GRADUATE AND PH.D. COURSE ON DESIGN AND MANUFACTURE OF MICRO MECHANICAL SYSTEMS

H.N. Hansen, A. De Grave

Department of Mechanical Engineering, Technical University of Denmark

ABSTRACT

Micro mechanical components play an increasing role in micro systems with product dimensions ranging from micrometers to millimetres. The use of metals, polymers and ceramics for miniature components requires product development methods as well as specific manufacturing technologies. Indeed it is now well known that micro/nanotechnology is not only a matter of downscaling applications and methods from the macro scale, and therefore an in-depth understanding and knowledge of product and process characteristics at this scale is necessary. Based on this challenge, a new course was developed at the Department of Mechanical Engineering at the Technical University of Denmark. This paper describes the framework of the course that has been applied both at graduate and Ph.D. level. The current structure of the course as well as the pedagogical approach and some examples of final projects will be presented. Moreover, the transformation of the traditional semester structure (13 weeks and 3 weeks project) into a 2 weeks PhD summer school is discussed.

KEYWORDS

Micro manufacturing, multidisciplinary teaching, theoretical and practical balance

CONTEXT: SPECIFICITIES OF MICRO PRODUCT DEVELOPMENT

The design and manufacture of mechanical micro and nano products (or systems) is still considered to be a very difficult and challenging task. For one, the manufacturing technologies used to produce them are either emerging or pushed to the limits of their capabilities [1]. In addition to that, the physical working principles and design solutions are often not in the same area as common engineering, taking roots in for instance biology and fundamental physics rather than in mechanics. Moreover, little of this knowledge corpus is stabilized and available outside of the research and development context. The very nature of micro products induce a collaborative and multidisciplinary way of working, such as in MEMS design [2]. All of these concepts require both specific research and teaching activities.

One major issue is the multidisciplinary community involved in the development process of those micro / nano scaled products. It creates communication problems and an interlaced network of knowledge-related topics. Indeed, manufacturing knowledge is reckoned to be extensively used all along the design process, although knowledge in this field is neither stable nor mature. Another major issue in the development of micro products is their integration with the external world or the system, and how to make them fit and interact inside macro scale products. Packaging for micro products not only includes electric connections and protection of the systems (as in VLSI chips), but the physical interface is also required to achieve specific functionalities, e.g. fluidic couplings [3].

Old design premises state that design is independent of the technologies or of the product involved. They also reckon that a product development process has to include analysis of the design problem, synthesis of possible solutions and evaluation of design proposals all in a traditional problem solving approach. It has been shown both in industrial practices and through research in design methodology that such premises are not only outdated but also most often can result in bad design. The products and the technologies are all part of the product development scheme and should be given attention throughout the development process. Moreover the designers represent a complete part of the design process where creativity and difficult-to-model activities abound. Design as a discipline should cover theses three aspects of product development [4].

The research conducted at the authors' group cover products, methods and manufacturing processes: On the products side close collaboration is carried out with industrial companies requiring mechanical solutions on the micro scale. The sectors include medical, hearing aids, electronics etc. and an example is an interactive optical display for Bang & Olufsen [5]. MID technologies are also part of the products investigated.
From a methodological point of view, studies comparing a product driven approach and a technology push approach in the design of for example a superhydrophobic surface using a biomimetic approach [6] are conducted. They include metrology and surface engineering issues [7]. The inclusion of life-cycle assessment in the development of micro technologies is also part of the line of research.
On the manufacturing process side, replication techniques for mass production such as micro injection moulding [8,9] or micro metal forming [10] are investigated. These technologies require tooling and therefore various manufacturing technologies are investigated: micro milling, laser processing, micro EDM, electrochemical deposition etc. [11].

As previously exposed, design of such products and using such processes can only be made viable in a very collaborative environment. A collaborative culture is needed to create the framework to work in. Indeed, more and more industries adopt multidisciplinarity and concurrent engineering based methods to achieve innovation and product development in accordance with the classical triptych "cost-quality-delay" dilemma, especially with the current fast time to market which is required. Such an approach has been called the PMP approach, Product-Method-Process [12], at the University of the authors, as illustrated fig.1.

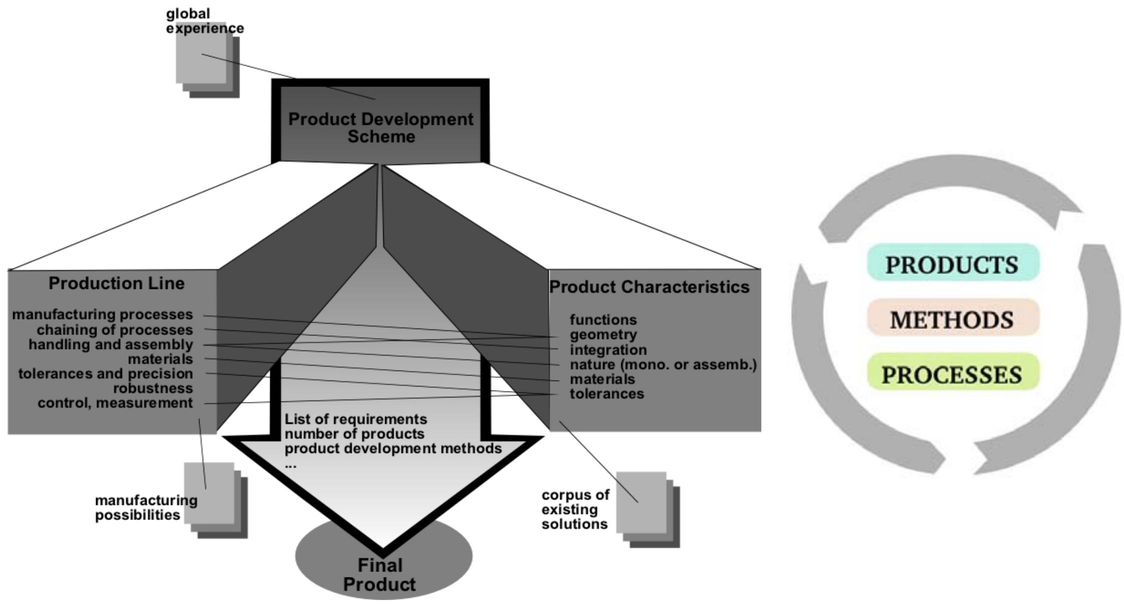

Fig.1. Representation of a product development scheme, product and process are developed concurrently and are tightly linked, as also shown in the PMP circle.

As often stated, real-world practices and education are feeding each others. Indeed students are the company employees of tomorrow and bring new methods and tools (e.g. the adoption of CAD/CAM systems in the history of automated production) to the industry. These new methods and tools are transformed by industrial usage and have to get back inside the classrooms. Therefore it is crucial to have not only product development courses that focus on all the multidisciplinary aspects of engineering design, but also which take into account the specificities of the micro/nano scale products and industrial practise.

PEDAGOGICAL CONSIDERATIONS

Numerous studies have been made about pedagogy and teaching. Some of them contain axioms or principles to enhance the student ways of learning [13]. Following such principles can help tailoring courses once scientific aims and objectives have been set. Important elements include:

1. Interest and explanation: It is very important not to make the lesson drudge but pleasant to follow, create it enjoyable to work at it. The beginning of the course should clearly show the benefits of the outcome.
2. Concern and respect for students and student learning: As Eble [14] states: "knowledge suffers no loss when it is shared", the availability from the teachers for consultation about academic work has to be provided. For example, in DTU, a website is available as a file sharing and forum to enhance discussion between teachers and students. Moreover appropriate assessment and feedback are necessary for the students to acknowledge their progresses. Evaluation and self evaluation is an essential issue.
3. Clear goals and intellectual challenges: A balance between freedom and discipline (interesting challenges are the core of the "romantic" aspect of learning) has to be found in order to keep the overall spirit of the course high and propitious for learning. Experience showed that colourful examples along with hardcore scientific matters keep the attention of students, as well as real-life industrial cases.
4. Independence, control and active engagement: Students have to practice the art of inquiry by themselves. Indeed independence ensures the individuality of some part of the learning because each student is different, although teaching cannot be tailored

for each one of the student. Moreover the grading system in DTU allows a significant value of independence, along with actual results to exams and exercises. Besides, collaborative learning and competitive (or individualistic) learning have to be among the practices of students. The course should provide both ways of learning.

5. Learning from students: Feedback from the students is essential to improve the course and keep it to a high level of education.

Surely the taught topic is of tremendous importance and brings many specific issues in the way to teaching. In the case of the described set of courses a full list of learning objectives will be given in the next paragraph.

However, teaching about design methods is somehow different than teaching specifically about manufacturing technologies or working principles for engineering solutions. For instance, there is no official generic theory about design. It is therefore difficult to lecture about how to design, as in a set of systematic rules and actions to perform that will ensure a good design. The authors think, along with Schon [15] and Prudhomme et al [16], that part of the education of designers should come from reflective practices where one (students but also engineers in the case of an industrial workshop) built experience and knowledge in a contextual way. Students learn to become more aware of how they know what they know, as well as what they have learned. That doesn't mean that design methods such as the axiomatic design [17] or the systematic top-down design [18] should be turned down, they are part of the background and the culture of designers. Especially in the field of micro technologies the Design for Manufacturing is a key point to be understood and applied by the students. Such methods provide a framework in which to work and raise relevant questions. It is fundamental to have a broad knowledge in terms of methods and also enough distance to know how to choose among them, their strengths and weak points. During the course the students will have lectures on design methods, on methodology and they will be involved in a reflective analysis of their own design practices in a design role-playing game: the Delta Design game [19]. We also believe that it is important to put product development in relation to the global economy and world development. It is not the purpose of this course to give extended knowledge about history or economics, a historical point of view is nevertheless given about design. Indeed it is important to understand how design evolved from being a one man craftsmanship to a multinational concurrent engineering team collaborative work.

The application of CDIO principles to this particular context seems intuitively straightforward. Nevertheless, the practical implementation of conceive-design-implement-operate into this context has involved the establishment of an industrial-like learning environment and the definition of learning objectives that reflect a holistic teaching approach (technical skills, personal skills, social and collaborative skills).The content of the course(s) is built around Design-Build experiences and a natural progression has been implemented in the course(s). The course(s) are constructed as a full blown engineering design process with “just in time” information given to or constructed by the students as they move along.

DESCRIPTION OF THE SET OF COURSES

Teaching is of course a matter of telling (or transmission) but it also consists of organizing student activities in order to make learning possible and with the best output possible. Therefore clear aims and objectives, and careful scheduling have to be defined. Aims are general statements of educational intents, whereas objectives are more specific and concrete statements of what students are expected to learn in single lectures. Also it is important to adapt from the students background and expectations, reasonably.

The course set encompasses two separate courses titled: "Introduction to micro mechanical system design and manufacture" (course #*41742* in the DTU catalogue) and “Workshop in micro mechanical system design and manufacture” (course #*41743*). The first course will give the students the necessary technical competences to actually be able to be succesfull in the second course.

The courses are designed for both graduate students and PhD students. By micro mechanical systems it is meant complex products, systems which are multi-material but not focusing on silicon (MEMS are not treated into details during the course even if an introduction to silicon manufacturing is given). The courses are as previously stated closely related to the industry, through examples, lectures, and excursions... Besides, the second one, more applied, is based on an industry-like project in order to give students an overview of a complete product development process. The students indeed acquire the necessary knowledge to achieve the complete product development and do actual manufacturing and testing of a specimen. That can be called process chain prototyping rather than simply product prototyping as the project is done within a real mass production frame and actual pre-series like production is realized. Examples of students realizations are given below.

The main aim of the course set is to build a new knowledge corpus applied to micro scale (most of the students already have some manufacturing or mechanical engineering basic knowledge) and develop new skills, including projects and teamwork. This has already been studied both in macro scale mechanical design and in pedagogical science, as previously discussed. Our teaching choices have clearly been focused towards multidisciplinarity. Students should understand the "real" nature of design activities, with collaborative phases and develop skills and competencies in various manufacturing technologies. The course plan is innovative in that it focuses equally on methods, various manufacturing techniques and specific micro mechanical systems issues from the product functionalities side.

In terms of learning objectives, after the described courses the students would be able to:

41742

- Evaluate the effect of miniaturisation on every aspect of product development
- Propose coherent complex micro manufacturing process chains adapted to specific micro components
- Evaluate quantitatively output and principle characteristics of single micro manufacturing processes
- Evaluate product characteristics and functional principles at micro scale
- Apply systematic methods to create a coherent sequence of actions leading to product production
- Apply a set of formal design methods based on design for manufacturing
- Perform basic calculation for validation of conceptual design solutions at micro scale
- Present decisions and results in reports

41743

41743

- Identify and derive detailed technical specifications of a micro mechanical component based on functional requirements
- Propose various designs
- Compare various design proposals based on technical capabilities by applying the design for manufacturing (DFM) approach
- Rank and choose different designs based on criteria such as functionality and manufacturability
- Evaluate selected micro manufacturing processes using experimental approaches
- Verify single components and assemblies using metrological methods
- Produce technical drawings for a specific micro mechanical system and related production equipment
- Present decisions and results in terms of reports and presentations

Lectures are designed to fall into the three PMP categories (sometimes overlapping): products, methods and manufacturing processes. As some processes are part of a bigger scheme, such as mass replication techniques, a particular attention has been given to the scheduling. For instance it was chosen to give the lecture about replication processes early in the course in order to introduce the notion of tooling, and subsequently come lectures about specific manufacturing technologies such as micro cutting, micro EDM, electroplating, etc. These methods have been successfully known to produce good candidates for real production as stated by [11,20].

Moreover, the described technologies are available in the laboratory and are extensively used during the three weeks project of the second course. In order to have the students more proficient with the necessary technologies and ensure a successful project hands-on workshops are given at the beginning of the practical course. Indeed in order to engage the students more in the practical project work, a series of intensive tutored workshops were developed in the first half of the course. The students are therefore divided into “specialist” groups. However, these workshops only stimulate the students. They do not enable them to be totally self-operating if no prior experience with practical manufacturing issues exists; a lot of interaction with laboratory and workshop technicians is expected. The requirements to enter such a course should be set carefully. Obviously having taken the introductory course (#41742) is a very highly recommended prerequisite.

In the beginning of the practical course the Delta Design game is introduced, a role-playing game / social experiment designed to present collaborative design ways in a practical form. Reflective practices have been discussed previously and the use of Delta Design in teaching design has been studied by [16]. Moreover, in courses such as the one described which target the global product development scheme, many theoretical notions have to be conveyed, in many different fields: design, project planning, manufacturing technologies, specificities of some areas of physics (fluidics, optics, solid mechanics, etc.). That can lead to a course not very attractive to some students, most of them being more eager to have “hands on” experiences than to manipulate endless streams of equations. One of the solutions is to create project works to apply the knowledge and competencies acquired during lecturing time. And to attract students one has to design attractive projects. These projects can be falling in 3 categories:

1. useful in real life
2. in partnership with the industry
3. fun!!!

It is very important to design projects that will stay in the memory of the students because students talk to each others. Also some of these projects can be used as a display by the communication department of the University through local newspaper, etc.

#	Lectures and/or activities			
1	Introduction	Process chain overview	Product overview	Size effects modelling
2	Correction exercise on size effects	Micro injection moulding, hot embossing and simulation for moulding		
3	Micro milling		Micro EDM	
4	Laser micro manufacturing	MEMS processes introduction	Electroforming	
5	Micro metal forming		Feedback session on report #1	
6	Micro tooling process chains (with exercise)			
7	Correction exercise on micro tooling		Metrology part I	
-				
8	Design methodology (historical perspective, collaborative design, ecoDesign)			
9	Micro glass moulding (with industrial partner)			
10	Metrology part II		Tolerancing	
11	Micro handling and assembly			
12	Industrial vsit at Sonion			
13	Feedback session on reports		Preparation for final exam	

	09:00 - 10:30	10:30 – 12:00	lunch	13:00 – 15:00	15:00 – 17:00
Week #1					
Monday	intro			Lecture on collaborative design	Delta Design rules and analysis method
Tuesday	Workshops			Workshops	
Wednesday	Students' presentation on workshops			Delta Design experiment	
Thursday	conceptual design	Lecture on micro fluidic theory		Conceptual design (continued)	
Friday	Detailed design + Process chain design			Detailed design + Process chain design (continued)	
Week #2					
Monday	Project work			Project work	
Tuesday					
Wednesday					
Thursday				Prototyping of test design	
Friday				Project work	
Week #3					
Monday	Project work (Design refinement)			Project work (Design refinement)	
Tuesday					
Wednesday					
Thursday					
Friday	presentation preparation			Examination (presentation + individual oral exam)	

Fig. 2. Example of the scheduling for the thirteen weeks periods of lectures followed by the three weeks project work..

Therefore the three weeks project is an important part of the course and is recommended to all students from the theoretical introductory course. Indeed it allows the students to apply their knowledge, skills and competencies acquired from the lectures. It also mimics an industrial project, reinforcing the link to real world. Moreover, it can be seen as a prolongation of the Delta Design game in real life and provides a ground to further reflective design practice. This organisational part is also of interest in the evaluation of the project and the assessment of the students.

The 3 weeks course starts with a kick-off meeting where an on-purpose very rough list of requirements is given to the students and where they learn about their assessment. Each student is assigned to a speciality regarding his background, level, etc. In addition to the four roles of tooling, joining, polymer processing and metrology, the one of project manager, in charge of organising meetings and keeping track of time, availability, delay and enhancing the communication in the group is created. Sometimes the teachers impose the population of that role and sometimes some students fill it up themselves. The students have to produce a report in common with specific parts related to their field of speciality. They present their project at the end of the three weeks in front of a jury composed of teachers and external censors and are furthermore questioned individually on their speciality and general concepts on micro technologies.

An application often chosen as topic for the project is a micro fluidic device. It is so because of the relatively intuitive understanding of the general concept. An example of such specifications could be a fluid mixer. E.g. two chemicals have to be inserted with syringes and shall mix in channels. They end in a chamber where the mix can be assessed through a change in colour. The project includes functional design, material choice and process planning, testing, etc. At the beginning of the project the students have a very contextualized and fragmented knowledge about micro technologies but in most of the cases they succeeded in designing a complex process chain and obtained a functional device, somehow meeting the starting requirements. They not only succeeded in each step of the design and manufacture but also in their aggregation.

A special version of the course included a project with the aim of producing the “world smallest USB-powered espresso coffee machine”. This project obviously fit into the category of “fun project” and it encountered great success amongst the students. The final device featured a water container, a coffee powder container, a heating unit, a filter and a collection unit for the brewed coffee. The overall size approximately 30 x 30 mm and the channel and filter system has a variety of dimensions going down to 100 microns. The chosen technical solution was realised in polymer material and the working principle is directly inspired by the “Italian mocha.” It can lead to very complex calculations as it is highly multi-physics. Heating the water was achieved using a built-in electrical resistance introduced during the embossing process. The chosen process chain included micro milling, hot embossing, assembly and laser welding. Figure 3 illustrates the proposed design (left) as well as an illustration of the final component for testing (right).

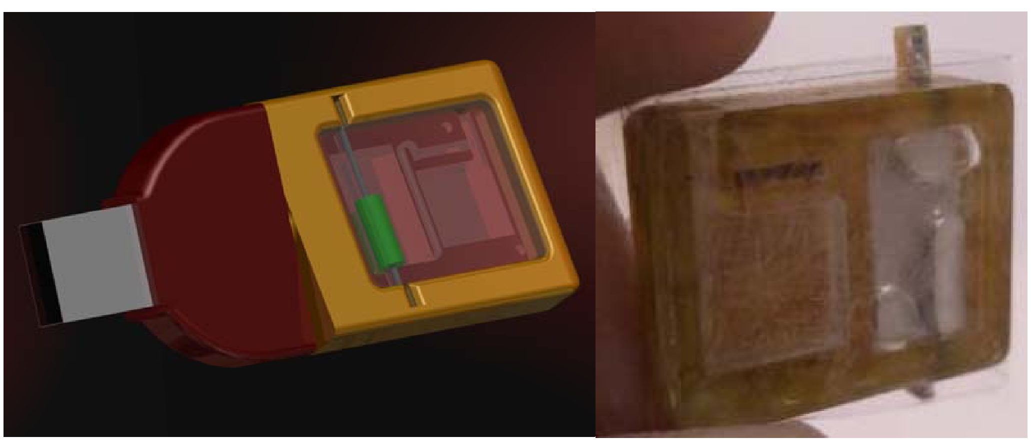

Fig.3. Micro coffee machine: conceptual design and final product held between two fingers.

THE EVALUATION ISSUE

The evaluation of the theoretical course is based partly on reports (by groups of two or three students) and on a final two hours written examination. The reports' aim is twofold it links products and processing in a real case example and it also prepares the students for the exam. Indeed each group is given a micro product (a description in an article, sometimes an actual part). The first report is based on functionalities with a link to critical micro features and targets a possible re-design of the part. The second report builds on the first one and focuses on the process chain to manufacture the given micro product in the case of the chosen re-design. As the second report is situated after the middle of the course the student should have the necessary knowledge to chose and describe the new process chain. Indeed, the final written exam consists of two technical drawings of micro parts that need to be studied in order to highlight critical micro features and to produce relevant descriptions of process chains for prototyping and full production. All aids are allowed as it is a matter of aggregating knowledge related to manufacturing, functional issues and the analysis of downscaling. The authors believe that completing the reports gives a good chance for the students to practice for the exam. Of course activities during the course are aimed at gradually getting the students to a level of proficiency allowing them to achieve all necessary actions in order to perform well at the exam.

In addition to technical skills, the authors believe that evaluation should be based also on communication skills. Indeed engineers use a significant portion of their time writing reports, crafting oral presentations... Moreover in the multidisciplinary framework for product development, negotiation and communication are everyday activities performed by designers. A pertinent evaluation should reflect it. Therefore the evaluation of the practical course involves a group presentation based on a sideshow presentation and a common report. The report also must contain description of and reflections on the project management during the 3 weeks. This allows to judge the technical knowledge acquired during the course as well as organisational skills and communication skills. In order to get an assessment of each student an individual oral examination is carried out after the common presentation. The questions are based on the role the student played in the project, global knowledge about the whole design process and specific micro technology knowledge.

ADAPTATION OF THE COURSE SET INTO A TWO WEEKS PHD SUMMER SCHOOL

The time frame of the summer school is very limited compared to the graduate “mother” courses, and the wide range of participants makes it even more multidisciplinary. It is composed of two weeks with approximately 8-10 hours of work per day. Nonetheless it was decided to keep the same structure and more importantly to keep the project work with actual hands-on experience and devices production. Two lecture slots are planned each morning and attendees were asked to actively participate in most of them. Whenever necessary, exercises and practical works are held as in the graduate course but of course fitting the time constraints. Lectures are placed usually during the morning and practical work is done during afternoons. The lectures in the morning would cover the necessary knowledge needed to continue the product development of the afternoon project, together with some technical workshops for more specific and applied knowledge and practice related to equipment in a “just in time” approach.

Concurrently, the attendees are asked to complete a design project running during the whole course length. For this work, the students are split into groups. In order to have successful working groups, the Delta Design game (as in the “mother” course set) is used again, which then not only teaches the collaborative nature of design activities but also helps the students to know each others better as they will be put into teams according to the same structure. The grouping is made in an arbitrary manner by knowing in advance the PhD study topic of the participants. The project starts the second day by some functional and process chain design (based on a list of requirements from the teachers, it can also be done in accordance with industrial needs) then moves to tooling, production of prototypes (in a "mass" production scheme) and testing of physical implementations of the design during the whole length of the two weeks. The last day a presentation of the project stands as a wrap up of the course and evaluation.

As this summer school is held in collaboration and with the sponsorship of various institutions (for instance the 4M - Multi Material Micro Manufacture former European Network of Excellence, now association (http://www.4m-association.org/), the French Embassy in Copenhagen) several international researchers and teachers are asked to give guest lectures; and one guest lecturer also acts as an external censor during the last day presentation. Furthermore, each group completes a report as documentation for their work. In order to reach a significant amount of working hours for 5 ECTS points the students also have to produce a conference proceeding-like paper and a short introduction to their PhD subject (held around the middle of the course). The papers are then grouped into an addamentum to the lecture folder provided.

DISCUSSIONS AND CONCLUSIONS

A graduate and PhD level course in the field of micro / nano mechanical products has been presented. The course is closely linked to industrial reality and to the key technologies within the field. Moreover, a specific innovative way of teaching it through products, methods and manufacturing techniques (PMP) is developed, applied also in research activities.
The course has been developed over 4 consecutive years, and the feed back from the students has been extremely useful and very positive. In particular the combination of theory and practical hands-on experience seems to be popular. This is one of the strongest characteristics of the course, and also the most critical point with respect to planning and execution of the course. The course requires access to laboratory facilities and also assistance from technicians. From this point of view the course is relatively expensive and labour intensive. When the course is being taught to PhD students, the ambition can be increased. In particular, the specific background of each student can be integrated into the planning of the project work. The course has been adapted and successfully run 3 times as a PhD summer school.
The overall experience of the authors is that teaching a multidisciplinary topic (as the one described in this paper) is highly supported by choosing a CDIO approach. However, a careful planning of the course is required if a positive outcome (as seen from the student's perspective, e.g. a working prototype) during the limited time should be achieved. It is also the experience that a very pro-active engagement of the teachers during the project work is necessary to guide and coach the students without falling into the “pit” of giving solutions.

REFERENCES

[1] Alting L, Kimura F, Hansen H.N, Bissacco G, "Micro engineering", Annals of CIRP 52, 2, 2003, 635-658

[2] De Grave A, Brissaud D, "Integrated Design of MEMS", Journal of Design Research vol6 no2, 2007

[3] Baldwin D.F, “Challenges and Solutions for Packaging MEMS and Microsystems”, in Proceedings of Electrochemical Society, vol 2000-19, 55-71

[4] Cross N, Design as a discipline, in support of the Interdisciplinary Design Quandary Conference in De Montfort University, 2002

[5] Prichystal J.B, Bladt H.H, Hansen H.N, "Invisible display in Aluminium", Photon Processing in Microelectronics and Photonics IV, Proceedings of SPIE vol. 5,7 no13, 2005, 215-222

[6] Wenzel R.N, "Surface roughness and contact angle", Journal of Physical Colloid Chemistry, vol.53, no. 9, 1949, 1466-1467

[7] De Grave A., Botija P, Hansen H.N, Tang P.T, “Manufacturing and characterization of water repellent surfaces”, Proceedings of the 2nd International Conf. in Multi Material Micro Manufacturing 4M2006, Grenoble, pp281-285
[8] Theilade U.R.A, "Surface micro topography replication in injection moulding", Ph.d Thesis Technical University of Denmark, 2004
[9] Tosello G, “Precision molding of polymer micro components”, PhD Thesis Technical University of Denmark, 2008
[10] Arentoft M., Paldan N.A., Eriksen R.S., Gastaldi T., Wert J., Eldrup M., “Bulk forming of industrial micro components in conventional metals and bulk metallic glasses”, Proc. 10th ESAFORM conference on material forming, 2007, 665-670.
[11] Bissacco G, Hansen H.N, Tang P.T, Fugl J, “Precision manufacturing methods of inserts for injection moulding of microfluidic systems”, in Proceedings of the ASPE Spring topical meeting, Columbus, Ohio, USA, 57-63, 2005
[12] Hansen H.N, De Grave A, Bissacco G, Micro products development methods, how do we focus on the right issues?, in Proceedings of the 4M conference, Karlsruhe, 2005
[13] Ramsden P, Learning to teach in higher education, Routledge edition, 1992
[14] Eble K.E, The craft of teaching (2nd edition), San Francisco, Jossey-Bass, 1988
[15] Schon D.A, The reflective practitioner, how do professionals think in action, Ashgate edition, Aldershot, England, 1991
[16] Prudhomme G, Boujut J-F, Brissaud D, “Toward reflective practices in engineering design education”, Journal of engineering education, n19(2), 328-337, Dublin, 2003
[17] Suh N, “The principles of design”, Oxford Series on Advanced Manufacturing, 1990
[18] Pahl G, Beitz W, “Engineering design: a systematic approach”, Springer Verlag, 1996
[19] Buccarelli L.L, Delta Design game, copyright 1991 MIT, All rights reserved
[20] Bissacco G, "Surface generation and optimization in micro milling", Ph.d Thesis, Technical University of Denmark, 2004

Biographical Information

Hans Nørgaard Hansen is a professor of micro manufacturing at The Technical University of Denmark, Department of Mechanical Engineering.

Arnaud De Grave is associate professor at The Technical University of Denmark, Department of Mechanical Engineering. He is specialized in design of micro systems.

Corresponding author
Pr. Hans N. Hansen
Department of Mechanical Engineering
Technical University of Denmark
Bdg 427S, produktionstorvet
2800 Kgs Lyngby
Denmark
email: hnha@mek.dtu.dk