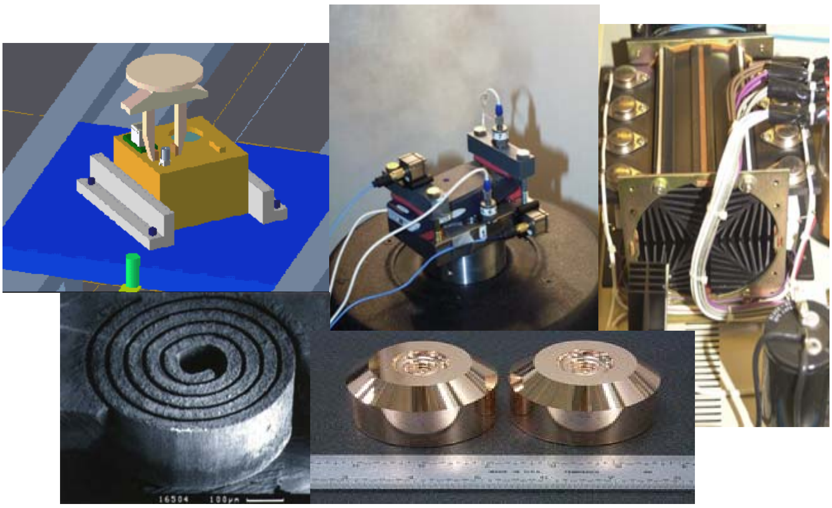

Mechanics for Electronics

VTT Research Programme 2000–2002

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Otamedia Oy, Espoo 2002

Preface

This publication documents the papers to be presented at the “Mechanics for Electronics” seminar to be held on 4 December 2002 in Otaniemi, Espoo. The seminar presents the main results of a research programme (2000–2002) organised and funded almost exclusively by the Technical Research Centre of Finland (VTT).

The aim of the research programme was to develop at VTT new research capabilities related to mechanics for electronics and so to strengthen the possibility for VTT to serve its customers in the field of the programme. The programme included five projects and a number of technology reviews. Three of the projects lasted three years and one project two years. The fifth project was linked to the programme within the last year and will continue into 2003.

In the project titled ’Assembly of mechanics for electronics’, the assembly of small-sized parts was developed. The framework that was created includes different methods and tools and helps the product designer to analyse the product design from the standpoint of assembly, manufacturing, and controlling of accuracy.

In the ’Thermal management materials in electronics’ project, new materials were applied to address issues of thermal management of electronics. Through the use of gel-like, easily-mouldable materials, the heat generated in electronic components can be dissipated in an effective way. Ceramic coatings were developed to meet the requirements of power electronics.

The third project focussed on development of procedures aimed at meeting the prerequisites of laser processing research services for the electronics industry. The processes developed and expanded include manufacturing of small parts, the welding and material removal of polymers and other non-metals, accurate cutting, drilling, material removal of printed circuit boards and other components, and laser-assisted assembly.

The objective of the fourth project was to provide the electronics industry with tailored and accelerated shock and vibration testing services. Also, NDT activities were further developed in order to better satisfy the needs of the Finnish electronics industry.

In the project called ’Micromachining’, the aim is to further develop the machining of small components and details. The work is focused on tools for injection moulding. This project, partly funded by the National Technology Agency and carried out in co-operation with the Injection Moulding and Tooling Engineering Centre, will continue in 2003.

Espoo, November 2002 Pentti Eklund

Contents

Tolerance analysis in assembly of mechanics for electronics

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Abstract

Assembly is more than putting parts together; it can be seen as a product and a process. In this article, the focus is on assembly modelling, product level dimensional variation analysis and automated assembly process tolerance analysis. Dimensioning philosophy and the choice of tolerances is a function of design, which affects not only the product 's function and performance but also its manufacture and assembly. Tolerances constrain affect ease and the sequence of assembly, determining the specifications of assembly technology such as jigs and fixtures, assembly machines, robots, and grippers. In robotic assembly, the different schemes for accomplishing a task may have different success rates depending on what mechanical accuracy or force levels are involved or how sensitive the technique is to small errors in how the parts were made. Parts, fixtures and other equipment vary in size and position. These variations can mean that the robot will assemble one set of parts perfectly, yet will create assembly error with another set. To ensure that parts are loaded and assembled reliably, without misfits, a tolerance study must be done. The authors shall review the importance of tolerance analysis in assembly, product and process development. Different tolerance analysis methods and types of tools exist and are shown in the paper. This is an introduction, a current state review of tolerance analysis and a feasibility study of potential method and software to be used in the tolerance analysis for the precise assembly of electromechanical products.

Keywords: Tolerance analysis methods, assembly modelling, assembly process and equipment design, digital plant technologies.

1. Introduction

Complex products with short life cycles are produced on a global market under high competitive pressure. High quality and short production start-up time is critical for business success and is achieved by robust concepts. The life cycle of a typical consumer electronics and telecommunication device is less than a year. The functional density of the products increases and thus miniaturisation of mechanical subcomponents is a must. This leads to increased precision requirements.

No manufacturing process can produce parts with exact dimensions. The allowable variations or tolerances must be specified by the designer, with the following objectives:

- to ensure fit and function
- to minimise manufacturing cost
- to maximise assembly friendliness.

It has been estimated [1] that 30% to 50% of scrap and rework is caused by poor tolerancing. In high-volume industries, such as the automotive industry and consumer electronics, scrap and rework are caused not only by poor tolerancing, but also by process variation. In production lines, dies and fixtures wear, and other changes occur in the process, eventually leading to a poor product.

One of the main problems in the application of industrial robots in assembly is in accommodating the lack of precision resulting from tolerance build-up between parts, fixtures, tooling and manipulator repeatability, and the lack of good product design for assembly. A number of different approaches have been employed to compensate for this lack of precision ranging from the development of mechanical passive compliance devices, active sensor-based compliance devices, or hybrid devises incorporating both mechanical and sensor-based elements. [2]. This paper presents a design approach for the problem.

It is a myth that if a part is manufactured within a prescribed specification (tolerance limits), it will turn out to be a good assembly at the end. Though it is a good practice to specify a tolerance range for the parts, tolerance stack problems will obviously occur as parts are assembled into components, components into subsystems, and subsystems into a system. In some cases, stacked tolerances may cancel out, while, in others, they may build up (cumulative). The greater the degree of complexity in the assembled system, the greater the possibility that the parts will be difficult to assemble. The resulting assembled product may fail to meet product specifications, even though each individual part is good, i.e. each part falls within an acceptable tolerance range. Tolerances contain the vital data concerning how far a part can deviate from the ideal and still be both functional and interchangeable. Determining appropriate tolerances for parts is a challenging design task. Errors in many assembled parts interact to produce the final state of assembly and operation. Tolerances that are too loose risk failure of the assembly, while tolerances that are too tight unnecessarily increase manufacturing costs.

2. Tolerancing

The final geometry of a product fulfils the product mission by realising its main functionality. The final geometry also has a great impact on, and is affected by, the way the product is to be produced. Often, the engineer must consider the relevant dimensions and tolerances on a mate-by-mate basis for the nominal design and nominal assembly sequence, assuming reasonable fixturing where appropriate. This is clearly a concurrent design issue in the sense that design, manufacturing, assembly, quality control, and cost accounting interests are each involved [3].

Design engineers are typically responsible for the general and detailed shape, functional analysis, dimensions, and tolerances of parts and assemblies. Manufacturing engineers are typically responsible for making the parts and are knowledgeable regarding manufacturing costs for different processes and tolerances. Assembly engineers are responsible for the general and detailed specification of the assembly system and choices of assembly technology. All are responsible for calculating the cost of making the product [3].

Dimensioning philosophy and the choice of tolerances is a design function, which affects not only the product's function and performance but also its manufacture and assembly. Tolerances constrain feasible methods of manufacture, strongly influence cost of manufacture, affect ease and sequence of

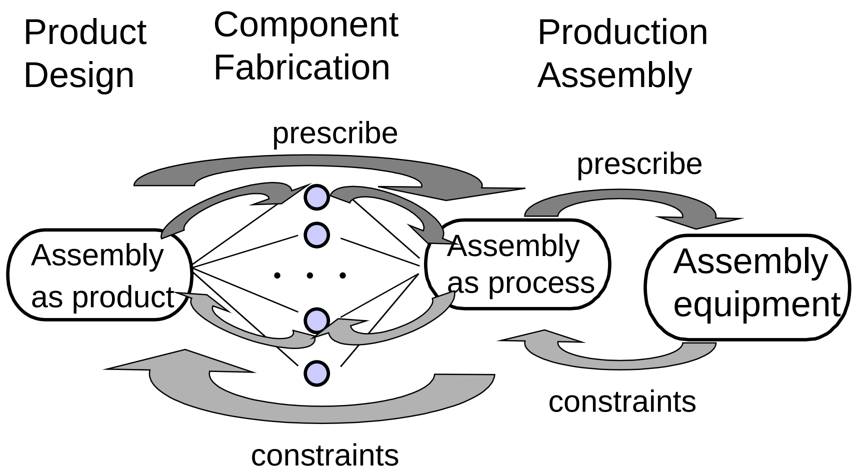

Figure 1. Assembly as product and process.

assembly, and determine the specifications of assembly technology such as jigs and fixtures, assembly machines, robots, and grippers. (Fig. 1). Each engineering department must have a common language. Visualisation, modelling and simulation are technologies for improving communication.

The effects of tolerancing are far-reaching; it is a concurrent design issue. At the earliest possible stage, tolerance analysis should be done, i.e. the use of assembly modelling and virtual design technology, digital mock-ups and virtual prototypes combined with tolerance analysis methodology. The aim is to eliminate unfeasible design solutions before building many prototypes or 0-series. This is especially true in mass production and robotic assembly. Tolerance simulation and variation analysis is the technology that has been used by the automobile and aviation industry; now this technology is applied to other industry branches, like consumer goods, as well.

Figure 2 shows the potential of virtual prototyping and digital plant technologies in the design of assembly products, process and equipment. More detailed information about virtual prototyping can be found from [12].

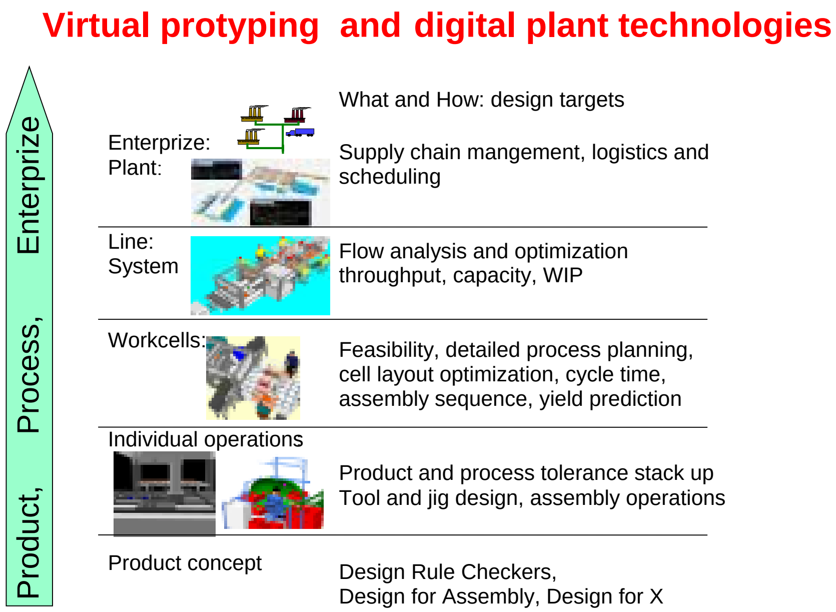

Figure 2. Virtual protyping and digital plant technologies for design.

2.1 Current practise in tolerancing

Traditionally, the design engineer assigned tolerances to component parts just before releasing the drawing. The values of the tolerances were based on past experience, best guess, or anticipated manufacturing capability. In some cases, a 1D tolerance stack was performed to determine if an assembly limit would be exceeded when adding the tolerances in any given 1D direction. This approach is still common in many engineering organisations today [4].

Traditionally, a designer makes decisions regarding type and magnitude of the tolerance not only on the product's form and shape, but also on several other factors, such as material properties, manufacturing capabilities, assembly and operating conditions, inspection and maintainability. The engineer uses a variety of sources in the decision-making process: handbooks and standards, numeric analyses, company policy, common practices and rules of thumb, personal intuition, preference and experience.

Today, a number of commercial CAT (Computer Aided Tolerancing) tools are available that can assist in predicting and avoiding geometrical problems that are related to geometrical variation. These tools are most often used too late: when CAD models have already been developed and when real manufacturing data is available, i.e. the concept is almost ready and the processes are known. A design change at this stage is often quite costly. [5]

2.2 Variations in assemblies

Geometrical variation in assembly product results from a number of different sources, design, part fabrication or assembly process. The result of these variations can be found as fit-up problems during assembly.

Variation contributors may be divided into three groups [6]:

1. The design concept itself, which may, if not optimised with respect to geometrical robustness, require unnecessarily tight tolerances and expensive manufacturing processes.

2. Variation in individual component geometry, resulting from machine precision and process variation over time.

3. Variation in the assembly process, related to the way that parts are assembled, which also may vary over time.

The three sources of variations are dimensional, geometric and kinematics [7]. Dimensional variations account for small changes in size due to manufacturing processes. Geometric variations describe the changes in shape, location and orientation of features. Kinematics variations describe the propagation of variation through an assembly by small adjustments between mating parts.

2.3 Tolerancing assemblies

The dimensioning and tolerancing issues associated with assembly are different from those associated with single parts considered individually. Multiple dimensions are involved, including translations and rotations and geometrical shapes. Dimensioning and choosing tolerances for successful assembly involve these issues [3]:

1. The analysis of dimensions, tolerances, and clearances of pairs, sets, or multiples of parts. The analyses must consider the relative positions representing approach, contact, partial engagement, and full engagement of one part to another or others.

2. The order or sequence of assembly.

3. An analysis of tables, jigs, fixtures, assembly machines, or robots as well as the set of multiple parts.

4. Choice of assembly technique.

The activity of assigning proper tolerances does not solely concern the design phase. Decisions are based on, and affect a number of downstream activities [3].

- At the design stage, product requirements are broken down into component requirements, datums and locators are chosen, tolerance analysis is performed and final tolerances are selected with respect to expected process variation and manufacturing cost.

- During manufacture, component datums and locators are manufactured and used. Process variation is controlled over time by statistical process control (SPC).

- At the part inspection stage, inspection is prepared by selecting measuring points and measuring methods. Components are then inspected and evaluated against tolerances on individual features, and results are saved for future use. During inspection, component datums are used for location.

- At the assembly stage, component datums and locators are used for locating components in assemblies, with or without assembly fixtures.

- At the final inspection stage, sub-assemblies and final products are inspected and evaluated against overall product requirements. Assembly strategies are evaluated, and root cause analyses are performed to track errors in the assembly process.

2.4 DFA

Design for Assembly (DFA) is focusing on the assembly friendliness and product evaluation. The selected tolerance values on part or the chain of tolerances on product level are evaluated during the DFA-index calculation [13], but current DFA methods do not make any tolerance or variation analysis (Fig. 3). The aim in product level is to eliminate the tolerance chain.

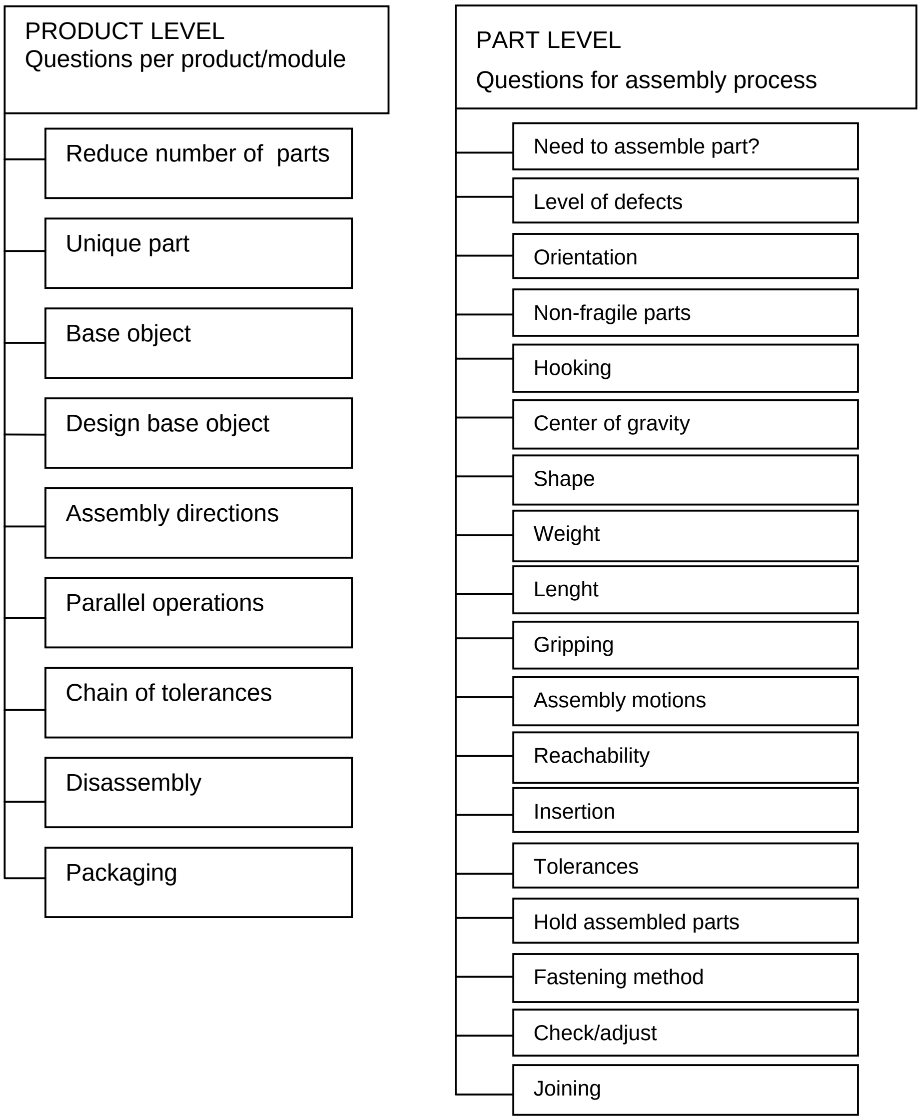

Figure 3. Design for Automated Assembly Overview [13].

3. Tolerance analysis

3.1 Tolerance analysis methods

Important methods for tolerance analysis include: worst-case tolerancing; linearisation (or root sum of squares); extended Taylor series; numerical integration based on quadrature techniques; and Monte Carlo simulation. A common approach to tolerance synthesis is to use tolerance analysis in an iterative way; thus, all tolerance analysis approaches become relevant for tolerance synthesis. Other methods for synthesis include mathematical programming and heuristic optimisation techniques; and the design of experiments [8].

Both worst-case tolerancing and to a lesser extent, statistical tolerancing, are currently practised in industry. Worst-case tolerancing involves establishing the dimensions and tolerances in such a way that any possible combination will produce a functional assembly; i.e. the probability of non-assembly is identically equal to zero. Consequently, worst-case tolerancing can lead to excessively tight part tolerances and hence high production costs. Statistical tolerancing is a more practical and economical way of looking at tolerances and works on setting the tolerances so as to assure a desired yield, accepting a small percent of non-conformance.

The current industry practice is to assign tolerances only during the late stages of design, after nominal dimensions have been fixed by designers. Many firms use Monte Carlo simulation to conduct tolerance analysis on a detailed geometric model of the product.

3.2 Tolerance analysis tools

The tools for tolerance analysis can be classified as spreadsheet type, CAD integrated or independent analysis tools. The study here is updated from [9].

Spreadsheet type tools are capable for 1D dimensional stack-up analysis. Different analysis methods are available, Worst Case, RSS (Root Sum Square), Six Sigma, Monte Carlo. The difficulty is to identify the tolerance chain, or stack-up in 2D or 3D (Fig. 4). The stacks can be solved using a spreadsheet, but the user needs to supply the tolerance sensitivities. This requires quite a lot of work, as the assembly equations must be derived for each problem, thus the number of formulae, and the possibility of errors, quickly adds up on designs that require two- or three-dimensional analysis and involve both linear and angular dimensions. Geometrical tolerance analysis is often too complicated for spreadsheet types of tools.

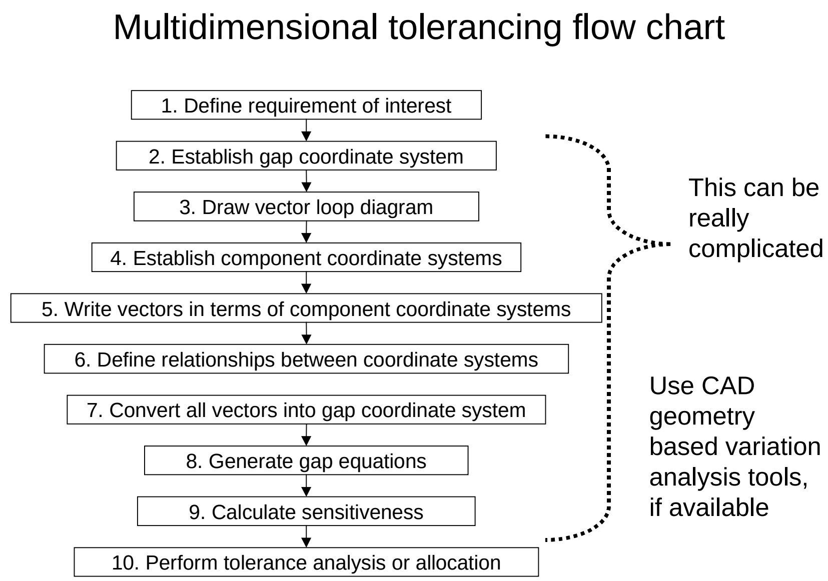

Figure 4. Multidimensional tolerancing flow chart [16].

Some CAD vendors have their own integrated tolerance analysis tools, usually to calculate linear stack-ups. Some other ones are co-operating with development partners and these integrated tools are embedded in the same CAD user interface. The independent CAT systems can be used with several CAD systems through direct and neutral interfaces. Usually, tolerance analysis is based on Monte Carlo simulation and the parts are considered rigid. The capability of neutral interfaces, like IGES or STEP, depends on translators and the capability of transferring tolerance information is limited.

There are new tools coming on the market, e.g. integrated solution for robotic system design, flow analysis, DFA and tolerance stack-up analysis. Use of this kind of sophisticated tool is presented in [9, 10]

The problem with high-end CAT analysis tools, is the expertise required for use. Thus, the area of tolerance analysis and the use of CAT systems are still limited to a small number of experts within the specific field of variation simulation. The main reasons why the technique is not yet widespread are that [6]:

- good skills in operating CAD or CAT systems are required
- good knowledge about how to apply GD&T effectively is preferred
- some basic statistical understanding is required
- good engineering and modelling knowledge about what assumptions to make in order to make the result reflect reality is needed.

3.3 Assembly modelling and tolerance decision

Current CAD systems are part-centric. One creates assembly models after completing the part design. CAD systems do not support a top-down design process. They have good drafting and 3D solid modelling capabilities. This makes them very useful for detailed part level design. However, the documentation of inter-part relationships and their management has to follow detailed part level design. One cannot design the framework of the assembly (constraint relationships among parts) in CAD before designing the actual geometry of the parts. Moreover, CAD systems do not really differentiate between part-level constraints and assembly-level constraints. [14]

Many 'assembly models' in use today contain no actual assembly information at all. Typical of these is the Bill Of Materials (BOM), which is an unstructured parts list. A structured BOM groups parts in hierarchies of subassemblies but still does not reveal which parts are connected or how. Any CAD model that places parts in a world (or absolute) coordinate system (often called digital preassembly) can make a correct-looking display of the assembly on a computer screen, but again the model contains no actual assembly information. Most CAD models are of this type, but newer ones are appearing with the ability to represent parts using part-to-part or relative coordinates. This information is typically used to animate motions that the assembly can execute. [15]

There is a need and potential for an integrated approach [8]

1. The continuous evolution of assembly structure and tolerancing information during the design process.
2. Close coupling between the design process and tolerancing decisions.
3. The availability of a variety of assembly modelling methods at different levels of abstraction and relevant for different stages of the design process.
4. The applicability of methods and best practices of design tolerancing to successive stages of the design process.

The development engineers need to generate the following information to make tolerance-related decisions:

1. rough shapes/form for the parts/sub-assemblies
2. parts list
3. parts location
4. layouts and configurations.

The information thus generated can be described in the form of a liaison diagram (relations between parts or sub-assemblies), a tree (assembly decomposition), and a partial Datum Flow Chain (DFC), functions-means tree, etc. These are used to capture whatever location logic is known at this point. Candidate layouts or configurations can be identified and represented using these models. These layouts or configurations and their related manufacturing/assembly process selection typically differ in terms of ease of tolerancing. The tolerancing considerations here are at a coarse level and may be directly influenced by customer specifications. To effect such high-level tolerancing decisions, aggregate level manufacturing process capability data will be required and is often available at this point. Simple statistical assumptions and probabilistic calculations can be used at this stage. [8]

The general aim is to make tolerance chains and stack-ups as short as possible. The engineers need methods to identify the tolerance chains in the product architecture creation phase, even if the detailed geometry does not exist.

It is question of information modelling combined with CAD geometry or without CAD geometry. The point is to be able to model the product's hierarchical structure down to the feature level and tolerance information. It is as important to be able find out the relations (potential tolerance chains) between the part, features and tolerance information, which mate or contact surface is related to other parts. The key factor here is find the potential tolerance chains and to be able to evaluate their effects.

One of the key factors in bringing the tolerance design to the pre-CAD design phases is suitable assembly modelling method. the availability of a variety of assembly modelling methods at different levels of abstraction and relevant for different stages of the design process is listed here. Potential assembly models and representation:

- Relational models; undirected graphs, liaison diagrams, assembly graph,…
- Hierarchical models; trees
- DFC; directed acyclic graphs
- Object-oriented models; object diagrams, multigraphs, function-means tree, design structure matrix, (axiomatic design), information modelling methods, object-oriented modelling, UML, entity-relationship models, network diagram, precedence diagramming method, arrow diagramming method, other network modelling tools
- CAD models, functional CAD models.

3.4 Functional Assembly Model

Assembly process sequencing will often have a significant impact on the total variation in any given part stack-up. The effects of gravity, part clamping forces and directions, as well as the selected locating points, surfaces and features (datums and subdatums) should be analysed.

With CAD-integrated tolerance analysis software or independent 3D variation analysis, the engineer can build a functional assembly model. Functional assembly model is more than a nominal assembly; a complete functional assembly model describes the order in which components are assembled, the mating surfaces used in the actual assembly process and the measurements used in the inspection process.

The complete model captures the assembly sequence, order (process tree) and assembly operations, using the features that are actually used in the assembly process – not just any feature that will put the component in its proper nominal position – the order that features are located (primary, secondary and tertiary locating features). Measurements are defined between components to reflect the actual inspection process and to enable the evaluation of the design.

4. Tolerance analysis for automated assembly

Assembly is more than putting parts together. Any time a part is designed, the accuracy of its manufacturing must be specified. Some of its surfaces are important to its function, so the designer assigns tolerances to them for this purpose. However, grip and jig surfaces deserve to be toleranced as well so that assembly can take place with the confidence that the parts will mate properly. Thus, the designer must see that the surfaces on which one part rests and the other is grasped are made accurately enough. Depending on the assembly sequence, the resting and grasping surfaces will be different. In addition, sequence issues highlight assembly machine and tooling design problems, such as part approach directions, tolerance build-up due to prior assembly steps, access for grippers, stability of subassemblies, the number of tools needed, tool change requirements, etc. This means that the product and parts designer must know the assembly sequence very early on in the design process. The assembly process prescribes the equipment and set constrains to product design (Figs. 1 and 5).

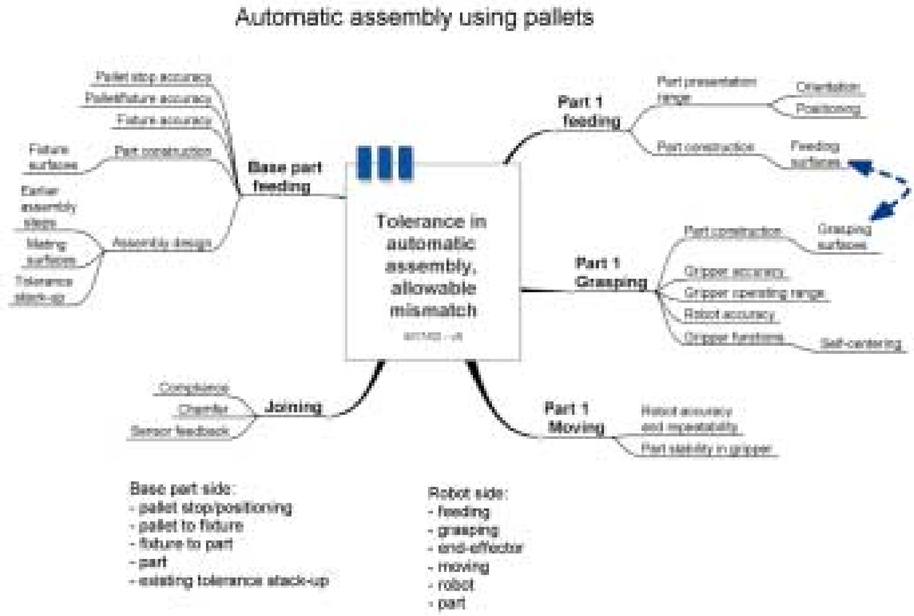

Figure 5. Overview of automated assembly.

The steps before actual joining are important as well, especially in automated precision assembly. These steps can affect the success of the assembly task. In automated assembly, the following process steps – part feeding, part positioning and orientation, part grasping and transfer before actual joining process – have their own variations. Parts and loading fixtures always vary in size and position. These variations can mean that the robot will assemble one set of parts perfectly, yet will have assembly failure with another set. To ensure that parts are loaded and assembled reliably, without misfits, a tolerance study must be done for each handling operation.

To perform a simplified tolerance study, solve the robot-side tolerance and the fixture-side tolerance, then determine the allowable mismatch between the two mating sides. The sum of the robot-side tolerance plus the fixture-side tolerance must be less than the allowable mismatch [11].

4.1 Case: Pallet conveyor system

Begin with the robot-side tolerances, input part; calculate the maximum variation in position of the workpiece. Robot-side tolerances include robot repeatability, end effector (gripper) repeatability, part feeding and workpiece tolerances. Some of the process steps can cancel out earlier displacement errors, e.g. self-centering gripper or the use of sensor feedback.

Do the same for the base part and fixture-side. Calculate the maximum variation in the position of the base part. Tolerances include the repeatability of precision stops, pallets, fixtures and workpiece.

The allowable mismatch between the robot-side and the base part -side is determined by the combination of the line of sight clearance and chamfer clearances between the two mating parts and the process requirements. Line of sight clearances occur when there is no contact between the two mating parts. With chamfer clearances, parts slide on each other and self-align to mate properly. When chamfer clearances are used, both the robot and end-effector must have compliance to accommodate the shift in position of the workpiece. The robot and end-effector have some inherent compliance, making them act like springs linked in series. However, the more the end-effector is pushed to the side, the greater the force between the workpiece and fixture. If this sideways force is too high, the workpiece will bind on the fixture or fall out of the end effector. Remote center compliance (RCC) devices can provide as much as 2.5 mm compliance in the system. They make the sideways displacing force very small, thus preventing binding due to excessive force [11]. With passive compliance, the clearance ratio that was reliably assembled was 0.0002 mm with an angular error of up to 1.25 º [2].

5. Conclusions

The miniaturisation of the products increases the accuracy needs of the assembly system. In most cases, the use of a compliance device and simplified tolerance analysis for assembly process should be enough, although it depends a lot on the product and the other requirements. Good product design, DFA methodology and 3D variation analysis on the product helps. The assembly system and product designer must communicate during the parallel development. Communication between engineering departments is one of the key factors in eliminating tolerance problems.

Many consumer and industrial electronics manufactures, including cellular phone manufactures, are using tolerance analysis and simulation. This conclusion can be made by looking at a reference list of CAT tools providers, but no detail level information is available.

Designers can use calculators or build spreadsheet applications to calculate tolerance stacks. But in designs that require two- or three-dimensional analysis and involve both linear and angular dimensions, the number of formulae, and the possibility of errors, quickly adds up. Investigating design changes becomes less and less attractive, and the end result is often a rather incomplete tolerance stack analysis. Spreadsheet applications do not capture the effect of assembly sequencing.

Worst-case analysis is on the safe side, although it leads to tight tolerances and manufacturing costs could be high. In mass production, statistical methods should be used. The least-squares method is a more accurate way to determine the total tolerance error due to several individual tolerance errors. By adding the tolerance errors arithmetically, the total can be deceptively large, e.g. worst case calculation. For example, the chances of four dimensions all being at minimum tolerance size at the same time are low (assuming a normal distribution of part sizes). The least-squares method compensates for this probability factor. This method can be used, however, when the tolerance errors are normally distributed [11]. Monte Carlo simulation brings the possibility of using other distributions than the normal one in modelling.

There are lot of tools available for tolerance analysis. Some of the tools are more suitable for simpler dimensional problems, some for complex 3D geometrical variation analysis. With spreadsheet type tools, the problem is in simplifying the real problem and generating the formulae for calculations in 2D or 3D. One-D stack-ups are relatively easy. With the currently available high-end, 3D variation analysis tools, the problem is in the investment for the software and the expertise required.

It is important to analyse the whole assembly process and equipment, not just the product itself. This is extremely important in mass production with shorter life cycles. Fast ramp-up to full-scale volume production is difficult if production engineers must solve assembly problems; in addition, errors in mass production are multiplied fast.

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Thermal management materials in electronics

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Abstract

Thermal management materials are widely used in electronics to facilitate the conduction of heat from components to the surrounding area. This group of materials is very large, including, e.g., metal cooling elements, greases, adhesives, phase change materials, and elastic pads. These materials can replace other cooling techniques, such as fans. In many cases the material solution is preferred because heat conduction is a more effective way to manage heating problems than techniques based on convection.

In this research project, two material groups were chosen for development: heat-conductive gel composites and ceramic coatings. Both of these offer good heat conduction combined with electrical insulation.

Heat-conductive gels and gel composites can be applied on components and circuit boards that need cooling. Gels fill air gaps between hot components and cooling material, thus improving heat conduction.

Ceramic coatings can be used as heat-conducting and electrically insulating substrates in power electronics. These applications are extremely demanding due to the necessity of resistance against high temperatures, mechanical compression, and very high electrical resistance.

1. Background

The interest in thermally conductive application-specific materials has increased in the electronics industry. The reasons are often related to increased packing density and decreased component size. Together these cause the need to conduct excess heat away from single components or systems. In particular, materials that are electrically insulating and simultaneously effectively conduct heat would be useful in many applications. On the other hand, sometimes it is necessary to match the thermal expansion coefficient of materials to that of actual components or chips. This can be achieved with tailored composite materials. The dielectric properties of insulating materials can also be critical in high-frequency applications. Choice of the right materials is important also from this point of view. For instance, in the case of high-frequency IC circuits it is necessary to develop materials with a low dielectric constant.

Essential to heat transfer applications is the fact that heat can be guided away more effectively by conduction than by convection. This is why novel heat-conducting materials offer new possibilities for designing and miniaturising electronic devices.

2. Groups of materials

This project focused on developing materials that are electrically insulating but offer higher thermal conductivity than insulating materials conventionally used in electronics. The basis for materials choice has been the information and feedback obtained from the electronics industry. In earlier projects, polymer composites were developed. In this project, the research concentrated on thermally conductive gel composites and ceramic coatings.

2.1 Polymer composites

The applicability of polymer-based materials is often restricted by their poor thermal conductivity, which is usually two or three orders of magnitude lower than that of metals. The thermal conductivity of various inorganic fillers is typically from 10 to 100 times higher than the conductivity of pure polymers.

The heat conductivity of polymers can be increased by using heat-conductive filler materials. Conventionally, heat-conducting polymers are manufactured by adding heat-conducting fillers to polymers. The fillers may be glass fibres, silicon oxide, mica, aluminium, or copper. In more demanding applications, boron nitride, aluminium oxide, magnesium oxide, and quartz have all been used as fillers. The heat conductivity of the base polymers typically varies between 0.1 and 0.5 W/mK. Normally the heat conductivity of crystalline polymers is better than that of amorphous polymers. Thus the choice of matrix material is also important in optimising the heat conductivity of the composite material.

Thermal management materials are to be tailored to provide the best possible performance in the given application. Development in material processing and manufacturing methods for the product are essential to obtaining competitive products.

The process of manufacturing polymer composites requires equipment for mixing polymers and fillers. The mixing can be performed using conventional plastic processing equipment or means such as ball mills. If polymers and fillers have been processed through milling, they can be compacted by, e.g., injection moulding. Also, coating methods such as thermal or electrostatic spraying can be applied.

2.2 Gels

The surfaces of components are always irregular, which significantly reduces the conduction of heat away from electronic components. The heat is conducted through the highest points of the surfaces, and the air gaps work as effective thermal insulators. On a typical contact surface, over 90% of the area will consist of air gaps.

A literature survey shows that various silicon-based elastomers (rubbers) have been developed for thermal management. These materials are meant to fill the air gaps between surfaces and thus conduct heat from components. Elastomers conform to the surfaces and do not require accurate installation or complete flatness. Gel-like materials conform much better to a variety of shapes and fill the gaps in rough surfaces. It is also possible to cover whole circuit boards with gel.

2.3 Ceramic coatings

In various components for power electronics, heat-conductive substrate materials are needed. These also need to be electrically insulating. These applications are extremely demanding because of the requirements concerning the resistance against high temperature, mechanical stress (compression), and very high electrical resistance. Often it is also important to match the thermal expansion of the thermal management material to that of the attached electrical component.

At VTT, various thermally sprayed ceramic coatings have been developed for electrical applications. Non-porous aluminium oxide (Al_2O_3) coatings have been manufactured using the HVOF technique. These coatings have reached breakdown voltages that are as high as 80% of the breakdown level of bulk aluminium oxide (15 V/µm). HVOF-sprayed coatings have substantially better breakdown properties than coatings manufactured with, e.g., plasma spraying since the HVOF material is considerably less porous.

This makes it possible to grow thin (some tens of microns) or thick (≈ 500 µm) insulating layers on copper. These conduct heat to the metal plate and simultaneously have very good insulating properties. The heat conductivity of aluminium oxide is about 26 W/mK (100 ^{o}C), which is less than 10% of the heat conductivity of copper but twice as high as that of stainless steel. Anodised Al_2O_3 on aluminium is already used in electronics applications. By manufacturing the coating using thermal spraying, the choice of substrate materials is made wider. It is also possible to apply the coating to only a selected area. This technique can be used in cooling elements of power electronics, mobile electric motor applications, the manufacture of power circuits, sensors, and in various electric filters.

Depending on the application the properties of coatings have to be tailored. Such customisation might occur when different coating methods and coating materials (ceramic pastes, sol-gel, etc.) are applied. Also, metal-ceramic-polymer composites can be synthesised. The manufacturing methods include powder metallurgical techniques. Materials can be in bulk form or coatings.

3. Experiments and results

3.1 Gel composites

The development of gel composites was started by surveying and purchasing commercially available gels. Their properties and gelling were investigated. In the beginning, for the most part various water-based polymers and the factors influencing gelling were examined, as well as gelling additives. Aluminium oxide was added to the aqueous solution of polyvinyl alcohol (PVA). This increased the viscosity of the solution, but no gelling was obtained. Alginate acid was added in order to initiate gelling, but the result was hard and brittle piece of aluminium oxide mixture, not a gel-like material.

To achieve the gelling of PVA, a separate crosslinking agent is needed. For instance, glutaraldehyde, maleic acid, or borax can be applied. These crosslinking agents were purchased for PVA experiments. PVA did not gel with glutaraldehyde as such. Gelling demanded the addition of nitric acid in order for a pH below 2 to be reached. With these conditions met, gelling took place in 30 minutes.

Also, other water-binding agents were tested with water-based gels. Bentonite bound water strongly. Combined with aluminium oxide and water, it formed a hard and brittle material exactly as did the above-mentioned combination of alginate acid and PVA/aluminium oxide. With bentonite, air bubbles were trapped inside the material. Adding ethanol decreased the number of bubbles. This material system dried slowly, and still the result was a hard and brittle material.

After experiments with water-based gels, the research was continued with RTV silicones (room-temperature vulcanising). Electronic grade RTV silicones are available in liquid and drip-free (thixotropic) form. Hardening can be performed at room temperature or at a slightly elevated temperature. After hardening, the gels can be adhesive or less sticky. The viscosity of the gel and the curing time affect the ability to use additives, the sedimentation of filling material, the removal of air bubbles, and so on.

Experimental work:

- Silicone gel without agents. Low viscosity, fillers easy to mix and disperse, air bubbles relatively easy to remove.
- Silicone gel + Al_2O_3: Aluminium oxide binds the gel. The gel is easier to remove from the mould.
- Silicone gel + Al_2O_3: Viscosity controlled with fine-grained SiO_2, which makes the material thixotropic; i.e., the mixture does not drain.
- The maximum aluminium oxide content in silicone gel was determined. It was discovered that about 40 volume per cent of aluminium oxide can be added and still the gel can be moulded and is liquid enough to form a smooth surface.
- The effect of particle size on the thermal conductivity of silicone gels was examined. Two types of aluminium oxide, three aluminium nitrides, and two boron nitrides were studied. Volume fractions were 20 and 30 per cent. Figure 1 shows scanning electron micrographs of aluminium nitride and boron nitride powders.

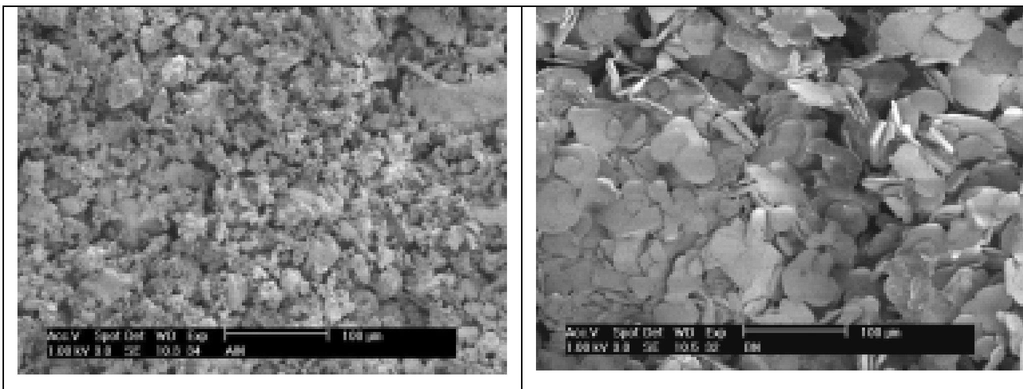

Figure 1. Scanning electron micrographs of aluminium nitride (left) and boron nitride powder.

The increase in thermal conductivity as a function of the amount of aluminium oxide can be seen in Figure 2. Also, in the case of larger filler particles the sedimentation in the material creates a concentration difference between the upper and lower surface. Using a smaller particle size or making the gelling reaction more rapid can reduce the extent of this phenomenon.

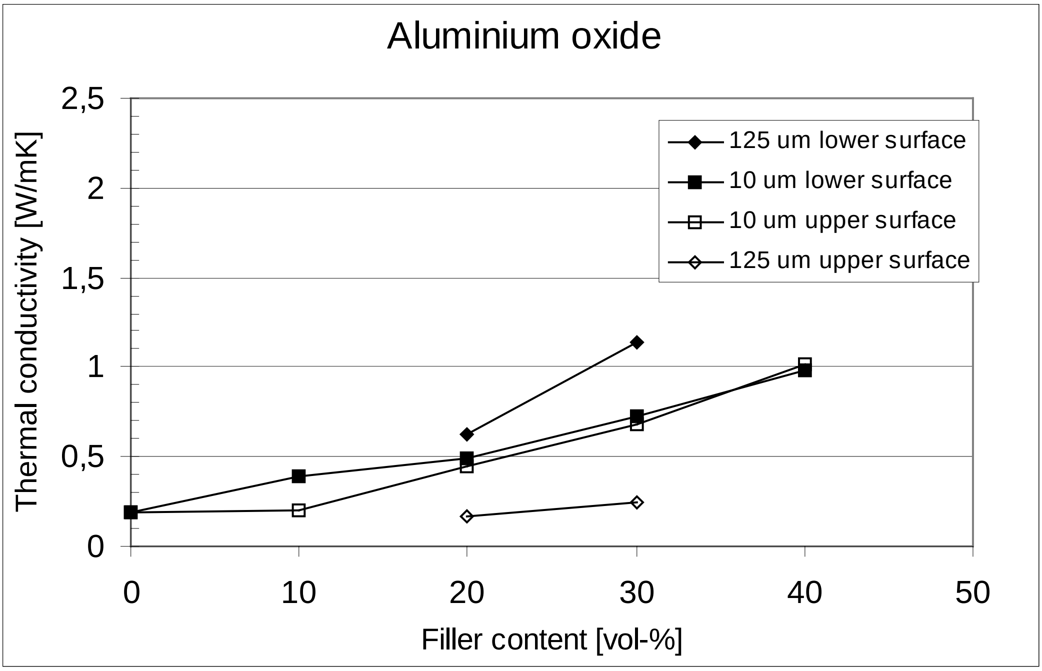

Figure 2. The effect of particle size and concentration of aluminium oxide on the thermal conductivity of gel composite material.

With boron nitride filler, a higher thermal conductivity than found with aluminium oxide was obtained (Figure 3). The highest values reached were above 2 W/mK. This requires a filler concentration so high that the material is difficult to process because it is cement-like. With a larger particle size, filler concentration varied between the upper and lower surface in the same way as with aluminium oxide.

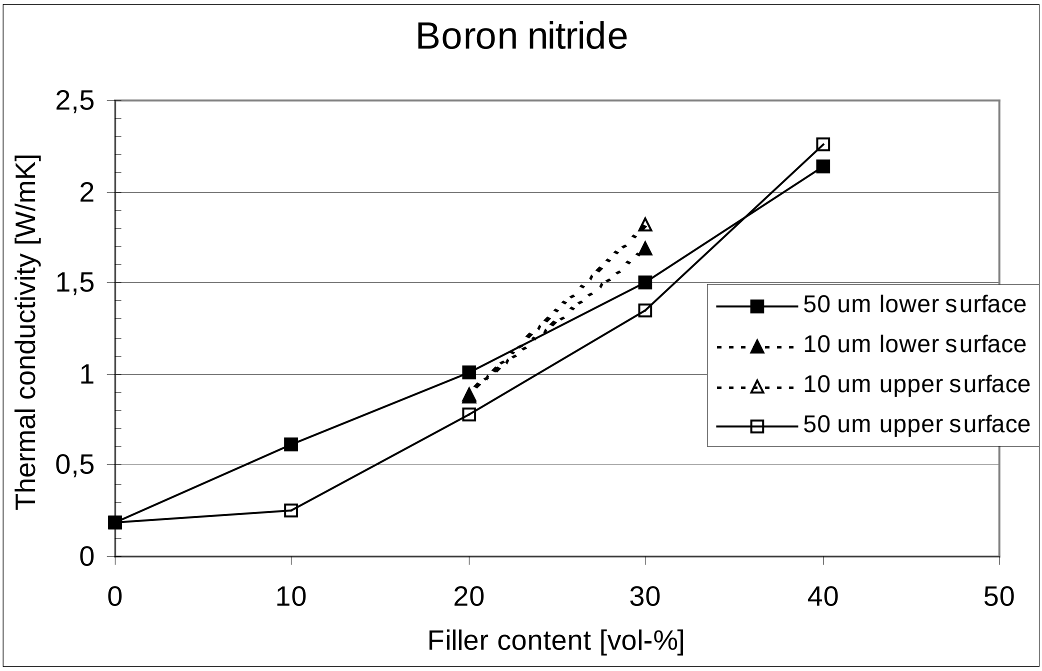

Figure 3. The effect of boron nitride particle size and concentration on the thermal conductivity of boron nitride filled gel.

3.2 HVOF-sprayed Al_2O_3 coatings

3.2.1 Electrical breakdown tests

The electrical insulation properties of Al_2O_3 sprayed with HVOF (high-velocity oxy-fuel) were tested in an IEC 60243-1 (1988) breakdown test. The sample cross-section of the tested coating is seen in Figure 4. Dielectric strength is defined as the maximum potential gradient that can be applied over the material so that the insulating property is preserved. According to the tests, coating thickness was found to be the most important factor affecting breakdown properties. In Figure 5 it can be seen that the dielectric strength of the HVOF coatings decreases as a function of coating thickness, which is not typical for insulators. On the other hand, breakdown voltages increase when the coating thickness increases (Figure 6). Yet attempts to improve insulation properties by making thicker coatings are quite ineffective. Another factor influencing dielectric strength was the fuel gas used in the HVOF process. With hydrogen, the dielectric strength was found to be better than with propylene.

Other process parameters, such as the fuel/oxygen ratio, thickness of one spraying sweep, and raw material powder, did not change the dielectric strength significantly.

Figure 4. Cross-section of the 620 µm thick HVOF-sprayed Al_2O_3 coating, 100x magnification.

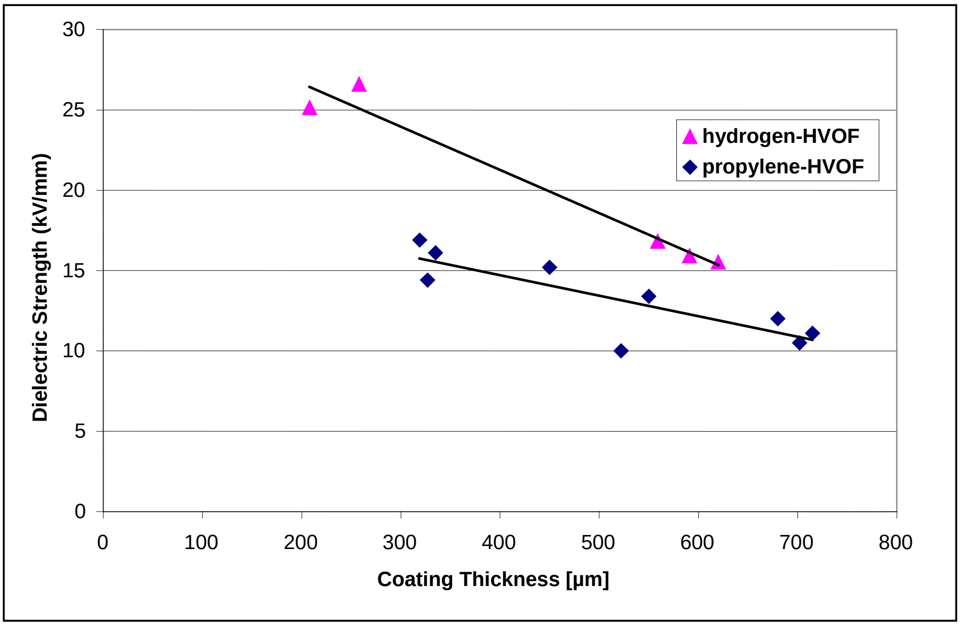

Figure 5. Dielectric strength as a function of coating thickness.

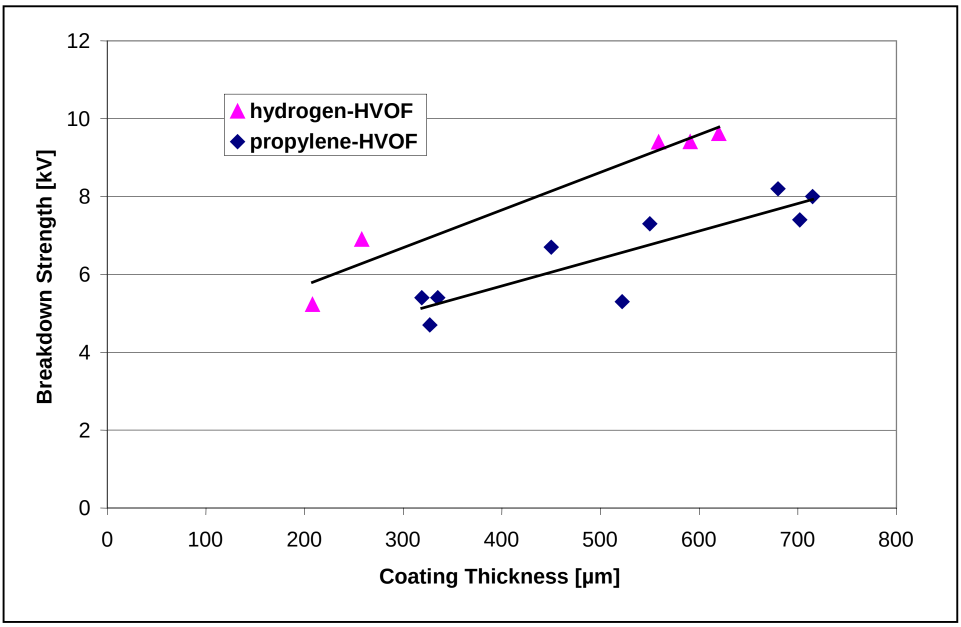

Figure 6. Breakdown voltage as a function of coating thickness.

The dielectric strength of the coatings varied from 10 to 25 kV/mm depending on the thickness. Values cited in the literature for sintered Al_2O_3 are 8 to 25 kV/mm depending on purity and sintering parameters. Thus, it can be concluded that the dielectric strength of the coatings was equivalent to that of sintered Al_2O_3 insulators.

3.2.2 Industrial experiments

In these experiments HVOF-sprayed Al_2O_3 coatings were tested in a potential application, the cooling element of a frequency converter. This cooling element must have good thermal conductivity as well as good electrical insulating properties. Insulation resistance and leakage current were measured at a pressure of 4 kg/cm^2. In actual conditions, there is a force of 70 kN on a surface area of 78.5 cm^2. The allowed leakage current for the insulating layer is 10 mA (2.5 kV test).

The coatings on cooling elements were manufactured using various spraying parameters. The measurements were performed with ABB´s insulation tester. An aluminium bar (20 cm^2) was placed on a coated cooling element. Above the bar, a 5 kg weight was added to increase surface pressure. The measuring spot was chosen to be on a smooth and good-quality coating. The coating on some cooling elements was rough or cracked on the rounded edges of the element. In these cases, the measurement area was restricted.

The insulation tester was connected with wires to the aluminium bar and an uncoated place on the element. The first insulation resistance was measured with a voltage of 1 kV/DC, and the voltage test used 2 kV/DC. In the voltage test, an initial triggering limit of >10 mA was used. This limit was decreased stepwise, and thus the value for leakage current was obtained.

The highest insulation resistance measured was 150 MΩ (1 kV/DC), and a leakage current value of 1.5 mA (2.5 kV/DC) was obtained. For a bulk aluminium oxide plate, the insulation resistance is >1 GΩ and leakage current < 0.5 mA. On the basis of these measurements, it was discovered that the coatings can not be used in this particular application. In order to fulfil the requirements for the cooling element, the insulation resistance should be near 1 GΩ.

Presumably, the porosity and presence of microcracks in the coatings degrades the insulating properties by letting the leakage current go through the coating as was noticed in the tests at ABB.

4. Conclusions

Materials for thermal management in electronic applications were developed. The research work concentrated on gel composites and ceramic coatings.

Electronic grade silicone gels were used as matrix material for various ceramic fillers, including aluminium oxide, aluminium nitride, and boron nitride. The thermal conductivity of the unfilled gel was about 0.2 W/mK. This was improved to above 1 W/mK with aluminium oxide and to about 2 W/mK with boron nitride while gel-like mechanical properties were maintained. It was thus demonstrated that it is possible to improve the thermal properties of gels considerably.

The dielectric strength of HVOF-sprayed Al_2O_3 was found to be comparable to that of sintered Al_2O_3. The possibility of producing effectively even 500 µm thick insulating layers makes this method competitive for some applications. The limitation to the usability of the as-sprayed coating is the frequent demand for very high insulating properties. According to the tests, the leakage current of this coating is too high and therefore insulating properties for high-power applications may be limited. To be able to use HVOF-sprayed Al_2O_3 coatings for insulation in high-power applications, a sealing must be applied to fill the porous surface of and possible cracks in the coating.

Laser applications in electronics industry

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Abstract

The pressure on manufactures in electronic industries to produce smaller components with high quality is driving the introduction of laser systems into the fabrication process. This paper outlines the state of the art in laser micro machining and in precision microfabrication.

The project is being carried out dealing with industrial needs and potential applications for laser precision microfabrication in the Finnish electronics industry. In connection with the project investments in laser equipment were prepared. International contacts and relations were created for the forthcoming co-operation.

1. Introduction

Welding, cutting, marking, soldering and ablation with lasers are all potential techniques for fine machining and micro fabrication in the Finnish electronics industry. Some industrial diode and Nd:YAG applications for welding of electronics components are already in use. Laser cutting and laser marking are becoming more and more popular. More investments in laser systems are expected to happen in the near future. Some of the new applications may include the following: trimming, cutting and welding of small components, laser welding of plastics, laser drilling, laser ablation, fabrication of high precision components, machining of silica and fused silica, laser assisted assembly and so on.

Potential new applications in laser machining in the Finnish electronics industry may be:

- laser cutting and laser welding of housings, capsules and other sheet metal parts,
- laser cutting and laser drilling of high precision components,
- micro machining with lasers: laser cutting, laser drilling, laser ablation and laser trimming and
- laser welding of plastics.

Most the research in laser processes and applications in Finland have been carried out in Lappeenranta Laser Processing Centre (LLPC) founded by Lappeenranta University of Technology (LUT) and VTT Industrial Systems. So far the research has mainly focused on high power applications. The research centre has two CO_2 lasers (2½ kW & 6 kW) and a Nd:YAG laser (3 kW) for welding, cutting and cladding. The 3 kW high power diode laser is used for welding and surface treatment of metals and the 90 W high power diode laser is used for welding of plastics and precision soldering applications.

The aim of the project "Laser applications in electronics industry" is to improve the LLPC's capability to offer research and development services dealing with fine machining and micro fabrication. The research topics include a study of the industrial needs in Finland, potential applications and future scenarios. The project was funded by VTT and the South-East Finland Centre of Expertice.

VTT Industrial Systems is getting four new lasers for precision micro machining applications at the end of the year 2002 and in the beginning of the year 2003. These lasers are a pulsed Nd:YAG laser for precision cutting and welding, a pulsed Nd:YAG laser for marking, an excimer laser and a copper vapour laser (CVL) for micro fabrication. Suppliers of the the lasers are the Laser Technology Center (LTC, St. Petersburg), the State Research Center of the Russian Federation – Troitsk Institute for Innovation and Fusion Research (TRINITI, Moscow), Federal State Unitary "Research & Production Corporation" (FSU "ISTOK", Moscow) and Galaktika (Moscow).

2. Fine machining of sheet metal parts with lasers

Sheet metal parts in electronics goods are mechanical components such as frames, housings and small high-precision parts, see Fig 1. Laser machining of mechanical components consists of cutting, drilling, welding, and soldering.

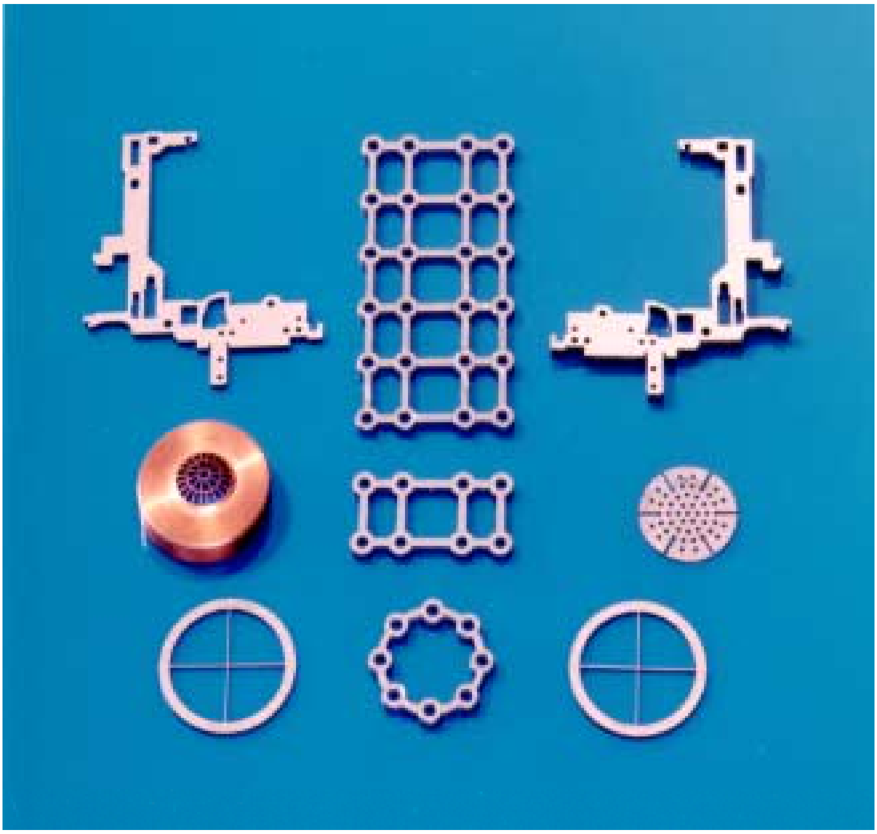

Figure 1. A variety of metals can be cut with high precision. Material thickness is 0.2–1.5 mm [1].

Processing techniques for frames and housings are:

- laser welding of sheet metal parts with CO_2-, Nd:YAG- and diode lasers,
- laser spot welding with pulsed lasers and
- laser cutting of metallic parts.

Processes for precision parts are:

- laser welding and cutting,
- laser drilling and
- laser soldering.

The advantages of laser machining in electronics include fast, flexible and contact-free processing. The heat input is low causing less distortion than other methods. The numerical control always used with the laser offers an easy and precise process.

Examples of applications for metals in the electronics industry are [1, 2 and 3]:

- cutting of precision and micro parts,
- drilling of holes,
- welding of capsules for sensors (see Fig. 2), battery and motor housings and other sheet metal parts and
- spot welding of electrical contacts.

Pulsed Nd:YAG-lasers are the most commonly used lasers for fine welding and cutting sheet metal and precision components in the electronics industry. Material thickness up to 4 mm and very fine contours can be cut. The laser devices are easily configured for beam splitting and beam sharing in order to weld at different working stations simultaneously.

The welding spot size can be adapted by the welding optics at a constant working distance of 0.1 mm up to 2 mm. Weld penetration is programmable up to 2 mm. Pulsed lasers typically are used for manual workstations as well as integrated in automated production lines. [4]

There are several pulsed Nd:YAG-lasers used in Finnish industry for fine machining. At the end of 2002 VTT Industrials Systems will receive a new pulsed Nd:YAG laser from Russia for scientific purposes. The laser unit will be placed to Lappeenranta Laser Processing Centre. The specifications of the laser are [5]:

- average power 50 W,
- pulse repetition frequency max 25 Hz,
- pulse energy max 10 J,
- pulse duration 0.5–10 ms and
- spot diameter 200 µm.

Figure 2. Seam welding of a pressure gauge. Material is stainless steel [1].

3. Laser Micro Machining

Laser micro machining was first demonstrated in the 1980's. It was based on continuous wave or long-pulse lasers. With these lasers, the heath transferred from the laser beam to the work piece introduced many restrictions that limited the precision and the quality of the process. In the early nineties, scientists discovered that the transfer of heat from the laser could be defeated using ultrafast laser pulses [6]. Ultrashort or ultrafast means that the laser pulse is shorter than about 10 ps – usually in femtoseconds [7]. Table 1 illustrates the time scales used in micro fabrication.

Table 1. Time units in micro fabrication [6, 8].

millisecond	1 x 10^{-3} second
microsecond	1 x 10^{-6} second
nanosecond	1 x 10^{-9} second
picosecond	1 x 10^{-12} second
femtosecond	1 x 10^{-15} second
attosecond	1 x 10^{-18} second
zeptosecond	1 x 10^{-21} second

Femtosecond lasers are already used in a large number of applications. Pulses in just a few attoseconds are becoming familiar to researches. In fact, optical scientists are now trying to produce pulses as short as a zeptosecond (1 x 10^{-21} s) [8].

Lasers used for micro machining and micro structuring are UV excimers, diode pumped Nd:YAG lasers (DPSS), copper vapour lasers (CVL) and Ti:Sapphire lasers. The wavelengths of the excimer laser are 157 nm (F_2), 193 nm (ArF), 248 nm (KrF), 308 nm (XeCl) and 351 nm (XeF) depending on the gas mixture used. In the Nd:YAG lasers such wavelengths as 1064 nm, 532 nm, 355 nm and 266 nm are available. In the CVL there are two wavelengths 511 nm (green) and 578 nm (yellow). The wavelength in the Ti:Sapphire laser is usually about 800 nm.

3.1 Excimer lasers

Excimer lasers are pulsed gas lasers. The word ”excimer” comes from the term ”excited dimer”, that refers to an excited diatomic bond. All excimer lasers use a noble gas, a halogen gas, and an inert gas. In a typical gas mixture, approximately 2% of the gas will be a halogen gas and 0.2 % will be noble gas [9].

The wavelength emitted depends on the gas mixture. The most commonly used combination of gases is ArF (193 nm), KrF (248 nm), XeCl (308) and XeF (351 nm). KrF is commonly used for machining polymers and XeCl for marking applications [9].

Typical parameters for an excimer laser are:

- pulse energy 400–500 mJ,
- repetition rate 100–200 Hz,
- average power 40–100 W,
- pulse duration 15–30 ns,
- peak power 10–30 MW and
- beam size 8–15 mm x 25–30 mm.

Excimer lasers can be used with a simple mask projection technique or they can be used for so called direct writing without the mask. Mask projection has the following advantages [10, 11]:

- the use of mask projection allows great flexibility in the types of geometries that can be produced,
- large areas can be machined,
- complicated patterns and shapes can be produced easily and
- can be used for batch processing of volume products.

The two main advantages of direct writing are [12]:

- no mask is required and
- the path to be machined can be fed directly from CAD files into the control of the machining system.

Figure 3 shows an example of laser precision cutting with an excimer laser.

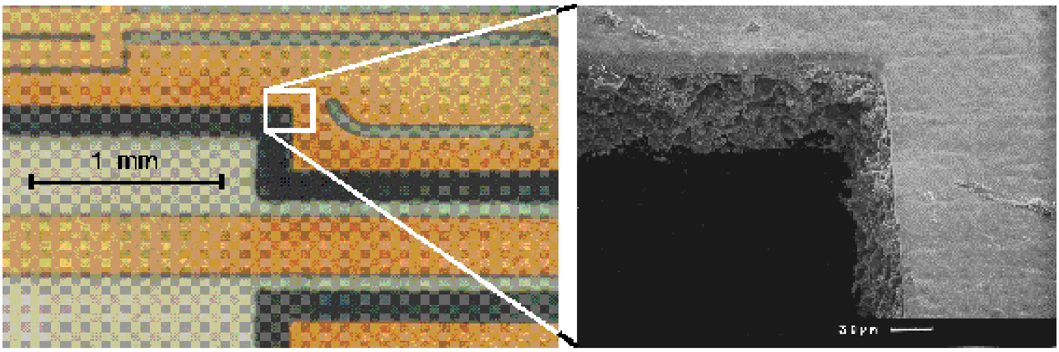

Figure 3. Precision cuts in a soft substrate using excimer laser radiation [13].

Typical applications for excimer lasers in industry are [14, 15]:

- drilling of printed circuit boards (PCB) for via formation,
- nozzle drilling for ink jet printers,
- direct structuring of microelectromechanical systems (MEMS),
- wire stripping and resist stripping,
- laser scribing of thin film in solar panels,
- laser writing of fibre bragg gratings,
- drilling of very precise nozzles into ceramics and stainless steel,
- microlithography to create microelectronics circuit patterns on the surface of a silicon wafer and
- silicon annealing for thin film transistors (TFT) in flat panel displays.

Excimer lasers can be used for micro machining materials such as:

- polymers, see Fig. 4,
- composites,
- ceramics,
- glasses,
- optical materials,
- diamond,
- thin films and
- photoresists.

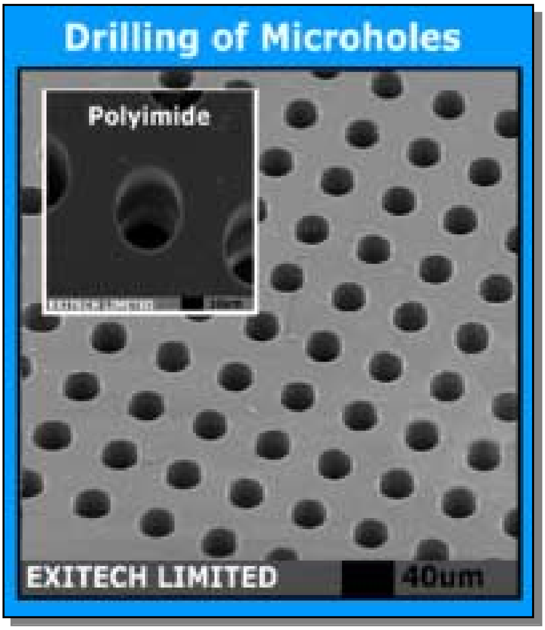

Figure 4. Microholes in polyimide drilled by an excimer laser [11, 16]. Polyimide is used in PCB's and ink jet printers.

VTT Industrial Systems will have an excimer laser in LLPC in 2003. The laser is a universal tool in the field of micro machining of plastics, ceramics and metals. Specifications of the laser are shown in Table 2.

Table 2. Specifications of the excimer laser of model 248-0,05-2000 [17].

Wavelength, nm	248
Maximum power, W	140
Stabilized power, W	100
Stabilized pulse energy, J	0,05
Pulse-to-pulse energy stability, %	2 ÷ 5
Maximum repetition rate, Hz	2000
Unfocussed beam dimensions, mm	3 x 20
Pulse duration, ns	12 ÷ 18
Beam divergence, mrad	2 x 5
Laser weight, kg	360
Laser dimensions, mm	840 x 1500 x 1600

3.2 Copper vapour laser (CVL)

The copper vapour laser (CVL) was first demonstrated in the sixties. Much of the early development of CVLs was a result of their use in atomic laser isotopic separation for the production of uranium reactor fuel.

The copper laser consists of a ceramic tube containing elemental copper and a buffer gas. The tube is heated by an electrical discharge between electrodes at each end of the tube. The heat raises the temperature to 1400–1500 °C. Approximately 1 % of the copper is converted to a vapour state. Laser results from the interaction of the electrical discharge with the copper vapour [18].

Typical specifications for a copper laser are:

- wavelengths 511 nm (green) and 578 nm (yellow),
- average power 20–120 W (15 W),
- repetition rate 4–30 kHz (8–17 kHz),
- pulse duration 15–60 ns (17–20 ns) and
- peak power 100–400 kW.

The values in the brackets are specifications for VTT's forthcoming CVL laser [19].

The combination of characteristics of copper lasers makes them ideal for micro machining applications

- visible wavelength,
- short pulse width,
- high repetition rate,
- high peak power and
- good beam quality.

Below in Figure 5 there are two examples of small holes drilled using a copper vapour laser:

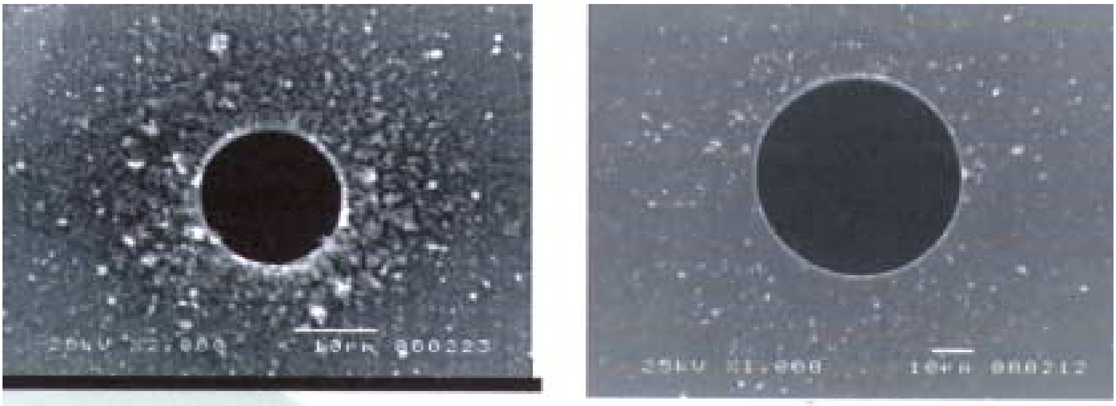

Figure 5. 17 µm hole 80 µm stainless steel (left) and 40 µm hole in 100 µm stainless steel (right) [20].

CVL's can perform precision machining on hard materials with little or no recast and minimal heat affected zones [21]. Examples of industrial applications for CVL's are [21, 22]:

- arrays of holes in metals and in ceramics,
- fluid devices and orifices,
- micro drilling of blind and through microvias in printed circuit boards,
- micro machining of CVD diamond,
- aerosol nozzle production,
- micro drilling of silicon and
- direct writing of fibre bragg gratings (with UV capability).

3.3 Diode pumped Nd:YAG lasers (DPSS)

Diode pumped solid state lasers offer process flexibility and good beam quality. They are strengthening their position in industrial applications ranging from micro machining of silicon and diamond to conventional metal cutting and welding. Diode pumped lasers are optically pumped crystal based devices, such as Nd:YAG and Nd:YLF, excited by a laser diode or an array of diodes instead of flashlamps [23].

DPSS Nd:YAG lasers offer a choice of wavelengths: 1064 nm, 532 nm (green) and 355 nm (UV). Typical diode pumped Nd:YAG laser produce 15 ns long pulses at 10 kHz repetition rate. Average power is reaching 30 W at 1064 nm, 15 W at 532 nm and 10 W at 1064 nm. The peak power can be >200 GW/cm^2 [14, 23].

DPSS lasers are ideal for drilling small diameter holes or micro machining features and components in materials like steels, titanium, ceramics, silicon, diamond and other hard materials. Small and compact (see Fig. 6) DPSS laser are used for manufacturing components in industries such as electronic & computer equipment, semiconductors, instrumentation, medical devices, automotive and aerospace [14].

Figure 6. A diode pumped solid state laser [14].

3.4 Femtosecond laser

Using ultrashort laser pulses can cause the ablation of nearly all kind of materials offering very precise machining results with minimal damage. This new technology will become a serious competitor to conventional micro machining techniques like electrical discharge machining, electron beam ablation and chemical etching. Powerful femtosecond laser systems are now commercially available. Titanium doped sapphire is the standard laser material for these systems [24].

There are more than 400 installations of femtosecond lasers systems in the world today, mostly at research and development facilities. Femtosecond lasers are available from a number of manufactures in the USA and Europe. Available output powers are generally in the 1 W range. The high energy Ti:Sapphire amplifiers operate in the kHz range. Most of the systems allow user-settable repetition rates. Pulse widths vary from 160 fs to 30 fs. [25].

All femtosecond laser systems are sensitive to changes in the environment. The stability is obtained in an ambient environment with ±1 or 2 °C control. For a cleanroom such a requirement usually does not present a problem. However, beam stability is sensitive to temperature changes and some manufactures of these systems use water cooling to control the temperature [25].

Examples of materials that have been machined with femtosecond lasers [6]:

- ceramics: alumina and silicon nitride,
- dielectrics: glass and diamond,
- metals: chromium, copper, nickel, rhenium, stainless steel, molybdenum, platinum, gold and brass,
- semiconductors: GaAs and silicon and
- others: teflon.

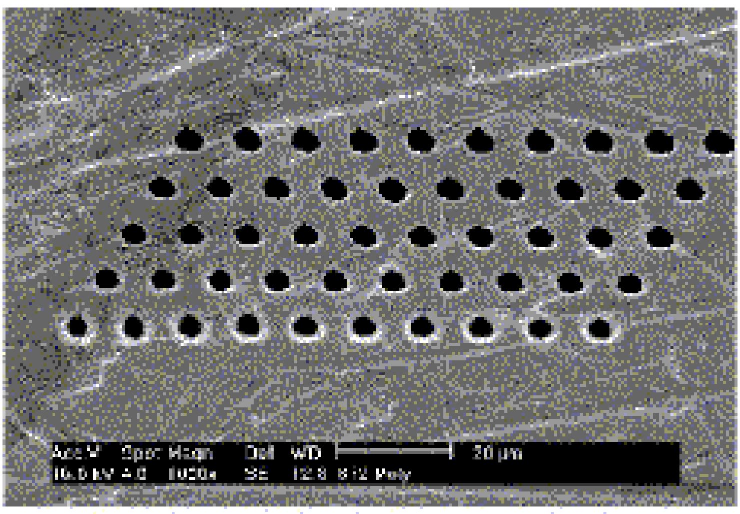

Figure 7. 5 µm holes in molybdenum sample [26].

A variety of materials that have increasing relevance in industrial applications have been micromachined using femtosecond pulses. Although the results with femtosecond lasers are exceptional in many cases, similar effects can also be produced by the use of longer pulsed lasers if sufficient care is taken in optimising the use of those systems [27].

4. Diode laser applications in electronics

The structure of a high power diode laser is something special. The high power of the laser is achieved by combining many low power semiconductor lasers to one incoherent laser source. The beam quality of high power diode lasers is limited but sufficient for polymer welding applications. The laser emits radiation in the range between 800 and 1000 nm, just below the wavelength of Nd:YAG lasers (1060 nm).

4.1 Welding of plastics

Polymer welding has been demonstrated already several years ago using CO_2 and Nd:YAG lasers. However, it didn’t become a big success due to cost reasons and the size of the laser systems. High power diode lasers are compact and reliable lasers sources with an electrical to optical energy efficiency of about 50 %, which makes them also very attractive from an economic point of view /28/.

The main advantages of laser welding are [29]:

- non-contact, easy to control process,
- no tool wear,
- minimized heat-affected zone,
- consistent weld quality
- applicable to a wide range of materials and complex shaped parts and
- problems related to conventional welding processes, such as scratching of part surfaces or melt sticking to heat elements, do not exist.

Using near-infared laser radiation, the welding process can be established based on two major principles: surface and volume absorption. In the case of volume absorption, the laser beam penetrates through the part and is absorbed over the cross-section of the joint. This technique is used to weld parts in a butt-joint configuration [29].

Overlap joints (Fig. 8) are more practical for industrial applications. In this method, the laser energy penetrates through the first polymer, without being absorbed. Through pigments or in the plastics integrated additives, the laser radiation is absorbed at the surface of the other polymer and converted into heat [30].

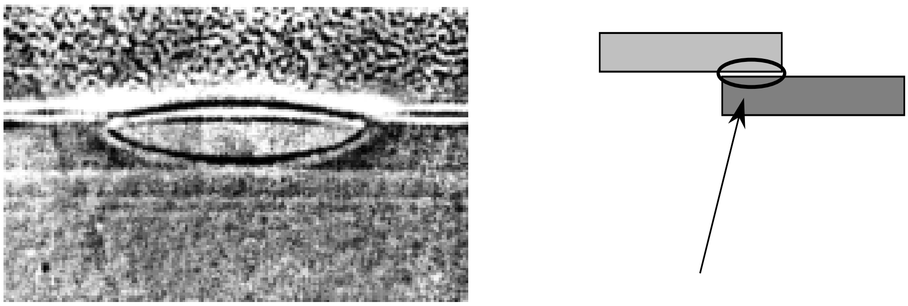

Figure 8. Cross section of the overlap-joint welding zone [30].

Diode lasers are capable of welding virtually all thermoplastics, such as ABS, PA, PC, PE, PMMA, PS, SAN, ABS+PC, and many other polymers. Welding thermoplastic elastomers to rigid thermoplastics is also possible [31].

Diode laser system for polymer welding typically provides several 10 Watts, which can be either delivered directly from the diode laser or from a fiber. A standard diode laser consists of a compact diode laser beam source, a control panel, and a supply unit containing power supply, a laser cooling system, and all the control and monitoring functions (Fig. 9).

Figure 9. An example of a diode laser system: the supply unit, the control panel, and the diode laser head [32].

4.2 Soldering

Laser soldering does not need any mechanical contact, provides a good accessability to tiny parts and is very good to control in terms of power and positioning. If the components to be soldered are sensitive to thermal load, laser soldering is an attractive choice [33].

A typical set-up of a commercially available soldering system consists of the diode laser, a wire feed system and optionally a pyrometer for the measurement of the surface temperature in the soldering region (Fig. 10).

Since the start of the electronics industry lead-containing solders have been used. However, in the Far East and Europe legislative restrictions have been proposed on the use of lead in electronics. Lead free soldering has been introduced as a response to this. Recent work on laser soldering has shown that a diode laser system can be used to successfully solder lead-free solder joints [34].

Figure 10. Scheme of a laser soldering system [35].

5. Conclusions

The advantages of laser fine machining in electronics include fast, flexible and contact-free processing. The heat input is low causing less distortion than other methods. Pulsed Nd:YAG lasers are the most commonly used lasers for precision cutting and welding of sheet metal and small-scale components in the electronics industry.

Lasers used for micro machining and micro structuring are UV excimers, diode pumped Nd:YAG lasers (DPSS), copper vapour lasers (CVL), and Ti:Sapphire lasers. Excimer lasers commonly used for machining polymers. CVL lasers can perform precision machining on hard materials with little or no recast and minimal heat affected zones.

Diode pumped solid state lasers (DPSS) offer process flexibility and good beam quality. DPSS Nd:YAG lasers offer a choice of wavelengths: 1064 nm, 532 nm (green) and 355 nm (UV). DPSS lasers are ideal for drilling small diameter holes or micro machining features and components in materials like steels, titanium, ceramics, silicon, diamond and other hard materials.

Using ultrashort laser pulses can cause the ablation of nearly all kinds of materials offering very precise machining results with minimal damage. This new technology will become a serious competitor to conventional micro machining techniques like electrical discharge machining, electron beam ablation and chemical etching.

Powerful femtosecond laser systems are now commercially available. Titanium doped sapphire is a standard laser material of these systems. Although the results with femtosecond lasers are exceptional in many cases, similar effects can also be produced by the use of longer pulsed lasers if sufficient care is taken in optimising the use of these systems.

The beam quality of high power diode lasers is limited but sufficient for polymer welding and soldering applications. Diode lasers are capable of welding virtually all thermoplastics, such as ABS, PA, PC, PE, PMMA, PS, SAN, ABS+PC and many other polymers.

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Environmental Test Tailoring – A Controlled Reliability Tool for Electronic Equipment

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Abstract

A general and easy-to-use environmental test tailoring process for civil and military applications is presented. The work is based on literary review and on new studies of real-life applications. The developed environmental test tailoring process is for all environmental factors, e.g. shocks, vibrations, temperature. In addition, the process may be used for complete systems or subsystems. The presentation does not go into great detail on a particular environmental factor, instead giving the framework and necessary phases for a successful environmental test tailoring process. As the approach here is general, the existing standards and tailoring methodologies may be used simultaneously.

1. Introduction

It is increasingly necessary to have better control over the reliability of products and to optimise testing for environmental loads. This is a challenge that typically needs teamwork and co-operation between different branches of engineering and organisations. In order to determine the probability of failure or malfunction, one must study the properties of the product and the true environmental loads it is exposed to. Furthermore, the obtained design has to be tested and there is a need to be able to reproduce the environmental effects in a limited time in laboratory conditions.

The process of producing realistic testing procedures on the basis of actual field conditions is often called environmental test tailoring (MIL-STD-810F, 1997). In general, this process needs expert knowledge since reproducing the true environmental effects or determining the actual level of reliability is a demanding task. In this report, however, a simplified, easy-to-use environmental test tailoring process is presented in brief. The work is based on a review (Vehviläinen & Juntunen 2002) of existing methods such those in ref. MIL-STD-810F (1997), DEF STAN 00-35 (1999), GAM-EG-13 (1986), CIN-EG01 (1999), DIN 30787. (1999), Lalanne, C. (1994), Karlberg, C. (1997) and new results of the study of real-life applications (Juntunen et al. 2000, 2001, 2002). In addition, a new test tailoring handbook (Juntunen 2002, KOTEL handbook) that has been developed on the basis of the work conducted is described.

2. The process development

The correct early stage design decisions are important for successful product development. Design changes later on in the product design process are typically difficult and significantly increase costs. Likewise, the requirements and specifications of products are important to determine as early on as possible. Environmental test tailoring may be used for optimal reliability and test generation. The test tailoring process can be used to bring together end users, designers, testing and marketing people, all of whom are necessary for an optimal result. Furthermore, the process helps to unify the approaches used in testing, design and environmental condition determination. As a result, it is possible to obtain more efficient product design processes and more reliable products. These basic ideas are built in the following principles of the newly developed test tailoring process:

1. Simple structure
    - easy-to-learn and adopt
    - unifying approach for tailoring
    - the same main process for a system or a subsystem
    - a tool for product development, management and marketing

2. Hierarchic structure
    - enables different tailoring levels, depending on resources and user knowledge.
    - may be used by test experts, design engineers and project managers.

3. Tool for project management

- goal, costs, timetable, subcontractors, responsibilities, documentation, etc.

4. The phases of test tailoring process

- a reminder list with a description of the phases
- evaluation of the phases: options, limitations and recommendations
- documentation of the phases

5. Accelerated testing

- the basis for accelerated testing is created
- recommendations
- verification

6. Learning process

- a continuous and iterative process
- new information may be used to improve earlier results
- cumulative knowledge
- statistical data
- lessons learned.

3. The Environmental Test Tailoring Process

The main phases of the new test tailoring process are presented in Figure 1. In practice, each phase of the process is further divided into more detailed steps. The final, more detailed process will depend on each set of goals, applications and available knowledge.

Tailoring work may be carried out with the co-operation of product developers, end customers, subcontractors, consultants and test laboratories, etc. The different parties agree upon the content and responsibilities for each phase in the tailoring process. The results are then documented and saved for possible use in the future. The documents should be updated each time new information becomes available, even after the actual tailoring project is already over. The goal is to have a flexible and iterative work process.

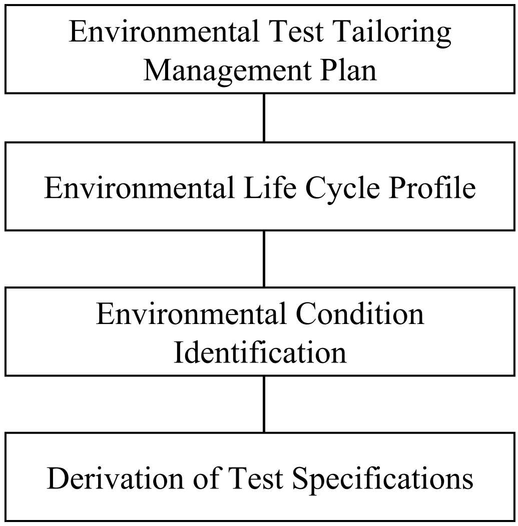

Figure 1. The main test tailoring process.

Table 1 shows the more detailed documentation and reporting that occurs during the tailoring process with a breakdown of the corresponding activities for each step. In the new test tailoring handbook (Juntunen 2002), the simple forms shown in Figure 2 are filled in during the tailoring process. These forms serve as reminder lists and the initial documentation for the detailed work. There is one form for each of the main phases presented in Figure 1 and in Table 1.

Table 1. The test tailoring process with information flow and corresponding activities.

INPUT	ACTIVITY	OUTPUT
ENVIRONMENTAL TEST TAILORING MANAGEMENT PLAN		
Background Need, market possibility, technical and economical circumstances. New or updated requirements. System or subsystem level. Test tailoring standards and handbooks.	***Planning*** Goal, strategy, participants, responsibilities, resources, timetable and financing. System and subsystem level. Boundary conditions, limitations. Level of tailoring: difficulty, costs. Technological and financial risks.	***Environmental Test Tailoring Management Plan (ETTMP)*** - overview, goal and strategy - deliverables
ENVIRONMENTAL LIFE CYCLE PROFILE		
Existing knowledge of life cycle profile and environments. Experience, customers, literature, standards, handbooks and databases. Life cycle, duty cycle. Internal and external environments. Self-generated influences.	***Data collection and development*** Basic information of all possible environments and their characteristics and statistics. The existence and influence of environments: co-existence, parallel or in series. Possible failure modes. Evaluation of the critical env. factors and corresponding failure modes. Teamwork of all participants.	***Environmental Life Cycle Profile (ELCP)*** - baseline document - for project management - clear technical information - state of art information - critical environments - critical failure modes - updated when necessary
ENVIRONMENTAL CONDITION IDENTIFICATION		
Env. Life Cycle Profile (ELCP) Existing knowledge of critical environmental conditions.	***Data collection, field and laboratory measurement, computer simulation.*** Detailed information of environments. Product properties and behaviour. Interaction phenomena.	***Critical Environment Descriptions (CED)*** *- detailed information of collected critical environments*
Product characteristics. System and subsystem behaviour. Product, mounting system and platform information. Physical properties: material, geometry etc. Critical functional properties.	***Determination of critical failure modes and mechanisms.*** The controlling physical laws and equations for corresponding failure mechanisms. Interaction phenomena. Test acceleration laws. Combined env. factors.	***Critical Failure Modes and Mechanisms (CFMM)*** - failure modes and mechanisms - the controlling physical laws for failure control and test specification determination.
DERIVATION OF TEST SPECIFICATIONS		
Environmental Test Tailoring Management Plan (ETTMP) ***Env. Life Cycle Profile (ELCP)*** ***Critical Env. Descriptions (CED)*** ***Critical Failure Modes and Mechanisms (CFMM)***	***Derivation of testing conditions.*** Raw environmental data, combination of environments, events, statistics. Reliability considerations. System and subassembly. Test acceleration. Financial and technical factors. Resources and facilities.	***Test Specifications (TS)*** - format according to the ETTMP - test program - system and subsystem level - raw environmental data - test type and purpose
Data for verification Test Requirements and the corresponding technical data from all test tailoring process phases. State of art knowledge.	***Verification of realistic testing.*** Comparison to existing requirements and specifications. Comparison of different testing levels and time duration. System level and subsystem level testing and simulation. Failure identification: means and results Failure mechanism controlling laws. Collection of field feedback from real environmental conditions.	***Test Specification Verification (TSV)*** - existing test requirements - at different test loads - at different test duration - critical failure modes and mechanisms. - field feedback - feedback from testing - recommendations for long term verification plan. - recommendations for test updating.

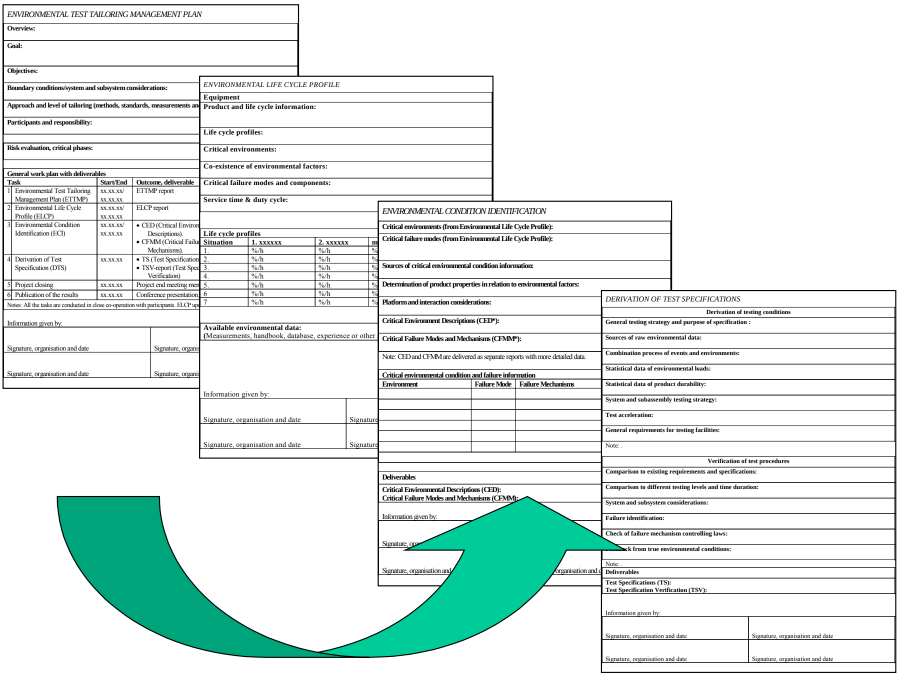

Figure 2. The test tailoring process forms.

4. Environmental Test Tailoring Management Plan

The development of the Environmental Test Tailoring Management Plan (ETTMP) is the first phase in the test tailoring process. ETTMP is used to achieve an overview and agreement on the general framework of the environmental test tailoring process. Some of the tasks and points to be considered here are:

- need and overview
- system and subsystem
- boundaries of the programme
- goal, methods, budget, resources and timetable (people, time, money)
- participants and their responsibilities (resources, financing)
- level of tailoring: difficulty and costs
- technological risks
- deliverables and outcomes (reporting, documentation, database, quality management).

5. Environmental Life Cycle Profile

The Environmental Life Cycle Profile (ELCP) determination is important for both administrative (schedule, budget) and technical (reliability, usability) reasons. In the new tailoring process for this report, the ELCP may be determined for system or subsystem levels with the same basic steps.

The Environmental Life Cycle Profile can be described as following:

- include all phases of a product's life
    - include manufacturing, distribution and end user profiles, etc.
    - maintenance, disassembly, re-use, withdrawal from service
    - all environmental factors (vibration, temperature, pressure, etc.)
    - end users
    - different platforms
    - character, sequence, co-existence, correlation of events and environments
    - statistic information such as probabilities, extreme and mean values.

- research and development tool
    - integrated information on environmental conditions
    - the current state-of-the-art situation, the level of knowledge
    - cost effective approach for design and testing
    - risk management (load/durability)

- useful documentation
    - important product characterisation baseline
    - the same baseline for design and testing
    - administrative tool

- teamwork amongst all parties ensures the best results.

ELCP is an evolving document and may be updated during design or later on through feedback from end users; thus, it may be connected closely to product documentation (e.g., quality management). ELCP does not give answers on what to do or how to deal with a particular situation; it serves as a document and a baseline for further consideration. As a document, it is simple enough to be understood by all parties and project management levels.

6. Environmental Condition Identification

The environmental conditions of each life cycle phase must be determined and should be included in ELCP. In addition, critical environmental influences should be determined as realistically and detailed as possible. In the influence study, the installation platform, the product properties and critical failure modes should be taken into account. The emphasis is on the most critical life cycle phases.

Information can be gathered from literature, field measurements, computer simulation and database systems, etc. Standards and handbooks may give useful technical information. In addition, common sense and information from end users should be applied.

The results are presented in separate documents: Critical Environment Descriptions (CED) and Critical Failure Modes and Mechanisms (CFMM). Furthermore, the results should be added to ELCP in a simplified form.

In Figure 3, an example of the determination of shock and vibration environmental loads with field measurements is given (Juntunen et al. 2001). Measurements were conducted from different locations in the car while driving on different road surfaces and while causing impacts by slamming doors or driving over ramps. In general, the product properties and failure mechanisms should be considered before making field measurements in order to ensure proper measurements and analysis methods.

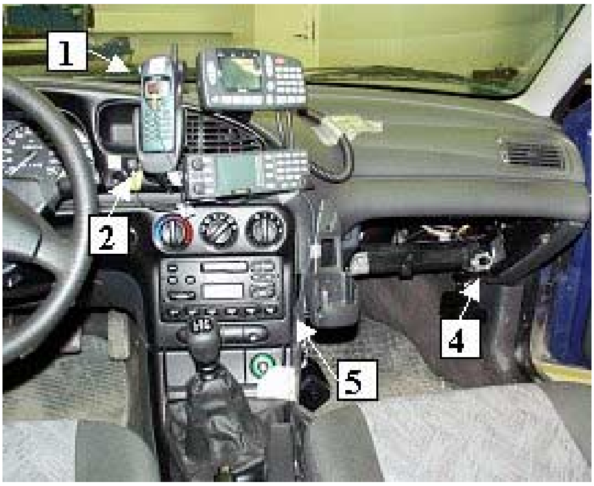

Figure 3. Determination of shock and vibration environmental conditions in a passenger car. Some of the acceleration measurement locations used are presented (Juntunen et al. 2001).

7. Derivation of the Test Specifications

7.1 General

The previous steps of the tailoring process give the environment-specific life cycle information. The test specifications should be derived on the basis of the obtained results. In addition, one should adjust the tests and test levels according to the desired level of reliability.

For the test generation, of the following information is mandatory:

- environmental life cycle
- environmental conditions
- critical failure modes
- cause-effect relationships and acceleration laws.

For the test severity determination, an important question is the combination of different events of a particular environmental factor. In addition, environmental factors may not only co-exist, they may also have combined effects that should be taken into account. Furthermore, time compression and test acceleration are typical objectives for more efficient test development. The challenge is to be able to accelerate the correct failure modes with realistic testing methods and severity.

7.2 Derivation of testing conditions

For each environmental factor various methodologies exist for the derivation of testing severity and conditions. Variations in test severity may occur, however, due to different methodologies being used, even if the same input data are used. This may be a question of different strategies and testing purposes, although it may also be due to variation in the accuracy of the analysis procedure or in the desired reliability level for the final product. This phase in test tailoring is thus very critical and requires special emphasis.

One has to be careful to have a clear strategy and to fully understand the tailoring process. The purpose of the testing and its application area should be well established. It is interesting to note that the tailoring process offers a natural bridge between the traditionally more separate environmental and reliability testing procedures. Some of the important issues in the derivation of testing conditions are the combination of events and environments, the evaluation of the interaction phenomena, the level of reliability and the used statistical methodologies.

For the test severity generation, it is necessary to properly identify the target levels of structural and operational reliability. The target probability of failure is typically product-dependent; e.g. high-reliability equipment such as space, medical, military, etc., needs higher margins for uncertainty. In addition, the number of test items influences the defined test severity.

In Figure 4, an experimental set-up is presented for determining the internal dynamic properties of a mobile phone mounted on a shaker table (Vehviläinen & Juntunen 2002). The obtained data may be used to evaluate natural frequencies, magnification factors, failure modes, substructure interaction phenomena, accelerated testing, etc.

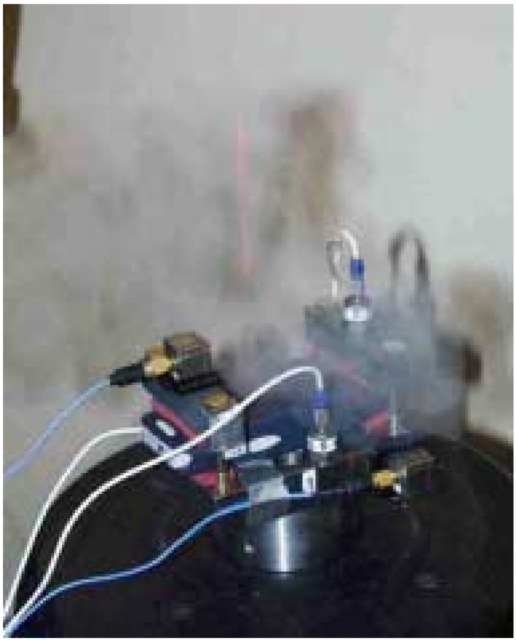

Figure 4. Determining the internal and substructure dynamic properties of a mobile phone with the use of a laser vibrometer measurement system and a shaker table. The smoke is used to illustrate the red laser beam.

7.3 Verification

After producing the test specifications, it is necessary to ensure that the obtained results are realistic. The tests should simulate the effects of the true environmental conditions; thus, the effects and failures of the tests should correspond to the feedback from actual field usage. This information is critical to time reduction, where one has to ensure that the relevant failure modes successfully accelerate.

Several methods exist for studying failures in electronic equipment. Various non-destructive testing methods offer possibilities for studying different failure modes without unnecessarily affecting the product. Figure 5 shows an acoustic image of an electronic device with some delamination.

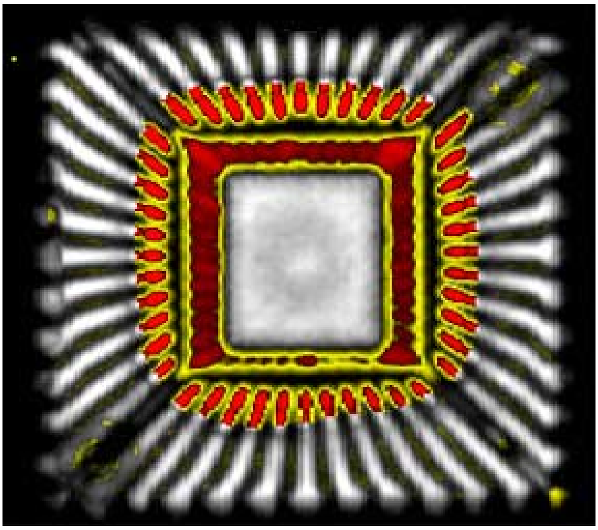

Figure 5. Acoustic image of a device. The red areas are delaminated.

On the basis of test verification results, one can further optimise the acceleration by increasing or decreasing the test levels, etc. The test tailoring process enables the learning process and the modification of test specifications according to the best available data. With the use of more conservative test levels, the need for updating is reduced, but then the tests are not as optimised and efficient.

8. Conclusions

Standards and handbooks exist for environmental test tailoring, but it was felt that a simplified, general process for different environmental factors with the most important phases to be remembered was needed. Thus, a simplified process and handbook for test tailoring was developed on the basis of literature survey and real-life tailoring studies. The approach is general as different environmental factors for system or subsystem may need to be considered.

A short description of the process is given, along with the key considerations that need to be taken into account. For special applications, other existing test tailoring standards and methods may be used simultaneously with the general procedure presented here. The developed handbook should make it easier to learn the philosophy of test tailoring and assist in adopting the necessary methods for practical work.

The developed process may be applied at the system or at the subsystem level for any environmental factor. Furthermore, it is interesting to note, that environmental test tailoring offers a natural bridge between the traditionally more separate environmental and reliability testing. However, even if the basic process itself is easy-to-use and serves as a tool to control the tailoring work, the tasks within the process need various levels of expert knowledge depending on the studied application. The benefits of tailoring, however, have shown to be worthwhile. If real control over the reliability level of a product and using accelerated testing methods are desired, the basic steps used in a test tailoring process cannot be avoided.

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Micromachining

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Abstract

The miniaturisation of products and their manufacturing processes is considered one of the key trends in technology development. Accuracy requirements for mechanical, electrical/electronic, and optical products and components have increased greatly in recent years. Ultra-precision machining is now recognised as one of the key technologies for the manufacture of the most modern optoelectronics for opto-mechanical devices. One of the most important fields in which ultra-precision machining technology can be applied is ultra-precision die and mould making, as mass production of ultra-precision optical parts is required for many different types of products.

1. Micromachining applications

Many products that are part of modern life, such as CDs and DVDs, printers, projectors, cameras, and other devices employing computer technology include micromachined components. Combined systems, whose components utilise micro-fluidics, micromechanics, micro-optics, and microelectronics, are placed in the smallest amount of space possible; such combined microsystems are used in the biomedical fields, the information and communication technology applications, and the manufacture of new automotive products and applications. This breakthrough occurred because of economical manufacturing methods. The manufacturing methods used in precision engineering have been developed through application of the basic principles of conventional machine building to microelectronics, as seen in the areas of lithography and micromachining. Table 1 summarises current trends in the development of ultra-precision machining technology, with some practical applications.

Table 1. Representative fields of development in ultra-precision machining technology.

1. Higher accuracy/better surface quality • Short-wavelength optical devices • X-ray related devices
2. Machining of parts with complicated geometry • Aspheric mirrors and lenses • Troidal mirrors
3. Machining of larger parts • Large-scale SOR, telescopes, laser devices, etc.
4. Machining of small parts/microparts with complicated shapes • Micromachines
5. Machining hard-to-machine materials • Hardened steels for dies • Ceramics and other hard and brittle materials

The continuous development of cutting processes is making it possible to manufacture microparts cost-effectively. The wide selection of materials, freedom from geometric constraints, good surface roughness, and short machining time are some of the benefits in cutting technology. The most important application is diamond cutting of non-ferrous materials. The surfaces of very hard and wear-resistant work pieces are structured, but also new applications are developed. Almost all materials can be machined without imposing limitations on the geometric design. (Bierhals et al. 1999).

There are several methods used in micromachining. Micro laser beam machining, micro ultrasonic machining, micromoulding, LIGA, micro-electrochemical machining, and micropunching can be applied in the fabrication of microparts.

The continuous miniaturisation of structural parts, electronic components, and equipment is increasing the demand of small structural parts. Microtechnology (Bader et al. 2000) and microassembly are considered to be key technologies. Special accuracy micromachining achieves a surface roughness of R_a = 2–20 nm and a dimension accuracy of within 1 μm. The application of microtechnology started in the end of 1960 in the optical industry in the USA. Later, several ultra-precision machining applications were developed to meet the needs of optical, electronic, and mechanical component production (Ikawa et al. 1991).

A very small shaft with a small diameter is presented in Figure 1, and micromachined grooves are shown in Figure 2.

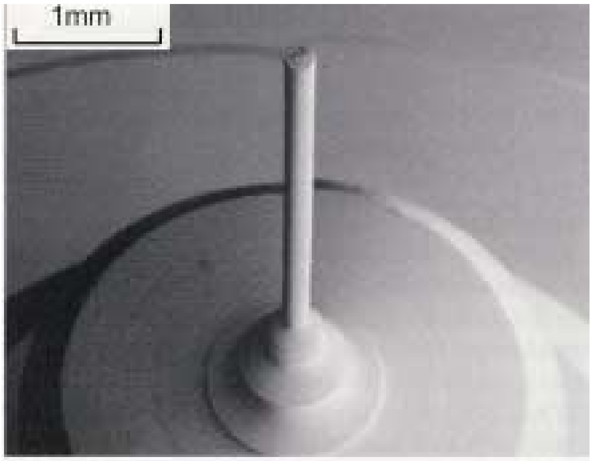

Figure 1. Photograph of a microcylindrical part, a turned work piece. Hardened die steel, HRC44, Ø0.22x4 (Moriwaki and Shamato, 2000).

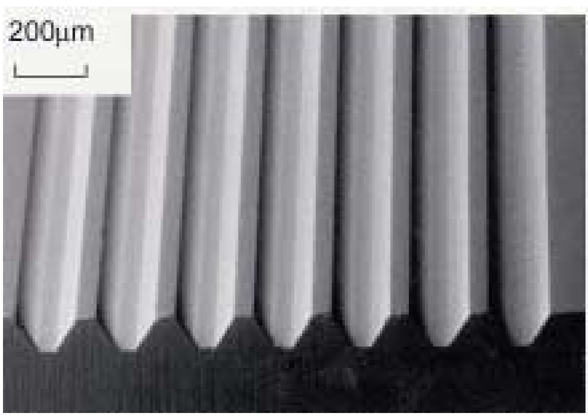

Figure 2. Photograph of a microgrooved, machined work piece. Hardened die steel, HRC 55 (Moriwaki and Shamato, 2000).

The accuracy of the pitch presented in Figure 2 is 220±0.25 µm, depth 102±0.43 µm, and surface roughness 0.06 µm R_y (Moriwaki and Shamato, 2000).

The ultra-precision machining of non-ferrous materials with diamond tools and the structurisation of surfaces have become established applications in the optical industry. The number of applications using non-ferrous materials is increasing, whereas the micromachining of steels remains in the research stage (Schmidt et al. 2001). In micromachining methods such as turning, milling, and grinding, special high-precision machine tools are applied and single block diamond tools are used as the cutting tool.

The material being machined with an ultra-precision cutting tool is often aluminium, copper, plastic, or ceramic in nature. The machining of steels is normally not possible with diamond tools; instead, the tools' contact points are made of cubic boron nitride or micro-grain tungsten carbide. The ultra-precision machining methods for steel are single-point diamond turning, fly cutting, and micromilling. Ultra-precision diamond grinding is also applied. Diamond tools can be used for scratching. It is often possible to use special nano- or micromachining machine tools to perform turning, milling, scratching, or grinding operations.

The same micromachining machine tool can often be used as both a lathe and a milling machine. The machine tools are equipped with horizontal or vertical spindles. In turning operations, the single-point diamond tool is held without movement and the necessary machining movement is produced by rotating the work piece. Machinable geometries are plane or rotational surfaces. Rotating diamond tools can be used in the machining of planes or grooves in a prismatic work piece; the method is called fly cutting. Dimensionally accurate slots as well as three-dimensional sculptured surfaces, such as in moulds, can be machined. In IPT the scratching of a single-point diamond tool is researched (Weck, 2000). The material selected for the machine tool block is epoxy granite. Spindles are equipped with air bearings, and guide ways are hydrostatic. Temperature stabilisation, vacuum chucks, and tool recognition methods are used.

A new ultra-precision diamond cutting technology, called ultra-precision elliptical vibration cutting, has been developed and successfully applied in the machining of hardened die steels and glass materials (Moriwaki and Shamato. 2000). The principle of this technology is shown in Figure 3.

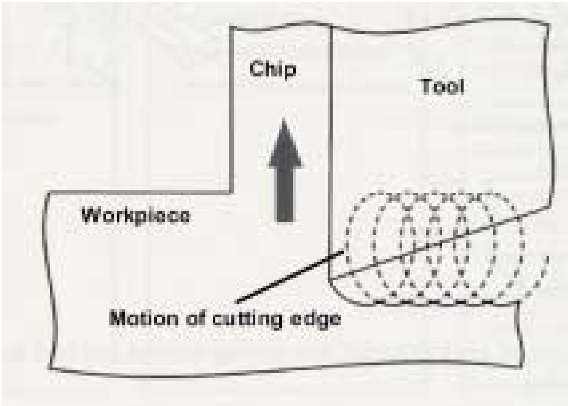

Figure 3. Schematic illustration of elliptical vibration cutting process (Moriwaki and Shamato, 2000).

An ultra-precision turning machine is equipped with an ultrasonic elliptical vibration cutting tool that vibrates at 21.5 kHz. Mirror surfaces of hardened steel with a hardness of HRC 39 are obtained, with a maximum surface roughness of 0.03 μm; with turning (Shamato and Moriwaki, 1999), a spherical mirror of HRC 61 tool steel is achieved.

2. Ultra-precision machine tools

Typical examples of practical applications of ultra-precision machining of actual products and ultra-precision machine tools are presented in Table 2. Modern work pieces with complicated curved surfaces are more demanding than the earlier flat and cylindrical ones. Accuracy and surface roughness requirements, as well as integrity specifications, are also becoming tighter. The key parts of today's most advanced opto-mechanical devices and IT devices are manufactured via ultra-precision machining.

Table 3. Examples of a machine element and machine tool for ultra-precision machining and applications (Moriwaki and Shamato, 2000).

Key Basic Technology	Ultra-Precision Machine Tool	Application/Products
Aerostatic spindle Aerostatic Guide Way V-V Hydrodynamic Guide Way V-V Roller Bearing Guide Way Hydrostatic Spindle Hydrostatic Guide Way High Speed, Low Vibration Motor Ultra-Precision Temperature Control Ultra-precision CNC	Polygon Mirror Generator Ultra-precision Lathe Ultra-precision Planer Ultra-precision Milling Machine Ultra-precision Slicer Ultra-precision Surface Grinder Ultra-precision Aspheric Grinder	Polygon Mirror (Laser Printer) Spherical/Aspheric Mirror Troidal Mirror Photosensitive Drum (Copier, Printer) Magnetic Disk (Hard Disk Drive) Oscillator (Cellular Phone) Fresnel Lens (Large Display Device) Lenticular Lens (Large Display Device) Magnetic Head (Hard Disk Drive) Die for Light Guide Plate (LCD) Colour Filter (LCD) Lens (Projection TV, Camera) Die for Aspheric Lens Die for Laser Printer Lens

Up to now, ultra-precision machine tools were built for the most part in a lathe-type design, limiting the possible final work piece geometries to those with rotational symmetry. An ultra-precision contouring machine tool is presented in Figure 4.

These machine tools are often equipped with rotating spindles to enable milling and grinding operations (Figure 5). The air-bearing milling spindle built as a hybrid design, combining the spiral groove technology with an externally pressurised bearing type, can achieve a maximum revolution speed of 100,000 rpm and a radial stiffness of 30 N/µm radially with a total maximum deviation under 100 nm (Weck, 2000).

Figure 4. An ultra-precision contouring machine tool (Precitech, 2002).

Figure 5. High-speed spindle for grinding applications (Precitech, 2002).

3. Micro-EDM

EDM (electro discharge machining) is a machining process based on removal of material by melting and partial vaporisation. Heat is provided in the form of pulsed electrical discharges or sparks. The technology is well established and used widely in die and mould making. By reduction of the discharge energy of each pulse, a small unit removal is achieved. The major technological issue for attaining low discharge energy is to reduce stray capacitance between the electrode and the work piece. A high machining accuracy is realised by introducing a precise mechanism for the moving elements, which must make only small movements, as little machining force need be applied. According to Michel et al. 2000, huge efforts will be necessary to develop micro-EDM techniques for industrial applications, especially for fabrication of complex tools and dies for injection moulding, embossing, and punching of microsystem components. For efficient production, special emphasis should be placed on the development of clamping, handling, and *in situ* measurement systems.

4. Microgrinding

Grinding has been widely applied for machining pins and grooves with small dimensions. The main reason for this is that the amount of material removed in grinding is small since cutting is effected by means of micrograins. One of the technological obstacles is the fact that the tool must be made up of an abrasive and of a matrix. When the tool size is very small, the grain size cannot be ignored. Microgrinding can be applied to the fabrication of micropins and microgrooves, where a grinding wheel with a large diameter can be used. Recent developments in the fabrication of grinding tools have led to the application of grinding in the creation of 2D and 3D microcavities in a system similar to mechanical or EDM milling. Very small grains are essential for microgrinding tools. Sub-micron order grains of diamond, WC, or CBN are desirable for realising good product geometry.

5. Conclusions

Ultra-precision machining technology is the key manufacturing technology enabling creation of various types of high-tech devices and products. One typical example is the ultra-precision diamond machining of hardened steel via the vibration cutting process. The realisation of new high-tech products and production technologies is expected to be enhanced by further development of ultra-precision machining technologies.

To take a typical example of the properties achieved in a work piece by advanced high-speed spindle equipped machine tools, Alschweig states that a surface roughness of $R_a < 0.2$ µm and an accuracy within 2 µm can achieved in the machining of titanium, ceramic, and gold work pieces and the drilling of 0.06 mm holes.

Although cutting is the most conventional machining process, continuous improvement in machining precision has enabled the application of cutting in the micromachining process. Recent results in molecular dynamics simulations suggest the possibility of reducing unit removal to 1 nm (Shimada et al. 1999). Since ultra-precision cutting machines can achieve a high level of positioning accuracy, micromachining by cutting is possible (Mazuzawa, 2000).

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Abstract

This publication documents the papers to be presented at the seminar 'Mechanics for Electronics' that will be held on 4 December 2002 in Otaniemi, Espoo. The seminar presents the m ain results of a research programme (2000–2002) organised and almost wholly funded by the Technical Research Centre of Finland (VTT).

The aim of the research programme was to develop at VTT new research capabilities related to mechanics for electronics and so to strengthen the possibility for VTT to serve its customers in the field addressed by the programme. The programme included five projects and a number of technology reviews.

The projects included in the programme were 'Assembly of mechanics for electronics', 'Thermal management materials in electronics', 'Laser applications in the electronics industry', 'Tailoring of mechanical tests and NDT' and 'Micromachining'.

Keywords
electronics engineering, electronic equipment, mechanics, assembly, manufacturing, mechatronics, mechanical engineering, ceramic coatings, tolerance, fits and tolerances

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