*

We have studied flow properties of 3D porous materials such as paper, fabrics and sandstone, by the lattice-Boltzmann method. The pore structures used in the simulations were obtained from realistic numerical modelling or from x-ray tomographic images of actual samples. For fabrics the simulated transport coefficients agreed well with the experimental results. For paper the simulated values of permeability typically exceeded the measured values by factor of two. This difference is attributed to the fine structure of fibre surfaces missing from the tomographic images due to insufficient resolution.

Flow of sap trough a pit between neighboring water-conducting cells in conifer xylem was investigated in relation to cell-level flows in (paper) fibres. In the first study the pit was described as a homogeneous porous plate. In a later study, flow through both regular and irregular screens made of fibres was investigated. For the creeping flow regime, we found simple functions of screen porosity that describe the pressure drop across both types of screens. Industrial applications of this problem include, *e.g.*, water removal in paper making and drying, and various filtering processes.

15.4 FUTURE ACTIVITIES

In the nearest future the main activity will be in further studies in liquid-particle suspensions, and in flow in tomographic images of real structures. Code development will obviously be part of this work.

15.5 PARTNERS

The present project had close connections to the Multiphase Flows in Process Industry (PROMONI) project funded by TEKES. The PROMONI project includes research groups from the University of Jyväskylä, University of Kuopio, VTT Energy, Åbo Akademi University, and Tampere University of Technology. Industrial partners in the PROMONI project are Metso, Fortum, and Foster Wheeler. Wall layer phenomena were also studied in a separate project in collaboration with Fortum. A new project has been started in collaboration with M-real, and another research consortium has just been funded by Tekes. This consortium involves collaboration with several universities and companies. Foreign collaboration has mainly involved the University of Stuttgart and the University of Minnesota, and recently also MIT.

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16 MODELLING AND OPTIMISATION OF DYNAMIC PRODUCTION NETWORKS BASED ON THE EVOLUTIONARY PRINCIPLES OBSERVED IN ANIMATE ORGANISMS (MODNET)

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ABSTRACT: The mathematical and computational investigation of industrial systems often lacks the consensus of the research community, mainly because the problems – e.g. in case of networked production systems – are not easily formulated, since the multiple levels of decision making and the complexity of issues involved encourage different strategies for solving the problems. In this work we have approached production networks as a computational problem and created an agentbased simulation modelling framework that enables researchers to share calibrated models and provide a basis for discussions. To provide testcases for the computational investigation a problem generator has been created. We have proposed a complex adaptive system- approach to production networks, since they exhibit the emergence of complexity and adaptiveness by nature, but this aspect is rarely investigated. The methodology proposed for the agentbased modeling and development of production network can serve as a basis for the industrial introduction of the method and the software.

16.1 INTRODUCTION

In a free market economy any new possibility, i.e. the new degrees of freedom can generate new ideas, motivate changes in organizational structures and find new applications of scientific tools. The increasing felxibility of production systems and logistic services typically created high complexity organizations, and the management of supply chains and virtual organizations challenged theorists and practitioners to develop formal methods, computer networks and software. Systems theories and natural principles are already important members of these scenarios but many of them are still competing theories and they had not enough time to develop into maturity. This project is not unique in its attempt to develop a new methodology and software framework for production network design and analyis, however it is unique in formulating a simple computational framework similar to Classifyer Systems that can serve as a basis for more detailed investigations. Since there are no standard simulation tools used by researchers worldwide it is very difficult if not impossible to reproduce each other's results and make comparisons, unlike in some other disciplines. The proposed method therefore includes not only a method for building agentbased models of complex production systems, but also includes a free and redistributable modeler software that supposed to be an ample foundation for creative investigations.
The agentbased simulations are based on the Swarm free simulation package that is the most wellknown and easily programmable e.g. in Java. The ModNet simulator saves the pain of coding every single simulation and allows the users to configure and parameterize their production networks freely and easily by editing text files that include the type of simulations, the configuration of the factory network, the available machine tools and their capabilities and the type of controll – all represented by tables of integers. With this software and the proposed approach even an inexperienced, not programming student can build simulation scenarios and investigate

them, share the models with others and publish verifiable and reproducible papers, propose theoretical progress.

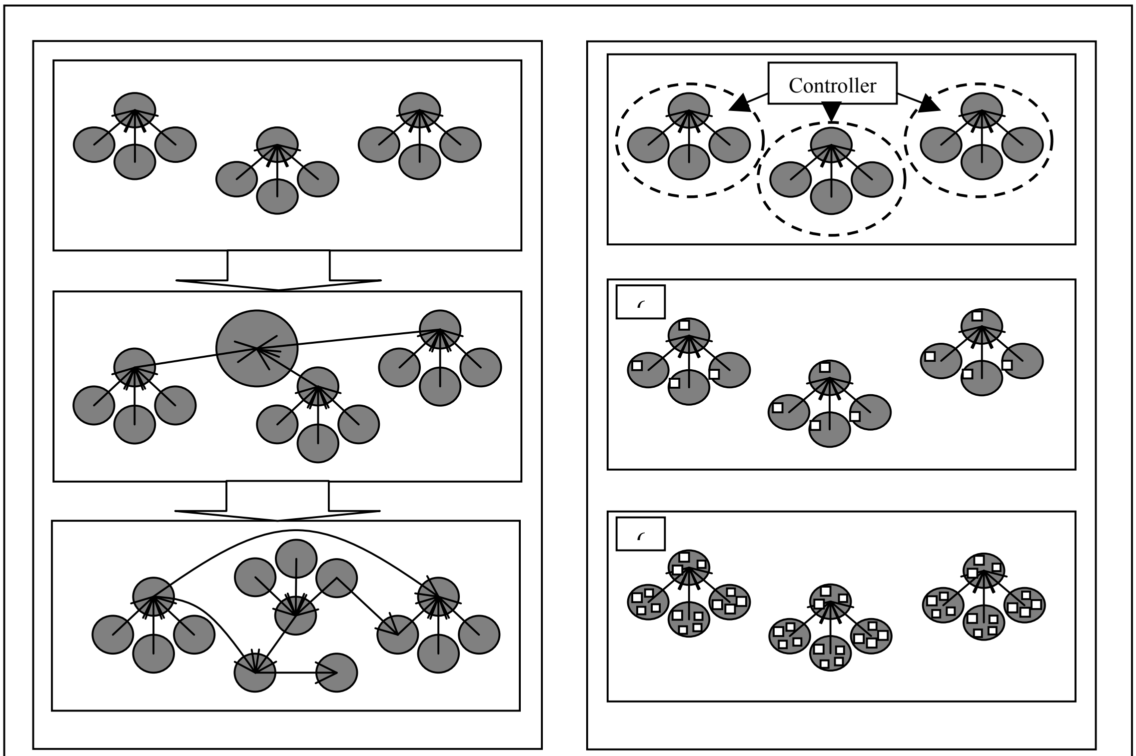
16.2 OBJECTIVES

The general aim of this project has been to create tools to model, simulate, understand, formalize and control the inherent complexity and adaptation of generalized – virtual – production networks. To achieve this we have formed the following list of tasks:

1. Building an agentbased simulation modelling software framework (this is the “ModNet simulator”)
2. Implement optimization algorithms and observe them in the framework
3. Generalize and formulate the problem of Virtual Production Networks mathematically
4. Design and implement a problem generator that builds test problems according to given parametrs randomly.
5. Propose a methodology for the agentbased investigation of complex and adaptive production networks.
6. Discover specialized hardware and software to tackle the increased need of computational power.

16.3 RESULTS AND ACHIEVEMENTS

The products of the research are a formal discovery of the problem, a problem generator software, an agentbased simulator software and a methodology for VPN investigations.



The emergence of adaptation in production networks (nodes represent factories)

Centralised, decentralised and distributed control in production networks

Fig.1. Schematic figure of the co-evolution of production networks and their distributed control

16.3.1 *Definition of the Problem*

The approach to modeling and describing production networks is somewhat analogous to the context of Mode Identity Resource-Constrained Project Scheduling Problem (MIRCPSP) presented by Salewski et al. [7]. In traditional resource-constrained project scheduling problem (RCPSP) each job in the problem may be performed only in one predefined way. In the Multi-mode Resource-Constrained Project Scheduling Problem (MRCPSP) the job durations are discrete functions of job performance modes [8]. In MRCPSP all mode-job assignments are mutually independent in the sense that assigning a mode to one job of a project doesn't force any other job to be processed in a specific mode. In the case of mode-identity, where the set of all jobs is partitioned into number of disjoint subsets where all jobs belonging to the same subset have to be processed in the same mode [9].
We provied the formal description of the problem formulation used in the ModNet – project. The problem parameters are summarized in Table 1.
J, O, S, M, F, O_i^J, S_i^O, O_i^M and M_i^F are all sets with certain number of appropriate members generated by the problem generator. C_i and T_i are both non-negative integers and x_{oj} and m_{it} are binary variables.

Table 1: Parameter summary

Parameter	Definition
J	Set of jobs in the current problem.
O	Set of operations in current problem.
S	Set of all the sub-operations in the problem.
M	Set of machines in current problem.
F	Set of factories in current problem.
O_i^J	Set of operations in job *i*. $(i \in J, O_i^J \subseteq O)$
S_i^O	Set of sub-operations in operation *i*. $(i \in O, S_i^O \subseteq S)$
O_i^M	Set of operations in machine *i*. $(i \in M, O_i^M \subseteq O)$
M_i^F	Set of machines in factory *i*. $(i \in F, M_i^F \subseteq M)$
C_i	Cost of processing a job in machine *i* for one time step. $(i \in M)$
T_i	Time to perform sub-operation *i* in a machine. $(i \in S)$
x_{ojm}	Binary variable that states whether operation *o* in job *j* has been performed in machine *m* or not. $(o \in O_i^J, j \in J, m \in M, x_{ojm} = \{0,1\})$
m_{it}	Binary variable that states whether machine *i* is busy (is processing an operation) at time *t*. $(i \in M, m_{it} = \{0,1\})$

As it can be seen from the table, the basic element of a problem is a sub-operation. These sub-operations represent the most low level division of job. Sub-operation is analogous to job in MIRCPSP approach. Operations are formed of groups of sub-operations. Each operation's all sub-operations has to be completed by the same resource (machine). In MIRCPSP the analogous element is subset of jobs and all jobs belonging to it has to be processed in the same mode. Jobs are formed of operations making ModNet job analogous to a whole project in MIRCPSP.
The resources are represented by machines, which are renewable resources. Despite its name, machine represents all kinds of workstations, not necessarily a mechanical machine. Machine can perform certain a set of operations O_i^M and has an operating costs of C_i per time unit. The time to

perform an operation in any machine equals the sum of times required to perform all sub-operations of the operation i :

$$\sum_{c \in S_i^O} T_c \,, \quad (i \in O) \qquad (1)$$

The ModNet approach differs in some ways from the MIRCPSP problems, tough most of the differences involve only terminology. The ModNet approach is designed to be less general than MIRCPSP in order to suit better the needs of practical applications in modeling Virtual Production Networks. The job structure in ModNet is linear, in other words, any job is predecessor only maximum of one other jobs and each job can have only maximum of one predecessor. This kind of structure prohibits any kind of cyclic structures from occurring. There are no defined time lags between workpieces or any kind of release or due dates. All the workpieces in the model are available for processing immediately. The ModNet approach has only renewable resources in form of machines. Nonrenewable resources are not taken into consideration in this model.

The formulation of the problem is:

$$\text{Minimize } (T, \sum_{i \in M} \sum_{t=0}^{T} m_{it} c_i) \,, \ T = \text{the completion time of the last job} \qquad (2)$$

The first parameter to optimize is the total completion time T of the whole schedule. This time T can be viewed as a throughput time for the whole schedule. The second part is the total cost for the completion of all the jobs in the schedule. This minimization of time and costs results into Pareto-optimum between the variables.
In addition to the equation to be optimized, the constrains of the ModNet – approach differ from the approaches taken by Salewski [7] and Kolisch [10]. In ModNet – approach the minimization of equation (2) has to satisfy that:

$$\sum_{m \in M} x_{oim} = 1 \,, \ (o \in O_i^J \,, j \in J, m \in M \,, x_{oim} = \{0,1\}) \qquad (3)$$

$$\sum_{i \in M} m_{it} \leq \sum M \,,$$
$$(i \in M, 1 \leq t \leq T, m_{it} = \{0,1\}) \qquad (4)$$

Operation i of job j, O_{ij}^J, $(i \in O_i^O, j \in J)$, can be performed on a machine $rand\{\ \}$ if:

$$O_{ij}^J \in O_m^M \qquad (O_m^M \subseteq O) \qquad (5)$$

$$m_{mt} = 0 \qquad (1 \leq t \leq T) \qquad (6)$$

$$x_{(i-1)jm} = 1 \vee O_{(i-1)j}^J = 0 \qquad (x_{oim} = \{0,1\}) \qquad (7)$$

The job completion constrain (3) ensures that each operation of each job is performed exactly once in one of the machines. Constrain (4) limits the usage of machines so that the resources are not exceeded. The constrains for performing an operation on an appropriate machine (resource) consist of three rules: the machine has to be able to perform the operation – the operation in question has to be found from the machine’s list of possible operations (5), the machine in question must not be performing another task (6) and the operation’s immediate predecessor has to be performed or the operation in question is the first operation of the job (7). Constrain (7) ensures that the operations in a job are processed in order and constrains (5) and (6) ensure that a valid machine is selected to perform the operation.

16.3.2 *The Problem Generator*

In order to test out our ModNet simulation package we have developed a fairly simple way to create large test problems with ease. In this section we describe the problem generation and the parameters needed.
The problem generator, as the ModNet toolbox, is programmed with Java programming language. The interface is text-file operated: the user characterizes the problem to be generated in one text file and the problem generator returns three files, one describing the job types and cuts, second describing the machines and the third describing the factory network. These text files are compatible with the ModNet toolbox
First the user should describe the production network with certain parameters summarized in Table 2.

Table 2: User inserted parameters for problem generation

Variable	*Explanation*
S^{Min}, S^{Max}	Minimal and maximal value for number of different sub-operations in the problem.
T^{Min}, T^{Max}	Minimal and maximal time for a sub-operation.
O_C^{Min}, O_C^{Max}	Minimal and maximal value for operation complexity. Operation complexity tells that of how many sub-operations the operations consist of.
O_V^{Max}	Maximal number of variants for an operation.
J_C^{Min}, J_C^{Max}	Minimal and maximal value for job complexity. Job complexity tells that how many operations the jobs consist of.
J_V^{Max}	Maximal number of job variants.
M_C^{Min}, M_C^{Max}	Minimal and maximal machine flexibility. Machine flexibility tells that how many different operations machines can perform.
C^{Min}, C^{Max}	Minimal and maximal machining costs. Machining costs tells the cost of processing the job in machine for one time step.
M^{Min}, M^{Max}	Minimal and maximal value for number of machines per machine type in a factory.
F_C^{Min}, F_C^{Max}	Minimal and maximal value for factory complexity. Factory complexity tells that how many different machine types exist in a factory.
F^{Min}, F^{Max}	Minimal and maximal number of factories.
R	Resource scarcity. Resource scarcity is the ratio of number of jobs per machine.

Let $rand\{a,b\}\,(a,b \in \mathrm{N}_0)$ be an integer pseudo random number out of the interval $\{a,...,b\}$. The rules for the problem generation are presented in Table 3.

Table 3: Problem generation rules

Number of different sub-operation types: $rand\{S^{Min}, S^{Max}\}$ s. t. $O_C^{Min} < \sum_{k=O_C^{Min}}^{n} \frac{n!}{(n-k)!}$, n = number of sub-operations.
Number of different operation types: $rand\{\max(J_C^{Min}, M_C^{Min}), \max(J_C^{Max}, M_C^{Max})\}$

Number of sub-operations in an operation type: $rand\{O_C^{Min}, O_C^{Max}\}$
Time for each sub-operation is different depending on the operation – not the sub-operation type. Time for each sub-operation is: $rand\{T^{Min}, T^{Max}\}$
Number of different machine types: $rand\{F_C^{Min}, F_C^{Max}\}$
Number of different operation types that can be performed in a certain type of machine (machine flexibility): $rand\{M_C^{Min}, M_C^{Max}\}$
Cost of processing a job for one time step in a certain machine: $rand\{C^{Min}, C^{Max}\}$
Number of factories: $rand\{F^{Min}, F^{Max}\}$
Number of different machine types in a factory: $rand\{F_C^{Min}, F_C^{Max}\}$
Number of machines per machine type per factory: $rand\{M^{Min}, M^{Max}\}$
Number of different job types: $rand\{J^{Min}, J^{Max}\}$
Number of different operations in a job type: $rand\{J_C^{Min}, J_C^{Max}\}$
Number of workpieces per job type: $J_i^N = rand\left\{1, R\sum_{i\in F} M_i^F\right\}$ s. t. $\sum_{i\in J} J_i^N \le R\sum_{i\in F} M_i^F$

Generally all the variables are uniform random numbers taken between minimum and maximum boundaries, but two points need some clarification. The number of different sub-operation types has to be large enough to be able to create enough different operations, which minimum complexity is also pre-defined. The total number of workpieces in the model depends on the total number of machines in all factories and the resource scarcity parameter. Resource scarcity can be stated as "how many workpieces there are in the model per machine". Thus, the total number of workpieces is the product of resource scarcity and the total number of machines:

The total number of workpieces in a problem is

$$R\sum_{i\in F} M_i^F \tag{8}$$

The sequence in problem creation is as follows:

1. Create different sub-operation types.
2. Create different operation types.
3. Assign sub-operations to the operations. Note that here the sub-operations are given the times required for complete them. The same kind of sub-operation can thus have different duration in different operation.
4. Create machine types. Each machine type can perform certain number of different operations depending of the given machine flexibility.
5. Create factories. Factories are assigned a random number of different types of machines.
6. Create jobs and assign operations to the jobs. Each job type can have multiple workpieces (manifestations) in the model. Total number of workpieces depends on resource scarcity *R*.

Assigning operations to both machines and jobs effectively prevents creating jobs that can't be completed, assuming that each operation is assigned to at least one machine. If individual sub-operations were assigned to machines, it would require extensive checks to ensure that all the jobs can be manufactured at least in one machine. It is possible to limit the number of workpieces to be

assigned for one job to a certain maximum percentage of all workpieces if the possibility of one job type becoming too dominating is wanted to be limited.
With the problem generator it is also possible to create variants for different job types. These variants differ perhaps only by one operation from the "parent" job and they can be used to model different product variants, which are manufactured in the production network.
Another possibility is to create jobs so that they can be performed inside one factory in order to model a situation where there is no inter-factory transportation or connections.

16.3.3 *The ModNet Simulator*

Based on the Swarm simulation framework a production network modeler has been developed, that suites the goals and requirements initially set. The package is called ModNet – modelling of networks. The hierarchical package structure consists of the following classes: Factory, Machine, Controller (Intelligence), Orderstore. The Machine class is basically a resource that can be a cutting machine, a human, or a logistic unit. From these basic and simple components complete production networks can be built. The whole simulation can be configured by three "csv" (comma separated) text files, where we have to define the type of machines and their ability to carry out operations, the orders received by the whole production network, and the factories' layout, including resources. The package allows the definition of different distribution of decision making – as it is depicted in Fig.1. – namely centralised, decentralised and distributed control. In case of the centralised control all the scheduling decisions are made in one central for the whole network. In the decentralised case the individual factories or suppliers make the decisions based on the information they are provided. In the latter, fully decentralised, distributed decision making case the individual resources have the ability/intelligence to decide about the use of their own resources. These basic control options allow us to run our agentbased models in a non-agentbased fashion, and even compare the results obtained. This also provides a possibility for a weak verification of the model – especially if we have no analitic model or real data to verify against.
The problem generator (ProGen) is implemented as part of the ModNet package. Its parameters are set up in a "csv" file, and the output is another text file that belongs to the aforementioned configuration files of the ModNet package.
In the current simulations several wellknown heuristic rules are used in place of the "controller" unit to demonstrate its proper operation. New developments and plans include an evolutionary method to evolve the intelligence of these controller/decision maker agents, preserving simplicity but increasing their efficiency.
Throughout our investigations several generations of testproblems were tested, and it was concluded that:

- the ModNet simulation tool can be reliably configured by text files, therefore no programming or recompilation of code is needed
- the ProGen package provides arbitrary large and realistic testproblems for investigation – opposite to typical operations research testproblems that are usually small and novel
- the extensibility of the ModNet controller allows us to experiment in any decision rule that can be programmed, including evolving/learning intelligence

In [3] there are more detailed investigation and a longer description of the ModNet package.

16.3.4 *Applicability*

This work provides a (1) computational model (2) an easily configurable software and (3) a methodology for giving directions on the use of (1) and (2). This package is suitable for researchers and students to carry out theoretical investigations with the proposed computational model, set up agentbased models and observe the desired properties like emergence, evolution, adaptation, or any other complex phenomena. After enough theoretical and computational studies were carried out, these ideas can be introduced in industry.

16.3.5 *Researcher training*

In the course of this project three doctoral students have been working and a fourth one temporarily. Since the applications of Complexity Science are not yet researched in Finland, this opportunity has been important for our laboratory, establishing a good foundation for further research.

16.4 FUTURE ACTIVITIES

Research

- Exploring basic research results and their applicability (dissipative structures, systems biology)
- Working out practical tools for scientific investigation of production systems

Networking

- *Domestic* – preparation for Centre of Excellence status
- *European* – preparation for EU projects, Network of Excellence membership or network proposal (www.complexityscience.org)
- *International* – gaining a reputation, representing Finland in with more integration in Complexity Science and especially in its applications

Knowledge accumulation and education

- Educational website development with theoretical and practical (software) excersises
- Moderated chat forums on various topics
- Course development
- Thematic days, regular events for industrial partners
- Initiating an international yearly conference on the applications of complexity science

Software Integration

- Compiling a web-based software framework for agentbased simulations of production networks
- Including online simulation possibilities in the educational website
- Creating a database of simulation scenarios and their documentation on the website

16.5 PARTNERS

The following partnerships were used and developed during the project:

- Swarm Development Group, Santa Fe, NM, USA – about the Swarm simulation system
- University of Turin, Italy, Prof. Pietro Terna – about his similar research efforts and simulator

- Budapest Polytechnic, Institute of Mathematical and Computational Sciences, Prof. József K. Tar – about dissipative structures, complexity science issues.

16.6 BUDGET AND SCHEDULE

The budget goals have been met during the project, no deficit was generated.
In the schedule minor modifications were made, since the duration of the tasks were not properly estimated. However, this has not affected the main tasks and their completion.

16.7 CONTACT ADDRESS

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16.8 PUBLICATIONS

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[2] Janne Keskinarkaus, Béla Pátkai, Seppo Torvinen, *Generating and Solving Resource-Constrained Project Scheduling Problems Emulating Virtual Production Networks,* ICPR'03, The 17th International Conference on Production Research, August 3-7, 2003, Blacksburg, Virginia, USA. (To appear)

[3] B.Pátkai, J.Keskinarkaus,S.Torvinen, *An Agentbased Computational Framework for Production Network Modelling,* International Conference on Computational Cybernetics, ICCC'2003, Siófok, Hungary, August 29-31, 2003. (Accepted for publication)

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16.9 UNFINISHED DEGREES

Some of the results of the project have got proper emphasis only in the following PhD thesis that is due to final submission in August 2003.

PhDs in progress:

[5] Béla Pátkai, to be defended in the end of 2003. *Computational Synthesis of Complex Adaptive Production Networks.*

[6] Janne Keskinarkaus, due to finish in approximately 2 years (depending on funding).

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17 FATIGUE STRENGTH MODELLING OF LASER WELDED JOINTS

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ABSTRACT: Laser welding is one of the newest welding techniques, which has been available for industry since 60's. Main advantages of laser welding are low welding distortions, high productivity and easy automation. Additionally, the laser welding techniques open new opportunities for design of steel structures. Car industry has applied laser welding in production since 80's. At present, the laser-hybrid welding has high potential for further development of the shipbuilding process.

Today existing design codes for fatigue strength are conservative when applied to laser welded structures. The properties of the laser welds can be much different from the conventionally welded joints. In this research project the behaviour of laser welds under cyclic loading was investigated to develop a sound design basis for laser welded joints. The advanced tests revealed the main parameters affecting fatigue crack initiation and propagation. On the basis of experimental results the notch stress approach has been developed further. This approach gives promising, but somewhat conservative fatigue strength prediction. Comparison between the predicted values and tests results indicates that average error was about 10 % for fatigue strength at 2 million load cycles. It is expected that by implementing an elastic-plastic material model the prediction method can be improved significantly.

17.1 INTRODUCTION

During the last decade ship building industry has had an increasing interest to laser welding techniques and first installations for production have been done. The guidelines of classification societies for acceptance of laser welded joints were published in 1996 (Guidelines, 1996).

Laser welding process differs from conventional arc welding which causes metallurgical differences. Previous studies indicate that the fatigue properties of the laser welds differ significantly from those of conventionally welded joints, see Figure 1. Due to this the level of fatigue strength and also the slope of the curves for laser welded joints is different compared to existing fatigue design standards for arc welding. The reasons for this discrepancy are not very well known at present. The fatigue test results indicate that the fatigue crack initiation and propagation phenomena are different for laser welds compared to those of arc welds. Weld geometry and the mechanical properties of weld seams are possible explanations.

At present, the arc welded joints are designed using either the nominal stress, hot spot stress or notch stress approach. There does not exist common understanding of the applicability of these methods for the design of laser welded joints. The earlier studies (Ring and Dahl, 1994; Weichel and Petershagen, 1995; Toivonen, 1998) indicate that the notch stress method is suitable for laser welds at the endurance limit ($N \approx 2*10^6$). In these studies, however, the modelling the fatigue strength at medium high cycle range is not considered. No fatigue strength data for laser-hybrid welded joints has been published so far.

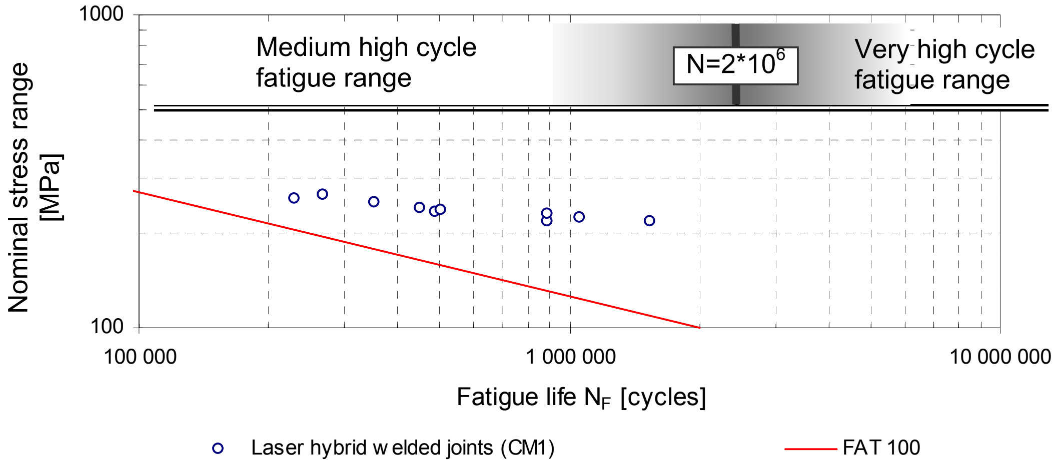

Figure 1. Fatigue test results for laser-hybrid welded butt joints (Open circles) and fatigue design curve of arc welded joints (Line), FAT 100.

17.2 OBJECTIVES

The aim of the project has been to improve the knowledge on laser welds under cyclic loading and to develop a sound design basis. The main parameters affecting fatigue crack initiation and propagation are clarified with the help of strength testing including also metallurgical observations. Existing approaches to predict crack initiation are improved and validated by laboratory tests. Finally, the experimental results give a possibility to develop new methods to predict fatigue strength of laser welded joints.

17.3 RESEARCH PACKAGES

Figure 2 shows the flow chart of the research work. Research included experimental research and theoretical modelling. The research project was divided into following main tasks:

1. Detailed analysis of the available test data. The main parameters affecting fatigue strength of laser welded joints are studied.

2. Comparison the existing test data with the available prediction methods such as the nominal stress, hot spot stress and notch stress approaches. As a result of this critical analysis the suitability of these methods to laser welds joints is presented.

3. Further improvement of the existing notch stress approach. This prediction model is verified by the new test data. This prediction method includes both initiation and propagation of fatigue crack.

4. Fatigue testing of $C0_2$-laser and $C0_2$-laser with MAG welded joint, see Table 1. Three different weld parameter settings are used for laser-hybrid welded test specimens. Emphasis was put on fatigue crack initiation and propagation. Test program included fatigue testing of weld materials and welded joints. These make it possible to figure out the main parameters affecting fatigue strength of welded joints. Both material and geometry effect are considered, and the S-N curves for fatigue crack initiation and propagation are determined.

5. The study of the mechanical and metallurgical properties of laser and laser- hybrid welded joints. The work package included such tests as hardness measurements, residual stress measurements, measurements of cyclic stress-strain curves and striation spacing measurements.

6. Simulation of welded joints using FEM and fracture mechanics with an elastic-plastic material model to explain some unexpected fatigue test results.

Table 1. Fatigue test matrix.

Steel grade	Plate Thickn.	Joint type	Arc weld[3]	Laser	Laser-hybrid A	Laser-hybrid B	Laser-hybrid C
NVA	4 mm	Butt weld			X		
NVA	6 mm	Butt weld	X				
NVA	12 mm	Butt weld	X				
RAEX S275 LASER	6 mm	Butt weld	X	X	X	X	
		Fillet weld	X[2]	X[2]	X[1]	X[2]	
RAEX S275 LASER	12 mm	Butt weld	X	X	X		X
RAEX 420MC LASER	6 mm	Butt weld			X		
GL-A36TM	6 mm	Butt weld			X		
RAEX 420MC LASER	12 mm	Butt weld	X		X		
		Fillet weld	X[2]		X[2]		
RAEX 700 OPTIM	4 mm	Butt weld			X		

Superscripts: 1 = One side fillet weld, 2 = Two sides fillet weld, 3 = Reference series

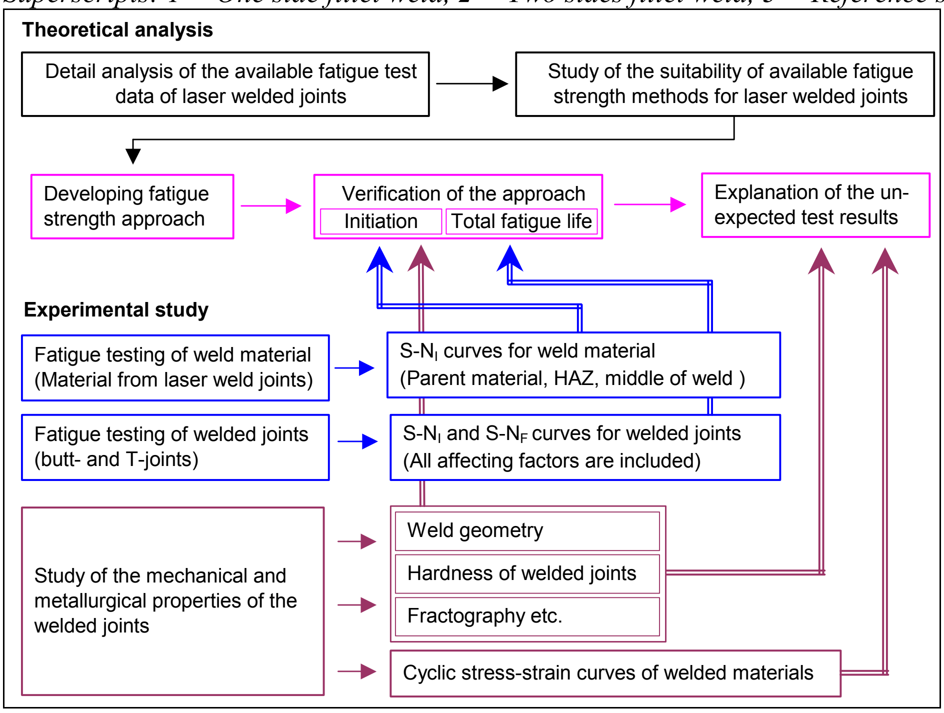

Figure 2. Flow chart of the research work.

17.4 RESULTS AND ACHIEVEMENTS

17.4.1 *Scientific*

17.4.1.1 Analysis of the available test data of fatigue testing of laser welded joints

The detailed analysis of the available results of fatigue tests indicated that several parameters affect fatigue strength of laser welded joint. These are: weld geometry, a narrow weld zones and low welding distortions. The results of fatigue tests of welded joints are affected by all these parameters. Due to this, the influence of each individual parameter is difficult to evaluate separately.

17.4.1.2 Critical analysis of the available fatigue strength methods

The traditional fatigue design methods such as nominal stress and hot spot stress methods were not found very useful. When using nominal stress method, large scatter of test results was observed and thus the accuracy of this method was generally poor. So, the application of the nominal stress method without experimental testing to design work is considered limited. The use of hot spot stress method is also limited because of very different geometrical and weld material properties compared to the conventional arc welded joints. Theoretical analysis showed that in order to carry out elastic-plastic analysis based on fracture mechanics, the experimental data of the stress-strain behaviour of laser welded material during the cyclic loading is necessary. Critical survey of the notch stress method according to Radaj/Seeger (1989) reveals that the notch sensitivity and fatigue properties of weld material are assumed to be equal between different weld joints. Most promising method is presented by Lawrence (1977) the basic elements of which are applicable to fatigue strength modelling in the case of laser welded joints.

17.4.1.3 Experimental study of the fatigue characteristics of laser and laser-hybrid welded joints

Based on the results of tasks 1 and 2, a special test programme was carried out. This programme included fatigue testing of weld materials and welded joints. CO_2-laser, CO_2-laser with MAG and also submerged arc welded test specimens were studied. The programme made possible separately to analyse the fatigue behaviour of laser weld materials: parent, heat-affecting-zone (HAZ) and weld metal and also the effect of weld geometry.

In the first part of the tests weld materials made from butt joint were studied. The raw plate was 12 mm thick RAEX S275 LASER steel. The research focused on early crack detection and cyclic stress-strain behaviour. The results of uniaxial fatigue tests indicated significantly better fatigue strength for laser and laser-hybrid welded joints than for the parent material or for conventional arc welded joint. It was also possible to observe material damage process during the stress controlled fatigue tests from the change of inelastic strain range.

The second part of the test programme focused on butt and fillet welded joints. The test specimens included all main parameters affecting on fatigue strength of welded joints. A force controlled constant amplitude axial fatigue tests with load ratio R=0 were conducted, and the fatigue strength of the welded joints were determined. The results indicate excellent fatigue strength with very gentle slope of S-N diagram for laser-hybrid welded joints with parent material RAEX S275 LASER steel grade.

A special focus was put on observations of macro crack initiation. During the force controlled fatigue testing strain in the narrowest part of test specimen was measured. Based on this macro crack initiation and propagation was observed, and S-N curves for the initiation phase were determined. Different behaviour of macro crack initiation was observed in laser and laser-hybrid welded joints compared to that of conventionally arc welded joints. This indicates different notch sensitivity. The test results showed also that macro crack initiation period can be relative long and it has to be taken into account in the theoretical modelling of medium high cycle fatigue. This is an important observation as the physical behaviour of short cracks at initiation and propagation phase is significantly different than that of the macro crack propagation.

Also the testing of different steel grades as shown in Table 1 was carried out, but the summary of these tests not yet available, but it will be included in the final version of the report.

17.4.1.4 Fatigue strength modelling of laser welded joints

The fatigue of welded joint is assumed to consist of macro crack initiation and macro crack propagation periods. On the basis of the theoretical and experimental observations conducted in the previous research tasks, the notch stress method according to Lawrence (1977) was further developed in order to estimate macro crack initiation period. This period consists of short cracks initiation, propagation and coalescence to a macro crack. Hardness value (HV) is defined as a basic material parameter. The initiation strength expressed with the help of nominal stress σ_{nom} as a function of macro crack initiation time N_I is as follows:

$$\sigma_{nom} = \frac{\left(\sigma'_f(HV) - \sigma_m\right)\cdot N_I^{\,b(HV)}}{K_f(HV)}, \tag{1}$$

where σ_f’ and b is fatigue strength parameters calculated from material hardness value at crack initiation point, K_f is fatigue notch factor and σ_m is local mean stress at macro crack initiation point.

Macro crack propagation period is calculated using the Paris Law. The size of initiated macro crack is assumed to be 0.2 mm, which is similar to a typical weld defect. The macro crack initiation and the propagation models are verified with experimental data from the previous task. These models were found to give promising macro crack initiation and fatigue life predictions as shown in Figure 3 and 4. The averaged difference between the initiation strength perdition and the results from weld material tests was about 3% and the maximum value of difference was 12%. Figure 4 gives the comparison between calculated and measured fatigue life for welded joint with RAEX S275 LASER steel grade. This initiation-propagation approach gives a conservative estimation. The average error of the prediction was about 10% for fatigue strength at 2 million load cycles, but maximum error was even 22% for laser-hybrid welded joint.

17.4.1.5 Mechanical and metallurgical properties

One part of the research work was conducted in co-operation with the Rautaruukki company. It included non-destructive and destructive testing of the welded joints such as tensile, impact and bending tests, as well as hardness measurements and metallography observations. The test results indicate better laser-hybrid weldability of the laser steel grades compared to the other steel grades and also increased welding speed and reduced hardness of the butt joints compared to laser welding were observed.

The programme conducted in Laboratory of Engineering Materials at HUT consisted of residual stress analysis, measurement of cyclic stress-strain curves and fractography. The test specimens were laser-hybrid and submerged arc welded butt joints with 12 mm thick parent material of RAEX S 275 LASER and A grade steels.

The residual stresses in the welded specimens were studied with X-ray diffraction during mechanical loading. The results of the measurements show that the residual stresses are redistributed and reach a stabilised state during the first tensile loading cycle. The magnitude of the relaxation was greater in the direction parallel to the loading than in the transverse direction.

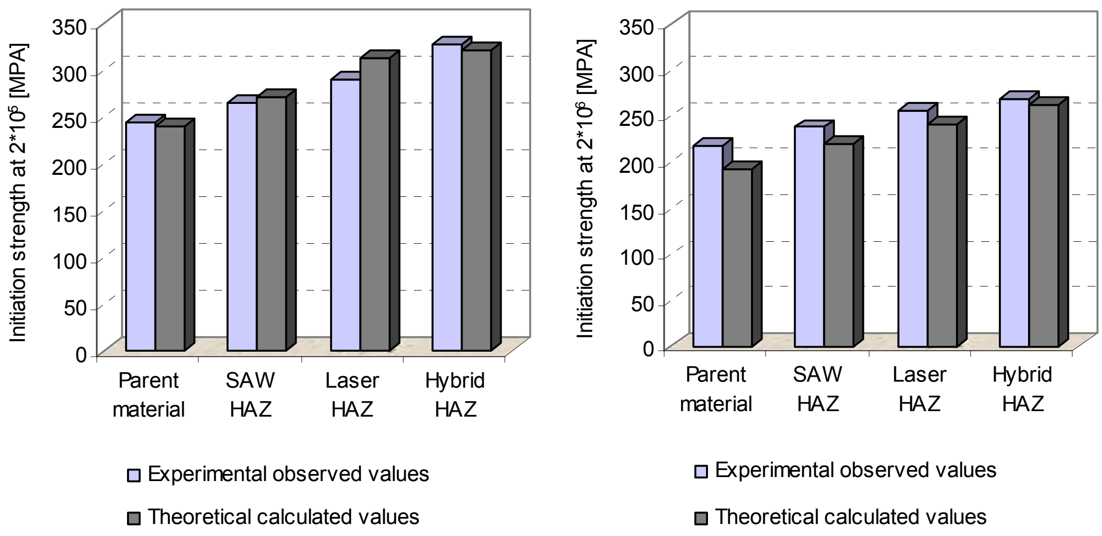

*Figure 3. Comparison of calculated and measured initiation strength at 2 *10^5 (left) and 2 *10^6 (right) load cycles for parent material and HAZ material of laser, laser-hybrid and submerged arc welded butt joints with RAEX S275 LASER steel grade.*

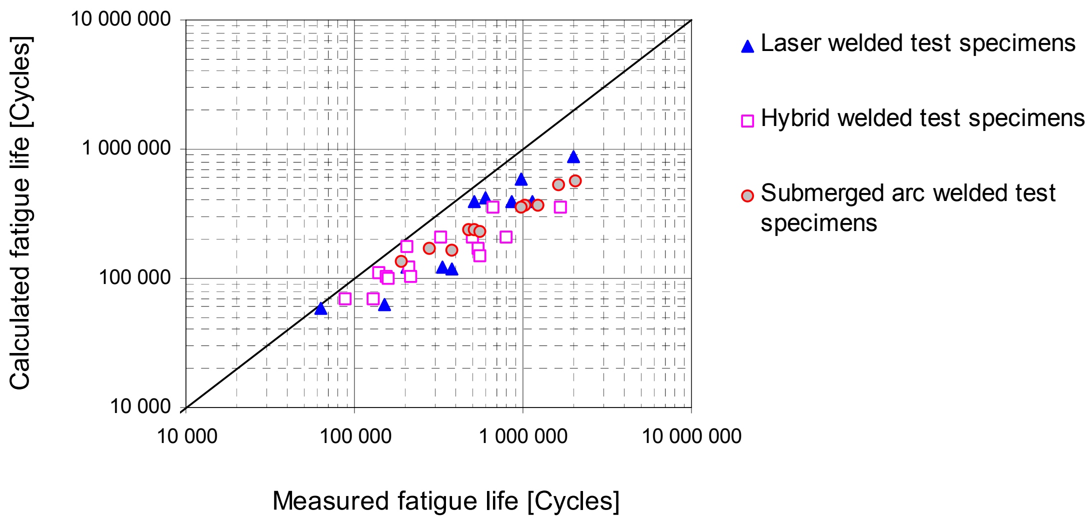

Figure 4. Comparison of calculated and measured fatigue life for laser, laser-hybrid and submerged arc welded tests specimens with RAEX S275 LASER steel grade. The conservative and non-conservative region for calculated prediction are separated with line.

The cyclic stress-strain curves were determined both for base materials and welded materials by incremental step procedure consisting of a regular distribution of linearly diminishing and increasing strain amplitudes. A quantitative analysis of the stress-strain data was carried out by fitting Ramberg-Osgood type equation where elastic and plastic strains were separated as

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2k'}\right)^{1/n'}, \tag{2}$$

where *Δε/2* is the total strain amplitude, *Δσ/2* is the total stress amplitude, E is the elastic modulus, n´ and k´ are the cyclic strain hardening and strength coefficients.

The test results are presented in the form of stress-strain curves, both monotonically and cyclically loaded. The values of the parameters of Ramberg-Osgood function for cyclically stabilised curves are also presented. Figure 5 shows the monotonic and cyclic stress-strain curves for parent and weld material of laser-hybrid welded butt joints with RAEX S275 LASER steel grade. The both steels, RAEX S 275 LASER and A grade steel showed cyclic hardening with laser welds. The submerged arc welding process caused cyclical softening of the weld and HAZ material with both steel grades. Similar phenomenon occurred with the laser-hybrid welding process. However, all the welds were stronger than the parent materials regardless of cyclical softening or hardening under the fatigue load.

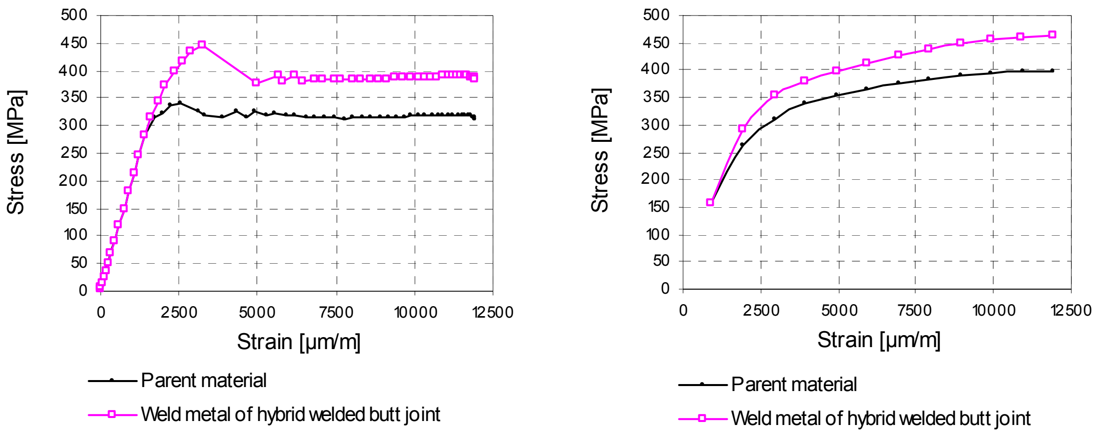

Figure 5. The monotonic (left) and cyclic (right) stress-strain curves for parent material and for weld metal. The test specimens were laser-hybrid welded butt joint with RAEX S275 LASER steel grade.

Optical macroscopy revealed that test specimens which had been fatigue loaded with a higher stress value contained more short crack initiation points than those with lower stress. The local fatigue crack growth rate (CGR) based on measurements of striation spacing using SEM technique was used to evaluate the global fatigue CGR by using the empirical Paris-Erdogan equation

$$\frac{da}{dN} = C_0 \Delta K^m, \tag{3}$$

where *da/dN* is the crack growth rate, *ΔK* is the stress intensity factor range and C_0 and *m* are material constants. The determined CGR values were compared to reference data from IIW design guidelines (Hobbacher, 1997). The crack growth rates determined from striation spacing are local crack growth rates opposite to the global CGR that is determined from the fracture mechanics specimens. A great discrepancy was observed between the obtained results and the earlier published data (Hobbacher, 1997). It has been found out that the crack does not propagate during every loading cycle at low stress intensities (Hertzberg, 1989), but this fact did not improve the compatibility of the results. Striation spacing measurements have been successfully used to determine CGR value in austenitic and duplex stainless steels (Au et al., 1979; Yokobori et al., 1975). However the method turned out not to be suitable for this type of welded steel grades.

17.4.1.6 FEM analysis to explain some unexpected fatigue test results

The results of theoretical analysis and experimental test programme indicate that the higher fatigue strength of laser or laser-hybrid welded material is caused by prolonged macro crack initiation. As plastic deformation does not occur so extensively in notch root zone due to lower strength properties in base material. Additional theoretical analysis with elastic-plastic material model is needed to confirm this assumption. The results of analysis will be available in early autumn 2003.

17.4.2 *Technological, applicability*

The advanced experimental investigations and theoretical modelling improves knowledge on fatigue of laser welded joints. The understanding is crucial for the development of new innovative structural solutions. For example, the laser welded steel sandwich panels can give 40% weight saving compared to that of existing marine deck structures. An obstacle in reduce existing steel plate thickness in cruising ships with laser welding technique is the poor understanding of fatigue. Laser welding also makes it possible to improve fabrication of box type structures when the fatigue and corrosion problems are solved.

The cyclic stress-strain tests showed that the elastic-plastic properties between the base material and the welds differ from each other. Strain hardening and softening depend on the welding method. Exploiting these results in design improves reliability of welded structures.

The test arrangements used in cyclic stress-strain tests, welded joint tests and weld material tests proved out to be reliable and accurate. These systems are fully applicable to fatigue research of other structural and material solutions.

17.4.3 *Research training*

The project offered comprehensive research training by combining a good balance between experimental testing and theoretical modelling. The task to measure local strain at the weldment in the cyclic stress-strain tests offered a great challenge. Similar challenges were met in the fatigue testing with geometrically narrow laser welds

During the project the international co-operation with other research organisations gave a good training experience. Especially, the visiting period in Polish Academy of Science was found to be fruitful.

17.5 FUTURE ACTIVITIES

The test results showed the difference in the elastic-plastic properties between base materials and welds. The future research is focused on elastic-plastic material modelling of narrow laser welded joints, and analysis of the influence of this on the new fatigue strength approach. This work forms the basis for the new EU-founded Network of Excellence related to the marine structures scheduled to start in early 2004. In this project HUT/Ship Laboratory is a partner concentrating on the analysis of the fatigue strength of laser-hybrid welded joints.

17.6 RESEARCH GROUP AND PARTNERS

Ship Laboratory of Helsinki University of Technology has been the main conductor of the research. The mechanical and metallurgical aspects of laser welds were studied in Laboratory of Engineering Materials at HUT. The research project has employed M. Sc. Remes and his aim is to present a doctoral thesis on this subject. The doctoral thesis is planned to be finished in 2004. M. Sc. Gripenberg has also been employed in the project and he is finishing his Licentiate thesis during this year. Post-graduate student Tamminen carried out a part of the fatigue strength tests.

FORCE Institute (Denmark) and Kvaener-Masa Yards (Finland) supported the welding of the test specimens. Some of the mechanical and metallurgical studies were carried out in co-operation with Rautaruukki Company (Finland). Rautaruukki funded also the additional laser-hybrid weld tests and fatigue testing in Institute of Fundamental Technological Research (IFTR) of Polish Academy of Science.

The advanced experimental investigations of fatigue crack initiation and propagation of laser and laser-hybrid welded joints were carried out with close co-operation between HUT/Ship Laboratory and IFTR/Department for Strength of Material. Both organisations are partners in the EU-funded Centre of Excellence for Laser Processing and Material Advanced Testing (LAPROMAT). LAPROMAT supported a part of travel and subsistence costs of researchers.

17.7 BUDGET AND SCHEDULE

The overall budget of the project was 179 793 € covering the salary (49 man-months) of the postgraduate student employed in the project. The budget included also 27 718 € for preparation of test specimens and the strength testing in IPPT in Poland. The travelling costs were 11 663 €. The additional weld tests and fatigue strength tests were funded by Rautaruukki.

Table 2 shows the schedule of the research project and man-months of the different research tasks. The first part of the project focused on the study of the available test data and the suitability of available fatigue strength methods. Based on this the theoretical work was carried out to develop a fatigue strength model. The middle period of the project included experimental work to study fatigue crack initiation and propagation of laser and laser-hybrid welded joints. Metallurgical and mechanical properties of laser welds were also investigated. The object of the final period of the project was focused on the development of fatigue strength model for laser welded joints.

17.8 CONTACT ADRESS

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Table 2. Schedule and man-months of the research project.

A description of the task	2001	2002	2003	Total
1. Detail analysis of the available test data of laser welded joints	1.5			**1.5**
2a. Theoretical analysis of the fatigue crack initiation and propagation 2b. Critical analysis of the suitability of available fatigue strength methods	3			**3**
3. Development and verification of fatigue strength approach	2	2.5	3.5	**8**
4. Fatigue strength tests with obs. of crack initiation and propagation	4.5	9.5	6.5[1]	**20.5[1]**
5. Study of the metallurgical and mechanical properties	3	11		**14**
6. Elastics-plastic FE-analysis to explain the fatigue test results			2.5	**2.5**
7. Final reporting			1.5	**1.5**
Total man-months	**14**	**23**	**14[1]**	**51[1]**

[1] Rautaruukki funded the additional part of the fatigue tests (two man-months)

17.9 PUBLICATIONS

The project results will be presented in four publications in laboratory series, in two conference papers and in two articles in international journals. Some of the publications are not yet finished and these will be published during this year 2003. Additionally, the project results form the basis of the doctoral dissertation manuscript to be completed in 2004. The scientific publications are presented below.

17.9.1 *Articles in international scientific journals (referee)*

Remes, H, 2004. Application of notch stress methods to estimation of fatigue strength of $C0_2$-laser welded material. (To be published)

Remes, H, 2004. Experimental and theoretical analysis of fatigue characteristics of $C0_2$-laser and $C0_2$-laser MAG hybrid welded butt and T-joints. (To be published)

Gripenberg, H. 2003-2004. A study of cyclic stress-strain response and residual stress changes in the base and weld material in shipbuilding steels. (To be published)

17.9.2 *Scientific monographs published in Finland*

Remes, H., 2004. Modelling of fatigue strength of laser welded joints. Helsinki University of Technology, Ship Laboratory, Doctoral Dissertation. Espoo, Finland. (To be published)

17.9.3 *Other scientific publications*

Laitinen, R., Kujala P., Remes H., Nielsen, S.E., 2003. CO_2-laser MAG Weldability of Laser Cutting LASER RAEX Steels, Hull Structural Steel Grade A and High Strength Formable Steel

OPTIM RAEX 700 MC. To be published in Proceedings 9th NOLAMP Conference, August 2003. Trondheim, Norway.

Gripenberg, H., 2003, A Study of Submerged Arc, Laser and Hybrid Weld Properties, Residual Stresses, CSS-Curves and Fractography, TKK-MTR-2/03, Helsinki University of Technology, Laboratory of Engineering Materials, 62 p.

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Remes, H., 2003. Fatigue test of $C0_2$-laser, $C0_2$-laser hybrid and submerged arc welded butt joint of RAEX S275 LASER and NVA. Volume 1 and 2. Helsinki University of Technology, Ship Laboratory, Research Report M-278. Espoo, Finland. 97+201 p.

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18 HIGH POWER DIODE LASER HPDL IN COATING AND SURFACE TREATMENT

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ABSTRACT: High Power Diode Lasers (HPDL) are the latest developments of laser equipment suitable for laser materials processing, including hardening, cladding and welding operations. A research project entitled "High power diode laser HPDL in coating and surface treatment" was performed in during 2000-2002 as a TEKES and industry funded project and as a part of the TUKEVA Programme. In the project a 6 kW HPDL system was installed in Laser Application Laboratory (LAL) of Tampere University of Technology. The HPDL equipment was used to study high-rate laser coating and hardening processes. The coatings manufactured by HPDL coating were thoroughly characterised and evaluated with their technical properties. HPDL coating was found to be a highly potential surface coating and hardening process for future industrial manufacturing.

18.1 INTRODUCTION

High power diode lasers (HPDL) represent the latest developments of high power laser equipment which are highly suitable for laser materials processing including heat condution welding, soldering, hardening, heat treatment and coating (cladding). HPDL equipment are based on high number of low power single semiconductor laser components, which are coupled together by special optical elements to provide high level of laser power from some ten watts up to several kilowatts. The advantages and disadvantages of HPDL in comparison to conventional lasers are as follows:

- operation at low wavelengths (0.8-0.94 μm), which increases absortion of the laser energy to common metals making the process more efficient vs. conventional CO_2 lasers
- high efficiency (30-50%), which enables the use of small sized power supplies and cooling devices
- small size laser source, which allows handling by industrial robots
- high level of power (6 kW) resulting in high power density
- HPDL possesses lower beam quality (beam-parameter-product), which limits its use in cutting, marking, drilling and deep penetration welding; however, low beam quality is not regarded as a drawback im hardening and coating
- reactangular beam geometries available, which make them suitable to hardening and coating processes
- low investment and operation costs, which is expected to increase the acceptance of HPDL based processes, such as coating and hardening, by manufacturing industry in the future.

In order to investigate the novel HPDL technology, its applicability to modern surface engineering purposes, and to evaluate the technological paramemeters and properties of coatings and surfaces prepared by HPDL based processes, a research project "High Power Diode Laser (HPDL) in Coating and Surface Treatment" was performed during the period of 1.9.2000 – 31.10.2002. The project was funded by the National Technology Agency of Finland TEKES, and by a group of Finnish industrial companies. Although the project was not funded by the Academy of Finland, it was agreed by these two funding organisations to be part of the TUKEVA technology programme.

This final report descibes the objectives of the "HPDL coating" project and the main scientific and technological results achieved.

18.2 OBJECTIVES

The aim of the research project was to transfer and develop the newest technology of high power diode lasers for use first in research laboratory so that the technology can next be adopted by industry in Finland. The primary focus of research was to use HPDL technology in laser materials processing, especially in surface engineering such as laser cladding and laser transformation hardening. Also laser welding was of interest to some extent. The aim of the project could be divided into the following sub-objectives:

- the use the latest technology of high power lasers, especially HPDL, for laser materials processing, especially for surface engineering (cladding, hardening)
- to develop the laser cladding technology and methods for high-rate surfacing
- to study and develop HDPL cladding and hardening process for selected industrial use and applications with some industrial cases
- make HPDL technology and its latest developments more familiar to industrial companies in Finland; to increase industrial use of HPDL technology
- to establish contacts and collaborative networks with other national and international universities and research laboratories.

The research was divided into four work packages, which were:

- Study of the basic operation parameters and performance of HPDL in practice, and integration of HPDL with an industrial robot; modelling of the laser materials processing cell; safety system
- Properties of HPDL equipment technology from the point of view of laser cladding and hardening; off-line programming of the laser cladding and hardening procedures; development of a fully automated laser materials processing system
- Development of sophisticated application pinciples and methods for the feedstock material, typically for powder
- Investigation of the structure and properties of coatings and surfaces manufactured by HPDL; selected industrial case studies are included in the project.

18.3 RESULTS AND ACHIEVEMENTS

HPDL Laser Coating

Laser cladding, over recent years, has generally only been carried out using CO_2 and Nd:YAG lasers. The major drawback with these types of laser cladding systems is their low deposition rates when compared to competing non-laser techniques such as PTA (Plasma Transferred Arc) and TIG (Tungsten Inert Gas) weld overlay processes. This has meant that laser cladding has generally been limited to small-scale repair work, since the laser at focus is usually restricted to only a few millimetres in diameter. However, advancements in the area of the high power diode laser (HPDL) means that HPDL units, delivering large rectangular beams, can also be utilised for laser cladding.

Laser Application Laboratory at Tampere University of Technology is a co-operation unit of the institutes of material science and production engineering. The most important research topics are laser hardening and coating, both processes especially with HPDL, for large surface areas. Research topics cover all areas of surface treatment processes from material properties to developments of equipment and system integration into industrial applications. LAL uses two high power lasers for various laser materials processing purposes. A general view of the laboratory is presented in Figure 1.

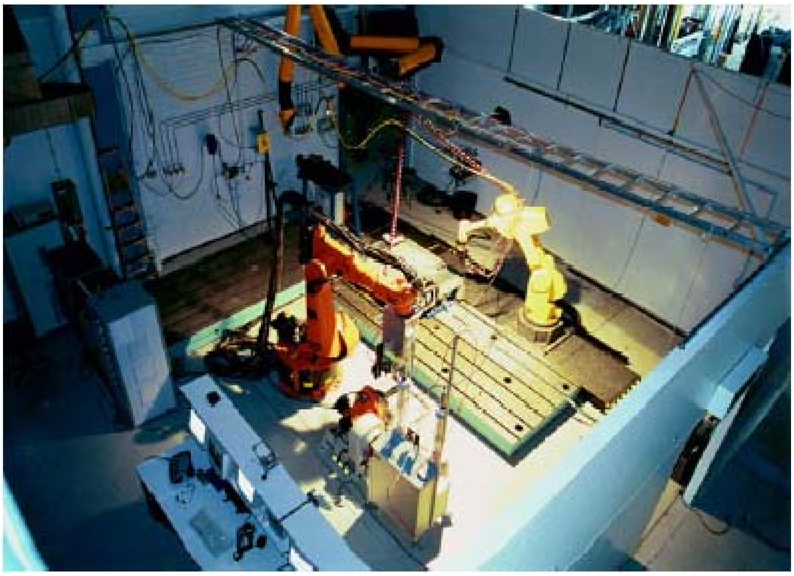

Figure 1. Laser Application Laboratory equipment.

The introduction of HPDL lasers, with wide rectangular focal spots, to the laser cladding world has opened up a whole new possibility to produce special purpose coatings at similar deposition rates as competing conventional non-laser technologies. LAL has developed an advanced laser coating technology, which is based on using a 6 kW HPDL laser system, an industrial robot, computer controlled powder feeder unit and special powder feeding principles.

All used equipment in different surface treatment processes are fully integrated with industrial robot controller. Use of robust industrially approved equipment, helps the transfer of processes and result into actual production environment. All process parameters can be controlled via robot user interface and programs. For repeatability and traceability of the results most of the important parameters are monitored and recorded into different databases.

Real life components are usually very complex in shape. For efficient processing, system setup and programming time should be as short as possible. For succesfull test layout building and shorter robot programming time, simulation methods are usually used from the early stages of projects. Hence actual test setup and robot programming time can be considerably reduced. Same software can be used for both layout design and robot off line programming, as shown in figure 2.

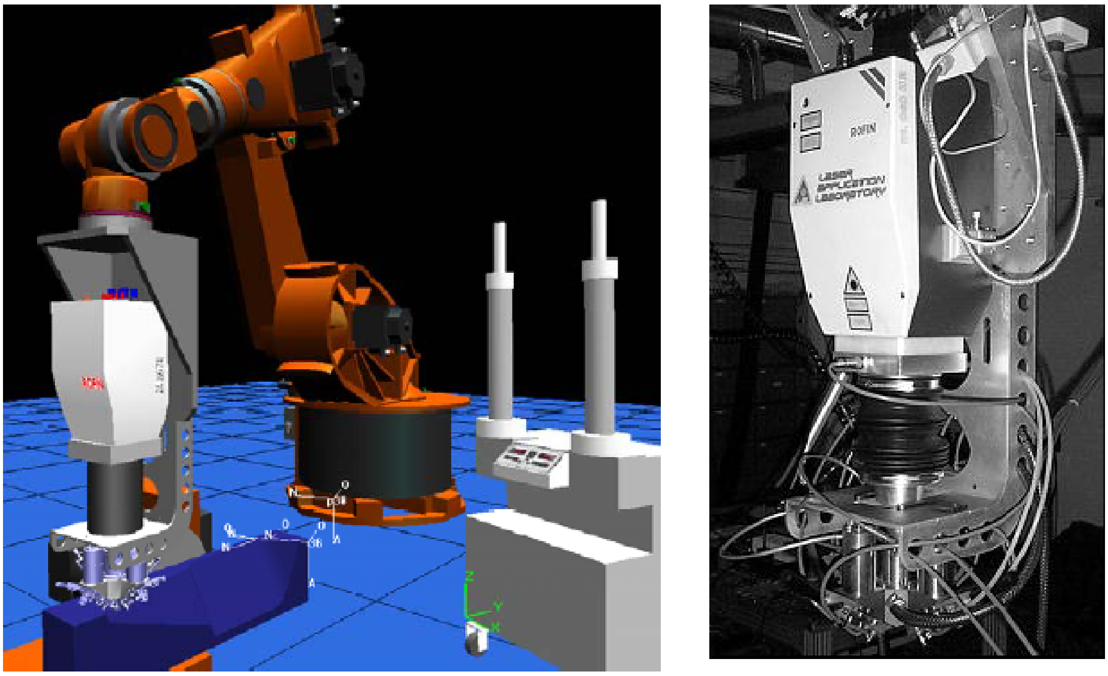

Figure 2. Simulation model of laser cladding process, multifeeder nozzle with 6 kW HPDL

One of the recent research subjects at LAL was to design and develop a coaxial blown powder feeding nozzle for use with a 6 kW Rofin-Sinar high power diode laser (HPDL). The laser was capable of delivering wavelengths of 808 and 940 nm, and gave a combined power of 6 kW, with the beam converging to a rectangular spot size of around 21 x 5 mm at focus. The working distance is quite large at around 445 mm. Different features of the nozzle have been carefully tested and analysed. Tests have proved that reaching high powder feed rates (e.g. <100 g/min for 20 mm wide beam) is easily within the working range of the nozzle.

A number of overlapping tracks were produced as continuous spiral on rods of Fe52 steel, which had a diameter of 49 mm and length of 500 mm. The area to be coated was 300 mm in length in the centre of the rod. One-step laser cladding of the rods was carried out using 6 kW HPDL and CO_2 lasers. Diode laser was equipped with off-axis and multi-feeding powder nozzles, which directed the powder stream to approximately rectangular laser beam spot of 22 mm x 5 mm on the workpiece. A cobalt alloy Stellite 21 in a powder form was used as the cladding material. As laser-clad coatings, it is widely used in power generation applications against sliding wear and cavitation erosion.

Table 1. Laser cladding parameters used in multi-feeder and off-axis HPDL cladding processes to produce different coating thicknesses.

	Multi-feeder			*Off-axis*		
Coating Thickness	0,5	1	1,5	0,5	1	1,5
Power (kW)	4.8	4.8	4.8	4.8	4.8	4.8
Powder feed rate (g/min)	79	91	106	89	91	98
Surface speed (mm/min)	500	400	380	450	400	330
Shield gas Ar (l/min)	50+30	50+30	50+30	50	50	50
Overlapping (mm)	10	10	10	10	10	10

Laser cladding experiments performed by multi-feeder nozzle exhibited stable and calm cladding process resulting in good surface appearance as shown in Fig 3. Only a slight amount of oxide layers was observed on the top of coatings. In contrast, off-axis cladding process exhibited plenty of sparks.

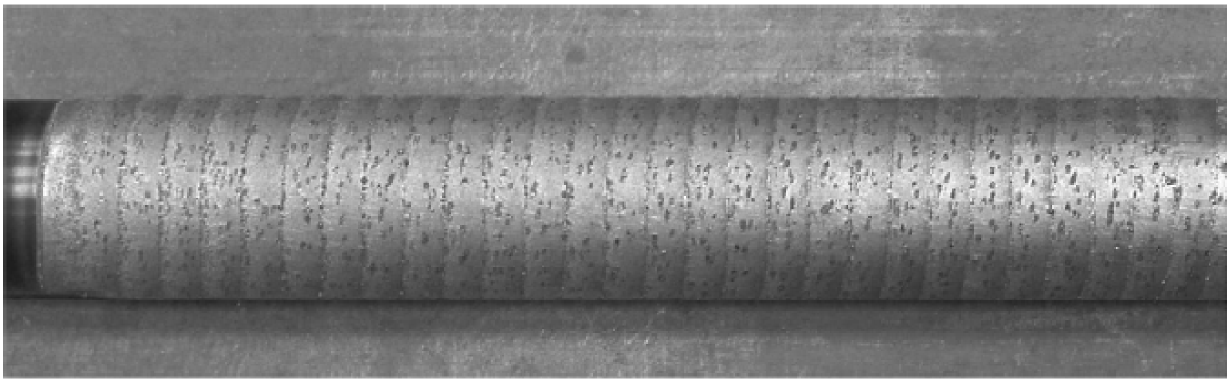

Figure 3. Stellite 21 coating on Fe52 rod produced by multi-feeder HPDL cladding technique.

Both powder-feeding techniques produced relatively high heat input into the workpiece. Heat-affected zones were in the range of 1.9 – 3.4 mm. On the basis of cladding experiments carried out here it can be concluded that high thermal load originates mainly from the relatively high amount of melted coating material on the base material. The effectiveness of HPDL laser cladding was tested against commercial coaxial CO_2 laser cladding (Table 2). Massive components, which weigh several hundreds of kilos or tons and where areas to be coated are several square meters, can be laser-clad 4 – 5 times faster with HPDL compared with CO_2, which are used today. When the deposition efficiencies of different cladding techniques are taken into account deposition rates are 4.7 – 6.7 times higher in multi-feeder HPDL cladding than in coaxial CO_2 cladding reaching the levels used in PTA welding.

Table 2. Technological and economic aspects of multi-feeder HPDL cladding technique compared to commercial coaxial CO_2 cladding technique. Laser power in CO_2 and HPDL experiments was 4.7 and 4.8 kW, respectively. The 0,5mm HPDL coating was laser-clad using two main powder-feeding units. The1,5mm thick coating was laser-clad using two side feeders and one main (leading) feeder.

	CO_2	CO_2	HPDL	HPDL
Coating thickness (mm)	0,5	1,5	0,5	1,5
Cladding speed (m^2/h)	0.075	0.042	0.30	0.23
Deposition rate(kg/h)	1.0	1.9	4.7	6.4
	0.44*	0.72*	2.07*	3.97*
Catchment efficiency %)	44	38	44	62
HAZ (mm)	0.9 – 1.4	1.1 – 1.7	1.9 – 2.6	2.3 – 3.4

* Deposition rate when powder catchment efficiency is taken into account

Laser coating applications include new production, spare part manufacture and as well as maintenance and repair of worn components and equipment. Laser coatings are used to produce surfaces which are resistant against abrasive, erosive and adhesive wear, wet corrosion, high temperature oxidation and corrosion, etc.

Twin-HPDL hardening

This case demonstrates a preliminary hardening test of large ring gear. The aim of the project was to explore the possibility of using two direct high power diode lasers to harden gear teeth. To achieve the required properties against wear and effects of high localised stress, the gear tooth profile needed to be hardened with one laser pass. A suitable hardening pattern could be achieved using two separate beams simultaneously, both directed at each side of the tooth profile at a specific angle.

Suitable parameters for tooth profile hardening were tested for both used lasers individually. For optimal hardening pattern, thorough beam analyses were completed. Results of the analyses are shown in figure 4.

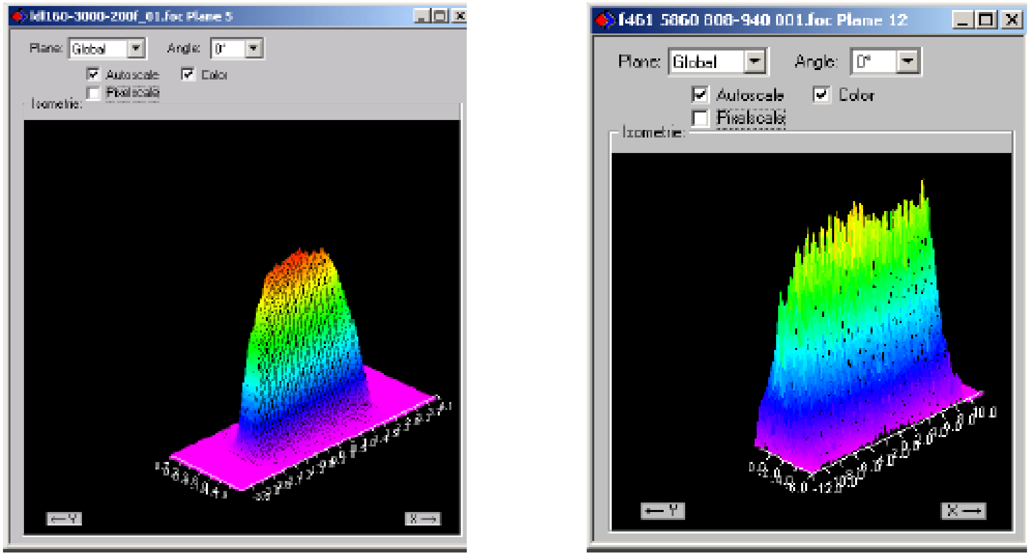

Figure 4. Intesity profiles of used 3 kW and 6 kW lasers.

Beam spot sizes used in hardening were approximately 21 x 5 mm for 6 kW laser and10 x 5 mm for 3 kW respectively, both sizes were measured with 86% of total beam power. Ideal beam width for this particular profile would have been 16,5 mm. Test were nevertheless completes since the main concern was more on the hardening profile at the groove bottom than teeth sides. Optimal beam alignment was tested with samples having the same profile and same material 42CrMo4VIT as the actual ring gear. Workpiece was pre heated since it was shown to increase the hardning depth by 200% in some cases. Hardening depth of 1 mm could be achieved in all areas of the tooth profile, using approximately 20 + 20 J/mm^2 specific hardening energy.

Test setup design was done using robot simulation software. Method turned out to be very useful. 3-D model of the test setup, illustrated in figure 5, was utilised in design of laser mountings as well as optimal robot motion planning. Since the hardening parameters require lasers to move very near to the ring gear, collision detection was also performed.

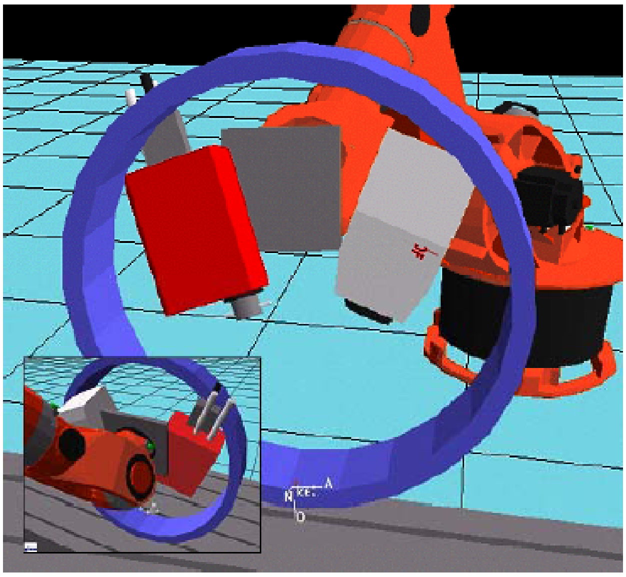

Figure 5. 3-D simulation model of the test setup.

Designed laser mounting plate was used to connect the lasers to an industrial robot arm. Lasers were aligned so that both beams were focused in a right angle at the teeth groove bottom. Ring gear rotation was arranged with a separately controlled servo roller. The beam alignment is very sensitive, hence a machine vision system was utilised to control the rotation of the gear ring. To maintain constant pre heating temperature, heating elements were used during the whole process.

Figure 6. Ring gear hardening test setup.

Completed tests and done cross sections, shown in figure 7, showed that hardening depth of 1 mm can be achieved on all functional surfaces when using correct pre heating and laser beam parameters.

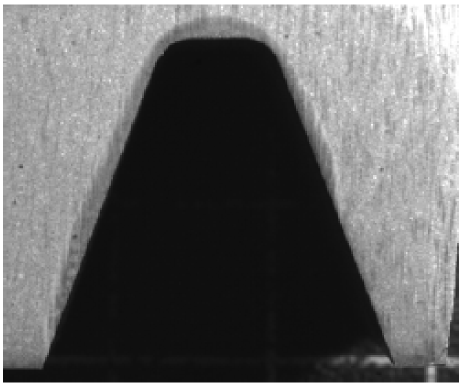

Figure 7. Gear groove cross section.

18.3 FUTURE ACTIVITIES

In summer 2003, Tampere University of Technoloy and Central Ostrobothnia Technology Centre Ketek have started a joint research project with a total budget of 560 00 EUR. The project is funded by Tekes and 8 industrial companies. The work consists of several work packages, which are: 1) laser coating process study, 2) novel coaitng materials by laser coating, 3) laser assisted thermal coating process study, 4) acceptance criteria for industrial laser coatings, and 5) industrial use of advanced laser coatings. The project will run till tye end of year 2005. Other international projects are under contract negotiations and proposal stage.

18.4 PARTNERS

The research performers were the Institute of Materials Science and the Institute of Production Engineering, both from Tampere University of Technology. Industrial partners were Metso Automation Oy, Metso Powdermet Oy (representing also Metso Paper Oy and Metso Engineering Pori Works), Andritz Oy, TTT Technology Oy and Kemira Pigments. External research collaborator was Central Ostrobothnia Technology Centre KETEK's Laser coating r&d unit LaserCo.

18.5 BUDGET AND SCHEDULE

The final total budget of the project was 340 434 0 €, of which TEKES (National Technology Agency of Finland) funding was 252 282 €, funding from industry 67 275 € and own funding 20876 €. The costs were distributed as follows: labour costs 213 269 €, travel costs 19 614 €, consulambles 25 337 €, equipment 72 467 € (including part for the HPDL equipment), external services 9 652€, and other costs 96 €. The project started on 1.9.2000 and ended on 30.10.2002.

18.6 CONTACT ADDRESS

Tampere University of Technology, Laser Application Laboratory, P.O.Box 589, FIN- 33101 Tampere, Finland. Resposible persons in the project were prof. Tapio Mäntylä (responsible project leader) and prof. Petri Vuoristo (project manager) from the Institute of Materials Science, and Mr. Jorma Vihinen (subproject manager) from the Institute of Production Engineering.

18.7 PUBLICATIONS

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J. Latokartano: "Robotised Hardening of Large 3-D Areas", CD-ROM Proceedings of ICALEO 2001, October 15-18, 2001, Jacksonville, Florida, USA, Published by Laser Institute of America, 2001.

J. Tuominen, M. Honkanen, J. Hovikorpi, J. Vihinen, P. Vuoristo, T. Mäntylä: "Corrosion resistant nickel superalloy coatings laser-clad with a 6 kW high power diode laser (HPDL)" International Congress on Laser Advanced Materials Process-ing, LAMP 2002, May 27-31, 2002, Osaka, Japan, paper 2210.

J. Tuominen, J. Laurila, J. Vihinen, P. Vuoristo, T. Mäntylä, L. Olaussen and T. Peltola: ”Comparison of CO2 and High Power Diode Laser (HPDL) Cladding”. Proc. 21st International Congress on Applications of Lasers & Electro-Optics – ICALEO 2002, October 14-17, 2002, Scottsdale, Arizona USA (CD-ROM proceedings).

P. Hayhurst, J. Tuominen, P. Vuoristo and T. Mäntylä: ” Coaxial Laser Cladding Nozzle for use with a High Power Diode Laser”. Proc. 21st International Congress on Applications of Lasers & Electro-Optics – ICALEO 2002, October 14-17, 2002, Scottsdale, Arizona USA (CD-ROM proceedings).

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Note: detailed scientific results are presented in the journal and conference papers.