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MICRO-SPECIFIC DESIGN FOR TOOL-BASED MICROMACHINING

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1. Introduction

Microsystem technology originally was based on technology for microelectronics. Silicon micromachining arised from these processes and matured to a discrete domain. At the same time, LIGA appeared as a novel technology enabling a great twodimensional design space, a high achievable depth of structures compared to their lateral dimensions (aspect ratio) and more applicable materials. Caracteristic for both silicon micromachining and LIGA are structuring steps by means of exposure to radiation through a patterned mask. Hence, theses technologies are mask-based. By miniaturization of established conventional machining technologies from mechanical or precision engineering, a new field of microtechnology, tool-based micromachining, came into being. Basically, the technology of tool-based micromachining is the entirity of all processes needed for creating microsystems consisting of casted or injection molded components. On the one hand, these are the afore-mentioned production processes for casting and injection molding of thermoplastics, metallic or ceramic powders. On the other hand, these processes comprises all of those that are required for creating mold inserts, i.e. separative (e.g. milling), erosive (e.g. electro-discharge machining) or laser ablative processes. A unique feature, compared to mask-based technologies, is the expansion of the design space into the third dimension enabling real threedimensional structures and even free-form surfaces. At the same time, design is strongly influenced by technological conditions and restrictions, e.g. minimum structure thickness, achievable aspect ratio or maximum flow lengths, which have to be considered mandatorily when designing such systems. Due to these influences by production technology, technology-specific knowledge has to be transferred to the preceeding stage of design. In order to ensure this transfer of knowledge, integration of means of knowledge management is required.

Established universal development and design processes are applicable for all kinds of technical systems. Due to higher complexity of systems and to conditions resulting from superior objetives (costs, development time and quality), universal development processes seemed to be not efficient and hence domain- or even product-specific processes, e.g. in microelectronics or mechatronics, were created. Thus, for an efficient product development for tool-based micromachining, a specific process description is required. Additionally, in contrast to macroscopic design, which is strongly driven by market requirements, the orientation on what is producible results in a technology-driven design approach. Due to peculiarities of tool-based micromachining, a special design flow was developed, which integrates design rules as a means for knowledge transfer.

2. Design Flow

2.1 Micro-specific Design in a Life Cycle Context

Observing a typical product life cycle of a tool-based micromachined system is required for getting to know its influencing surrounding, i.e. preceeding, subsequent and adjacent stages (cp. Figure 1a). In macroscopic product development, development initiation derives from the market, i.e. from three interacting players: customer, competitor and the producer. In addition to those three market players, a microspecific fourth one, technology, has to be added. In this case, technology means all scientific contributions to the development process, i.e. production technology or material sciences. Within the following product profile stage, general product features have to be defined without closer specification of material or shape. Target fields for possible products result from strategic freedom, customer demands and market trends. Now the task is to fill these target fields with product ideas. By the constitution of the system of objectives, all product-related objectives and their interactions are determined. This step is required for conretizing the task and clarifying vague demands to the object system (the later product). Therefore, the system of objectives is a structured constitution of target features of the desired object system.

Following the system-based approach, every system consists of associated and interacting elements, which interact as entirity with their surrounding. Each element again can be segmented into subsystems. This system-based concept can be applied for every kind of system, whether being a material or social one. Regarding technical systems, three types of system are of outstanding interest: the system of objectives, the operation system and the object system. When concretizing an idea, whether being micro-specific or not, the first step is the consitution of a system of objectives, which represents the mandatory features of the desired object system, i.e. the later product. Following the route from product idea to the final product, two significant subsystems have to be considered: development and production.

Based on the specification of the system of objectives, the operation system "development", i.e. design itself, creates the "development" object system, which at the same time corresponds to the system of objectives of the subsequent production process (cp. Figure 1b).

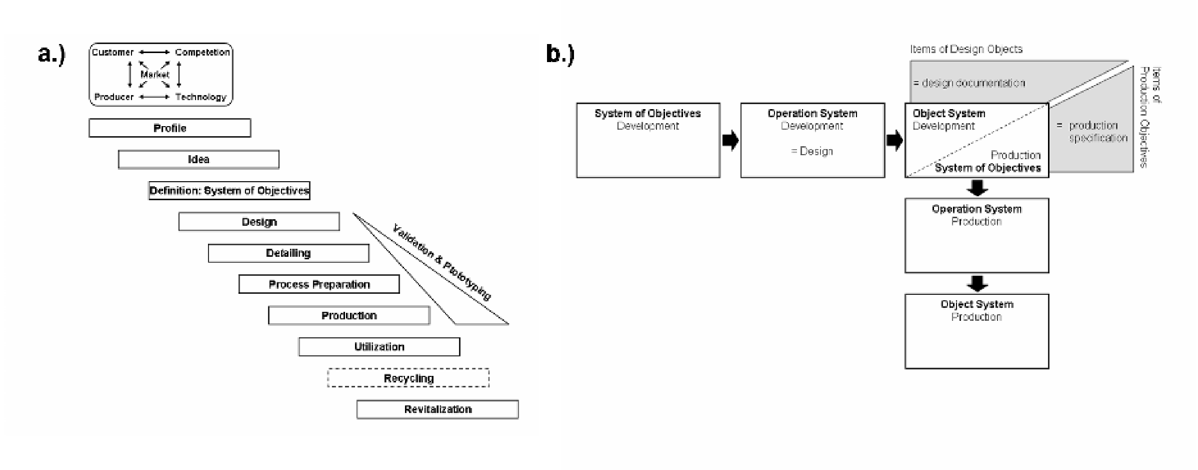


Figure 1. Life cycle stages (a.) and system-based description (b.)

During the detailing stage all development-related items, i.e. the "development" object system, are documented. Concurrently, production specifications representing the "production" system of objectives are composed. Hence, detailing converts the "development" object system into the "production" system of objectives. 3D-CAD models, assembly drawings or dimensioned drawings represent the "development" object system, while the "production" system of objectives comprises for example the same 3D-CAD models scaled in order to compensate for sinter-shrinkage, or mold designs for process preparation. Subsequent to the development process the stages of of process preparation and production follow in order to realize the final product. Simultaneously, validation and prototyping stages accompany the design, process preparation and production. Product utilization, possibly recycling and revitalization terminate the product life cyle.

Tracing back the influences affecting design leads to the stages of process preparation and production. These influences, i.e. technological conditions and restrictions have to be detected and provided, e.g. in form of design rules.

2.2 Design Flow for Tool-based Micromachining

Specific models for microtechnology were developed since several years. In 1983 Gajski and Kuhn [Gajski, Kuhn, 1983] presented a model for developing integrated circuits in microelectronics, which is characterized by a tripartite representation of design (Y-chart), which was enhanced by Walker and Thomas in 1985 [Walker, Thomas, 1985]. Their model consists of the three perspectives, the behavioural, the structural and the physical one, arranged in Y-shape with a common vertex and concentric rings, which represent the levels of abstraction, whereas the outer ring represents the system level and the inner ring the circuit level. For masked-based micromachining, Brück and Schumer employed a highly iterative “circle-model” [Brück, Schumer, 1998], which comprises the four steps of layout design, process development, verification and process modification being arranged in a circle and which especially considers the concurrent development of mask layout and production process. Hahn adapted the Y-model [Hahn, 1999], whereas the evident differences can be seen in the levels of abstraction, which are system, component and structural level. The concurrent development of product and its production process is essential due to the fact that the latter is application-specific and furthermore heavily influences the later shape. In 2003, Wagener and Hahn presented the “pretzel-model” [Wagener, Hahn, 2003], which also shows the parallelism when designing a microstructured product and its structuring process.

Considering tool-based microtechnology, there exists a strong orientation on what is producible. Hence, design is technology-driven – in contrast to macroscopic design, which is driven by conventional market requirements. This technology-driven approach leads to concurrent handling of concepting and designing stages on different levels of abstraction. Figure 2a.) shows the single stages when designing a tool-based micromachined product. While making conceptual decisions related to functions on system level (top-down), concurrently components have to be roughly designed and structures have to be detailed (bottom-up), due to the heavy influence of technology. Then single components can be designed detailedly. Finally, system design is accomplished. It comes to the fore that design continuously changes between considerations of the complete system and single structural details under special regard of conditions and restrictions deriving from technology. These technological conditions and restriction can be of of a geometrical or material origin, e.g. material characteritics or effects. In micromachining, special regard has to be paid to those effects: due to downscaling macroscopically intensively acting effects can diminish or even disappear while other macroscopically irrelevant effects appear. All of those technological peculiarities have to be considered when designing.

The special aspects when designing tool-based micromachined systems are visualized by the “sickle-model” (cp. Figure 2b.), which is named in accordance to the sickle shaped transition from the design stage to the detailling stage. Counterclockwise, the design flow with its three stages (conceptual, basic and detail design) is plotted. Concentric rings represent the three levels of abstraction on which design is performed, i.e. structural, component and system level. Superposing the bottom-up design from structural to system level and the top-down design from conceptual to detail design forms a global, sickle-shaped curve. On purpose the model is laid out iteratively. Thus, in case of a suboptimal result, the designer can pass through another iteration loop. For the transition from functional description to embodiment, regarding of the junction of design and detailling leads to a “methodological stage of transition”. The designer approaches on system level this transition stage with the results from conceptual design. Based on extracted functions and subfunctions, the designer uses methodological means, e.g. effect catalogues, in order to find working priciples, repectively effects, which fulfill the desired functions. Concepts derive from combinations of those working principles and partial solutions. They comprise functional items and basic shapes without any closer specification of materials or dimensions. The system is subdivided into components. Details of the functional items have to be defined on structural level with respect of technological conditions and restrictions. Latter are externally provided, e.g. by a knowledge representation, for which design rules are employed. The representation describes knowledge from subsequent or adjacent stages, e.g. process preparation, in terms of just realizable structural details, e.g. a minimum edge radius. Hence, in order to adhere to invariant structural details the transition stage is required.

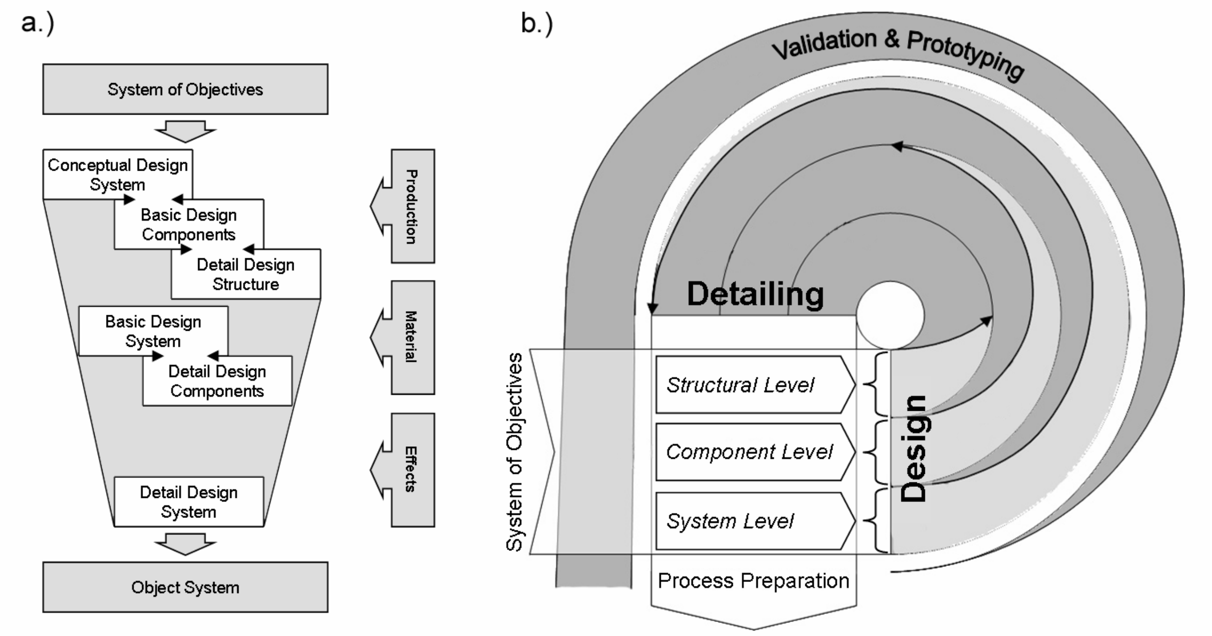


Figure 2. Single stages in design (a.) and “sickle-model” for design (b.) [Marz, 2005]

As an example, design of a microgear is discussed (cp. Figure 3): As afore-mentioned, already when desiging the gear on system level, structural details, e.g. the tooth shape, have to be considered. Assuming a primary shaping process, e.g. powder injection molding, production of a mold insert is necessary. In order to compensate sinter shrinkage, the cavity has to be scaled up by a certain percentage. Employing the smallest off-shelf end mill cutters (diameter 100µm), the minimum groove width that can be produced is 100µm, while the minimum producible edge rounding radius within the mold is 50µm. At the same time, the tooth width is restricted by the maximum cutting depth of 200µm, which affects the transmittable torque. Both technological restrictions strongly influence the structural detail of the tooth shape and hence gear design on system level.

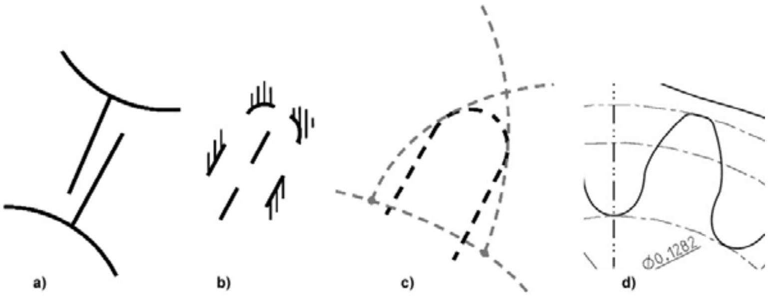


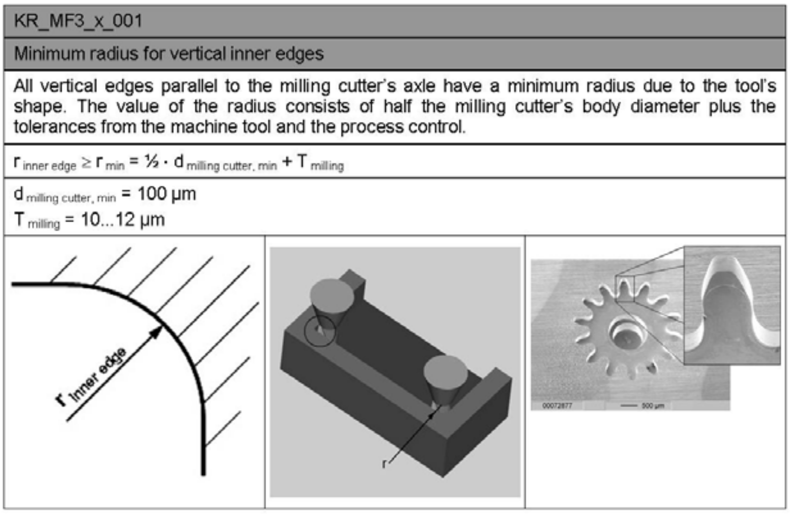
Figure 3. Designing structural details: concept (a.), functional item (b.), influence of restrictions (c., minimum edge rounding), final structure (d.)

3. Design Rules

A widely applied methodological means is the application of design rules in order to provide knowledge for designers by feeding production knowledge back to the design stage. In other words, knowledge from the “production” operation system is projected onto the “development” operation system, i.e. design in order to provide certain knowledge to the designer, which usually is reserved to the production specialist.

In microelectronics, design rules sucessfully bridge the separation of design and production, which was established by the design methodology of Mead and Conway [Mead, Conway, 1980]. Because of this separation, enterprises with costly fabrication lines (foundries) can provide production services to several customers, which are enabled by design rules to design process-compatible circuits. However, the terms design rule, design guideline, design advice or embodiment rule often are used in a synonym way, while design rule is used for rules of different levels of abstraction. Thus, the authors define design rule as an instruction which derives from technological conditions and restricitions, which have to be considerered mandatorily in order to achieve a realizable design. These technological conditions and restrictions derive from all methods and processes of stages subsequent or adjacent to design, e.g. process preparation, production or material sciences.

In macroscopic design, guidelines for embodiment design are an established means of support, which describe universal instructions that often are clarified by a positive and a negative example. Design rules are more concrete by issuing instructions that directly affect detail design. Rule contents have to be considered mandatorily so as to achieve a system being compatible to production. Being more abstract, design rules describe technological influences on structural level: When milling is applied, consider a minimum inner edge radius! On a more concrete level, design rules formally specify those technological conditions: When milling is applied, consider a minimum inner edge radius of $r_{Edge,min}=0.5 \cdot d_{Cutter,min}+T_{Milling}$ with the parameters cutter diamter $d_{Cutter,min}=100\mu m$ and milling tolerance $T_{Milling}=12\mu m$ (cp. Figure 4). Based on experiences from preceeding designs, even product-specific design rules can be defined, although these are not universal anymore [Albers et al, 2003].



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Minimum radius for vertical inner edges

All vertical edges parallel to the milling cutter’s axle have a minimum radius due to the tool’s shape. The value of the radius consists of half the milling cutter’s body diameter plus the tolerances from the machine tool and the process control.

$r_{inner\ edge} \geq r_{min} = ½ \cdot d_{milling\ cutter,\ min} + T_{milling}$

$d_{milling\ cutter,\ min} = 100\ \mu m$

$T_{milling} = 10...12\ \mu m$

Figure 4. Exemplaric Design Rule [Albers, Marz, 2005]

For deriving design rules, first of all, potential influences of a microtechnology on design have to be detected. Features of this technology have to be extracted, i.e. all relevant machine and process parameters that can influence design, e.g. the afore-mentioned minimum diameter of end mill cutters. This information has to be interpreted in a way relevant to design, i.e. the external knowledge is translated into the designer’s language. Based on that universal design rules have to be formulated, which are classified and filed. For the ease of application, design rules can be provided by a web-based information portal or by a knowledge-based engineering system. Latter enables the designer to execute online design rule checks on just created 3D-models within the CAD environment giving the designer direct feedback with respect to the compatibility to the filed rules. Additionally, in case of a detected incompatibility, knowledge-based engineering systems offer automatically executable alternative actions for corrections [Albers et al, 2005].

4. Summary and Conclusion

A microspecific design flow for tool-based micromachined products was presented. This design flow is strongly characterized by influences of technological conditions and restrictions, which derive from adjacent or subsequent stages of the product life cycle, from process preparation, production or material sciences. The peculiarities of this technology-driven design process are visualized by the “sickle-model”, which shows the superposition of the top-down design from concpetual to detail design and the bottom-up design from structural to system level. This results in a meet-in-the-middle strategy for designing products based on tool-based micromachining. Furtheron, derivation and application of design rules were presented. Both design flow and design rules could be validated when designing a micro planetary gear.

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