HOW TO TEACH DESIGN FOR MANUFACTURABILITY AT MICRO SCALE TASKS

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ABSTRACT
Designing for manufacturability is a big challenge for every designer. Every manufacturing process has its characteristics and its limits. Costs and manufacturing time are often difficult to estimate, especially for engineers who do not cope with the daily problems of production processes. The relative tolerances are much higher when manufacturing on micro scale than on macroscopic scale and the production processes are generally less stable. An increasing number of products in different industries possess micro geometries and this trend will continue. Therefore the competence to design micro systems for manufacturability is getting more and more important for the next generation of designers.
The wbk Institute of Production Science at the Karlsruhe Institute of Technology (KIT) is researching manufacturing processes on micro scale for more than 10 years. The institute is investigating processes such as micro milling, micro electric discharge machining, micro laser ablation and micro powder injection molding presently and will pursue this in future. Besides this research work the education of students in this field does have a high priority. Since about 10 years students are taught the basics of micro production processes and designing micro systems. Within the program of engineering studies a master course that comprises theory and application of micro systems is offered. This course consists of several lectures on the manufacturing processes at wbk and project work with one of the institute's industry partners. This assures that the students get acquainted with the present problems of manufacturing on micro systems in the industry. Furthermore they learn designing for manufacturability as it is required in real world manufacturing processes.

Keywords: Design for manufacturability, micro systems, project work, education, Q-model

1 DESIGN FOR MANUFACTURABILITY

Design is a very extensive field with lots of different aspects. Designers need a variety of skills to do a good job. Every trade and every company has its own requirements. Some products have to be especially innovative, smart or robust. But all products have one thing in common: they must be manufacturable. Designing for manufacturability is more difficult than it looks like at first sight. If this problem is neglected the consequences are higher production costs or an inferior performance of the final product [1], [2]. At early stages of a design process many aspects of the final product are not yet completely defined. Therefore it is not yet possible to validate the manufacturability of the design. Late changes in the design will have serious consequences: more time and costs must be spent on the designing and the manufacturing process. Existing approaches for this problem offer a solution by simultaneously designing product features and manufacturability.
The "d.school" at the University of Stanford teaches an approach of how to make innovators out of students of many faculties [3]. The approach is called "design thinking" and combines methods from engineering and design with methods from arts, social sciences and other disciplines. Design thinking is based on learning by doing. One of the main activities is generating rough prototypes again and again in order to gain new experience and knowledge.
A German survey shows the growing importance of micro systems in different industries [4]. But how important is the knowledge of production and manufacturing processes for a designer? In accordance with a survey, where design and production professors from universities across Germany were asked, it is of high importance [5]. For designers it is even more important than creativity or the knowledge of dimensioning. This is probably due to the fact that 80% of the product's costs are defined by the designer [6]. In the survey the professors were also asked which the best way is to teach students the necessary design skills and which way they do it today. According to 80% of the interviewees the best

way to teach students design skills is project work. Nobody thinks that lectures are the best way to teach it. This is due to the fact that many aspects of the design process cannot be taught in a lecture. Managing the uncertainty during the development process can only be learned by doing. Is the self-designed product producible and mountable? Students only know it when they do it. Nevertheless, lectures are important to learn the basics. Today, lectures are the most popular teaching method (40%), followed by project work (almost 30%).

2 MICRO PRODUCTION AT THE WBK INSTITUTE OF PRODUCTION SCIENCE

Research on the production of micro parts and systems is done at the wbk Institute of Production Science for more than 10 years. Since about 10 years students learn how to design and manufacture three-dimensional micro systems in a course called “Project micro manufacturing: design and manufacturing of a micro system”.

Within the Collaborative Research Centre 499 (CRC 499) several institutes at Karlsruhe Institute of Technology investigated and developed a process chain for molded micro parts. At the wbk the manufacturing processes micro milling, micro electric discharge machining, micro laser ablation and micro powder injection molding, as well as micro quality assurance were examined. The main task was to develop reliable and stable processes for manufacturing mold inserts. Different 3D parts (i.e. gear wheels) or free-formed 3D parts (i.e. turbine wheels) in overall dimensions from several millimeters down to several 100 µm were manufactured. Figure 1 shows several examples.

Figure 1. Manufactured mold inserts during the CRC 499: gear wheels (left) and turbine wheels as well as bearing shields (right)

3 PROJECT MICRO MANUFACTURING – THE MICRO MANUFACTURING EXPERIENCE

The main task for a course with project work is to answer the following questions: which experience should the students gain and hence which is the best course structure? The difficulty for a designer is to be creative and to get the link between the desired geometry and a rough idea how to manufacture it at the same time. This is what students should learn for micro tasks during this course.

The concept of the course is called the “Micro Manufacturing Experience”. The Micro Manufacturing Experience is the combination of learning by listening and learning by doing at micro scale tasks. Its core is called the “Q-model”. The name comes from the shape of graph (figure 2) whose two circles – Learn, Experience, Understand as first circle and Design, Manufacturing as the second one – remind of the letter “Q”. The Q-model consists of three main points: learning, experiencing and understanding. The learning part consists of lectures about the production processes as well as the CAD-CAM process chain. They are held by PhD students who research on the concerning processes. With this knowledge the students experience micro manufacturing in a workshop. There they have to program a NC-Code which is afterwards produced on the institute’s micro milling machine tool. Since the beginning the students research on the topic and then design a micro system step by step. They generate ideas, concepts and finally CAD-models and blueprints. At the end of the course the students are able to hold the manufactured parts in their hands. With these parts they assemble their prototype and validate the micro system. When the micro system is assembled the students understand for the first time what it really means to design and manufacture a micro system and how designed geometries look like on real parts.

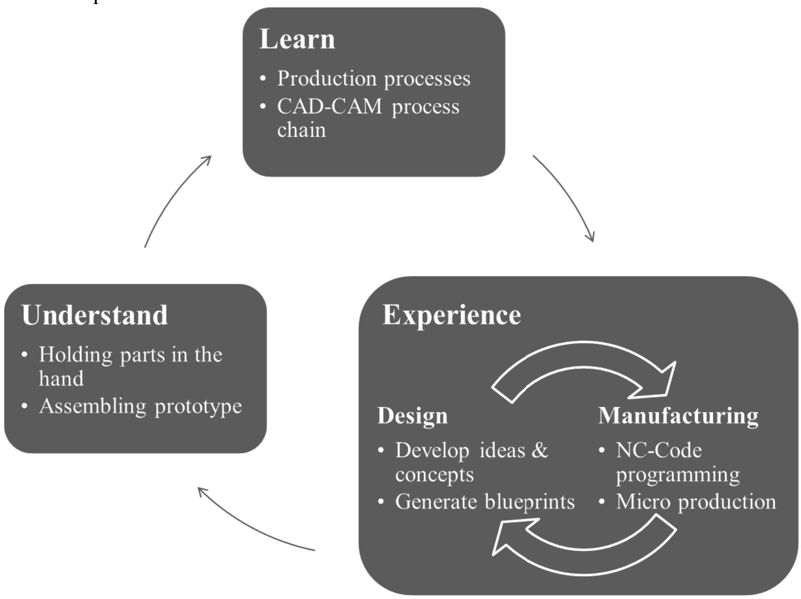

Figure 2. The basic concept of Project Micro Manufacturing: the Q-model

In 2012, for the first time, the task came from a current problem of a company. Traditionally, the task was created using geometries or parts which were already manufactured during the CRC 499 and the goal was to miniaturize the system as much as possible. Good examples are the gear pumps from the years 2009/10 and 2010/11, where the basic geometry of the gears wheels was adopted from formerly produced ones.

4 DESIGN FOR MICRO-MANUFACTURABILITY

So, how to teach design for micro-manufacturability? And what is the difference between design for manufacturability and design for micro-manufacturability? Both methods are about getting the link between geometries and the production process. The difficulty when dealing with geometries or parts on micro scale is that there are much more interference factors than on macroscopic scale. And each factor has a high impact on the tolerances. For example: due to the reduced milling tool stiffness its aspect ratio (length divided by diameter) has to be considered. Depending on the needed tolerances the cutting edge displacement can be a problem. When using micro electric discharge machining very small electrodes may break while touching. The surface quality of laser ablated structures depends on pulse duration and path distance. Depending on the pulse duration bulging can be observed. These are only a few basic conditions which have to be considered when designing geometries on micro scale. A general problem is that there are fewer alternatives to produce geometries or parts and manufacturing times are generally high.

The lecture where students learn the theoretical basics of how to design for micro-manufacturability is the CAD-CAM process chain. It begins with the basics of production development processes and then switches to production-related aspects. The core of design for manufacturability is that it is no dogma. It is always a trade-off between an attractive product design and a low-priced production. Figure 3 shows the difference between a high-end, attractively designed product and its competitor who features an optimized design for manufacturability. The attractive design has a realistic rail design which is mounted with screws onto the bed. When optimizing it for manufacturability the realistic rail design was changed into cheaper extruded sections which are bonded onto the bed.

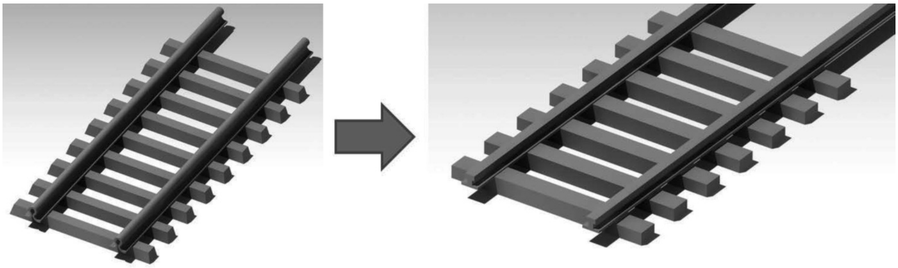

Figure 3. A piece of rail, optimized for design (left) and optimized for manufacturability (right)

5 LEARNING, EXPERIENCING AND UNDERSTANDING

During the learning part students study how micro production processes work and where the differences to macroscopic processes are. What are size effects? How does the process work? How do tools (i.e. an electrode) look like? How do the machine tools work? Which geometries and tolerances are manufacturable? Where are the process limits? Furthermore, the students learn that there are principal guiding rules, how to generate a correct blueprint and how to dimension geometries correctly. The lecture finishes with some CAM basics, first steps in generating NC-Code and the preparation of the machine tool: clamping and aligning the workpiece.

Based on this knowledge the students design their product and decide which production process suits the desired geometries. Then they learn in an iterative process whether the geometries and the chosen production process suit. If not: is it easier to change the production process or to adapt the geometry to the process? The students are forced to find the answer to this question for each geometry. This makes them think about the manufacturability of their parts and gives them a feedback of what is possible.

A very important issue of learning design for manufacturability is discussing it with the students: which process can be used for the desired materials? Which tools are needed for the desired geometries? How can the design be optimized for the chosen manufacturing processes? It is important to force students to think about the manufacturability again and again and to make them question their current design principles and production knowledge. This is why after each lecture the current development status is discussed and feedback concerning functionality and manufacturability of the micro system is given.

In the Experience Manufacturing part the students learn what an NC-Code is, how it is generated and how to get it into the machine tool. This is important due to the fact that most students do not understand what happens with a CAD model after the design process to get a manufactured part. An easy task like the programming of the three wbk letters (figure 4, right) can be done in a pretty short time and shows the basics of how it works. Another very interesting part is what happens after the NC-Code is transferred to the machine tool. What treatment a workpiece needs and which preparations have to be done so that a minimum of tolerances result. There are a lot of things to do before starting the production process which most students are not aware of. Figure 4 shows the machine tool and the milled letters.

Figure 4. The micro milling machine at the wbk (left), two different milled wbk logos (right)

There are two reasons why the wbk letters in figure 4 look different. The obvious one is that the shape of the "b" is different. This is due to the fact that when programming a circle the direction must be defined correctly – it also depends on the construction of the axes. The "b" of the lower letters is defined correctly, due to the fact that after milling the first letters the programming was adjusted. Not so obvious is that the upper letters are a little aslope. For students without manufacturing knowledge this seems surprising. Both wbk letters were manufactured with a tool with a diameter of 0.5 mm. But the upper letters were milled with a 9 mm long tool, the lower ones with a 3 mm long tool. The longer the tool, the lower the stiffness (the 9 mm tool has a stiffness of about 4% of the 3 mm tool) and the more it deforms elastically during milling. The result is that the tool does not enter the workpiece properly and that the lines are not perfectly straight. This is a demonstrative example what micro-specific problems appear and that during design the needed tools have to be considered, at least roughly.

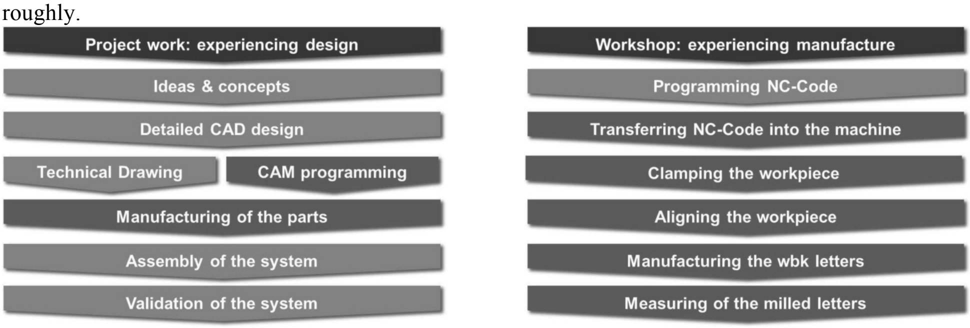

Figure 5. The topics of the project work (left) and the workshop micro manufacture (right). The colors show who is responsible for which job: the orange fields show the student's work, the green fields show what the institute's staff does.

Figure 5 shows the Experience part of the Q-model: the project work and the workshop micro manufacture. The workshop begins with programming the NC-Code. Due to safety reasons the operation of the machine tool is done by the responsible PhD student. Though the students do not operate the machine tool, they can see every step and experience what steps are necessary for preparation.

The project work begins with the announcement of the task during the first lecture. Then the students experience the whole product development process beginning with researching about the product, the market and competitors. Then the next important step comes: finding the problem. The real problem is often not the same as the problem told by the company, which was "too expensive" in this case. The students found out that not the price was the problem but the value for money. So they found ideas and concepts to increase the value without increasing the price. They generated CAD models and blueprints, the parts were manufactured at the wbk and then the students assembled them to prototypes. They validated and presented the prototypes to decision-makers at the closing event.

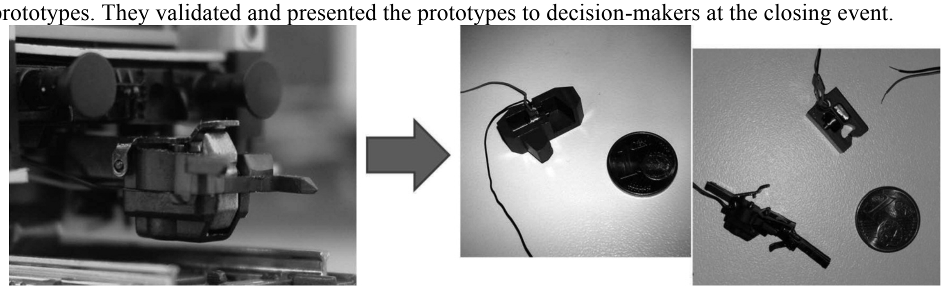

Figure 6. The task: a clutch for model railways (left) and the assembled prototypes (right).

Feedback is an essential part of every learning process. The feedback in the Q-model is given during the understanding phase. In this phase the students get the link between colourful CAD models, which can be created easily, and real parts. To see how small structures really are there is no better way than holding the parts in the hands. Due to the fact that zooming in is no problem for CAD programs and then parts look pretty huge students often forget how small they really are. For students this moment is always impressive. Many students, especially when they study industrial engineering and management, see manufactured (micro) parts for the first time in their studies. And not only manufactured parts but also self-designed ones. Figure 6 shows the task and the resulting prototypes.

6 EVALUATION

As every lecture at the KIT the Project Micro Manufacturing has to be evaluated. Besides the student's opinion it is also important whether the results are useful for the company or not. The evaluation shows that Project Micro Manufacturing is a lecture with a very intense participation, a high effort during the semester but where students learn a lot. The lecture got a very good overall rating which especially results from the real world task.

But not only were the students satisfied after the successful work the company was, too. Every team developed a promising concept. For each concept a prototype was manufactured at the wbk and shown to the company at the closing event. The prototypes showed the functional principle of the concepts and already worked well. Two aspects of the prototypes were persuading: they are innovative but also easy to realize.

However, some things will be improved next time due to multiple feedbacks. The lectures are held through the whole semester. But after several weeks the students would like to focus on the project work. Next time the lectures will be split into two blocks: one at the beginning and the other one at the end during the manufacturing of the prototypes. The students will learn all the important basics at the beginning of the semester. And everything that misses for a complete overview of micro production will be taught at the end when the project work pauses for prototype manufacturing.

7 CONCLUSION

The challenge of creating a task that comes from a current problem of a company is that it must be feasible within 120 hours. This is the available time for every student during the semester for this course. But nevertheless it must be a task where new ideas and concepts help the company to produce new and innovative micro products.

Teaching students how to design for micro manufacturability at micro scale tasks during this course is difficult because of two reasons. The first reason is that most students have to deal with micro systems for the first time. The second reason is that most of the students do not study Mechanical Engineering but Industrial Engineering and Management or Electrical Engineering and have little previous knowledge concerning design or manufacturability.

So students first have to get familiar with the topic and the project work. This is why the important lectures micro milling, micro electric discharge machining and CAD-CAM process chain are held during the research phase. When it comes to generating ideas and concepts students already have a basic knowledge of how to produce micro parts. The workshop where students have to write NC-Code themselves and experience the manufacturing of a part is held in the concept phase.

The "experiment" with a real problem from a company worked out really well and will be done again. For the students it is additional expenditure but they are also much more motivated than before. Additionally, a real task features the need to find good solutions for it and to present them to decision-makers.

REFERENCES

[1] Hermann, J.W. and Cooper, J. New directions in design for manufacturing. In *Design Engineering Technical Conference, DETC '04*, Utah, September-October 2004, pp. 1-9.

[2] Hesse M. and Weber, C. Manufacturability and validation methods in passenger car development – an industrial case study. In *International Design Conference, Design 2012*, Dubrovnik, May 2012, pp. 929-936.

[3] d.school: Institute of Design at Stanford, http://dschool.stanford.edu/.

[4] Arndt, O. and Hennchen, S. Wertschöpfungs- und Wettbewerberanalyse für den Spitzencluster MicroTEC Südwest, November 2011.

[5] Albers, A.; Denkena, B. and Matthiesen, S. *Faszination Konstruktion - Berufsbild und Tätigkeitsfeld im Wandel: Empfehlungen zur Ausbildung qualifizierter Fachkräfte in Deutschland (acatech POSITION)*, 2012

[6] Fischer, J.O. *Kostenbewusstes Konstruieren: Praxisbewährte Methoden und Informationssysteme für den Konstruktionsprozess*, 2008.