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Design

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Design Environment and Design Flow

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Abstract
The design flow for primary-shaped microcomponents and microsystems is presented. As a characteristic of microspecific design, the approach is predominantly driven by technology. To integrate the relevant technological demands and restrictions into the design synthesis for a realizable embodiment design in accordance with the specified function, design rules are defined. These represent mandatory instructions for the designer. To support the designer effectively the design rules are provided within a computer-aided design environment. In addition to an information portal, an embodiment design unit is built up on the basis of the 3D CAD system Unigraphics, which includes an application for knowledge-based engineering (KBE). The rule-based design methodology was used for the development and design of a microplanetary gear.

Keywords
design environment; design flow; target system definition; operation system; object system; design rule; knowledge-based engineering; methodological aid

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1.1 Introduction

Microtechnology involves technologies for manufacturing and assembling predominantly micromechanical, microelectrical, microfluidic and microoptical components and systems with characteristic structures with the dimension of microns. In doing so, microproduction technologies take on a key role, since their process-specific parameters and boundary conditions determine the smallness and attainable quality features of the components. Owing to the ongoing progress in microtechnology and the increasing penetration of the market with medium-sized and large-batch products, development steps preliminary and subsequent to production are becoming more and more relevant for an effective design in compliance with the requirements. Therefore, the designer needs to be supported by a technological basic knowledge and know-how, regardless of individual persons.

1.1.1 State-of-the-Art of Design Flows and Design Environments within Microtechnology

Microtechnologies include silicon microsystem technology, the LIGA process and mechanical microproduction technology.

Silicon microsystem technology is the most widespread microtechnology throughout the world. It is based on the process technology of integrated circuits (ICs) and benefits from a comprehensive know-how from microelectronics. Unlike in microelectronics, microtechnological products integrate active and passive functional elements, which rely on at least two elementarily different physical, chemical or biochemical effects and working principles. In addition to sensors and information processing, particularly actuator functions are performed. The predominantly 2.5-dimensional and sometimes three-dimensional structures use silicon as substrate with its excellent mechanical properties. Along with others, all these characteristics of silicon micromechanical systems have required a specific design methodology ever since a critical level of development from research into industry was reached. Different design process models are known [1–3], which among other things integrate analytical and numerical simulation tools. Silicon-based micromechanical products are developed in an iterative sequence of synthesis and analysis steps. A specific difficulty lies in the deviation between the designed target structure and the actual structure after the optical lithography and etching process. Therefore, compensation structures are introduced into the design and simulation environment, adjusting the determined structure by dimensional add-on and auxiliary structures [4–6]. Design rules are introduced as a methodological aid to represent this technological information. Design rules have been used in microelectronics since the early 1980s to enable very large-scale integrated (VLSI) circuits to be synthesized automatically to the extent of nearly 100% [7]. Silicon microsystem technology has now reached a high degree of development status. A lot of research programs have led to design flow descriptions and collections of design rules.

Like silicon microsystem technology, the LIGA process utilizes mask-based process steps. The LIGA process approaches an obviously broader range of materials and is characterized by extremely high aspect ratios with at the same time the smallest lateral structure dimensions [8]. LIGA permits the manufacture of mold inserts which can be used in replication techniques for large-batch parts (Chapter 8). In addition to thermoplastics, also metallic and ceramic materials are processed. To support the design and process, engineering design rules are utilized which give – depending on the process sequence – instructions for a design for manufacturing and for separating, manipulating and assembling components [9]. Within different research programs, design environments for computer-aided design of LIGA microstructures embedding design rules were developed [10, 11]. The computer-aided design of LIGA microstructures still shows a high demand. A standardized model for methodological design flow in the LIGA process is lacking to date [12].

1.1.2
Mechanical Microproduction

To come up with a more cost-effective, medium-sized and large-batch suitable process for manufacturing microsystems, the potential of miniaturizing mechanical production technologies has been increasingly investigated in recent years. Predominantly staged production process sequences for manufacturing mold inserts by wear-resistant materials followed by a replication step show outstanding future prospects. Technologies such as micromilling and laser machining are suitable for manufacturing complex three-dimensional free-form surfaces (Chapters 5–7). By replication techniques such as micropowder injection molding, high-strength microcomponents and microsystems from metallic and ceramic materials can be produced in large quantities (Chapters 11 and 12).

When designing primary-shaped microparts with respect to function and manufacturing, it is necessary to incorporate boundary conditions and restrictions from process steps downstream to the product development into the design activities as early as possible [20]. Thus, a design flow is introduced that uses design rules to support the designer effectively with respect to functional, geometric and capacitance demands. The process model and the method are embedded in a knowledge-based design environment.

1.2 Design Flow

1.2.1 Specific Issues Within the Design of Microsystems

In contrast to the procedures and methods commonly applied in mechanical engineering and precision engineering, product development of microtechnological systems requires attention to the following issues.

1.2.1.1 Dominance of Technologies

Going beyond the basic rules and guidelines of embodiment design microtechnology has a strong focus on parallelization of product and process development. Resulting from the rapid advances in existing production processes and the appearance of new technologies, the question of 'how to manufacture' becomes a conceptual part of product development. Microproduction technologies, materials and specific effects define the possible shape and function of new products.

1.2.1.2 Surface-to-Volume Ratio

Owing to the super-proportional rise in the surface-to-volume ratio in the range of the characteristic and functional dimensions of microcomponents, the global dimensions have a different ratio to local deviances. Higher level surface tolerances in macroengineering have the same significance as notch form deviation in microengineering. There is no longer a difference in magnitude between material microstructures and work-piece dimensions. The numbers of crystals and surface layers are relevant for the calculation of elastic properties.

1.2.1.3 Dynamics
As a consequence of their small volumes, microsystems have lower inertia. They can be operated in higher ranges of frequency and show high dynamics.

1.2.1.4 Standardization
Standards with regard to generic or product-specific dimensions do not exist for the design of microcomponents and systems.

1.2.1.5 Validation
Mostly, either no equipment for the measurement and testing of microcomponents is available at all or insurmountable physical obstacles occur (size of components, essential accuracy of the measuring equipment). Design can, therefore, only set requirements on what can be verified by means of measurement and with the use of testing equipment.

Compared with silicon microsystem technology, the LIGA process and the mechanical microproduction technologies show the following specific differences.

1.2.1.6 Enhanced Material Spectrum
Microsystem technologies with replication subprocesses possess an enhanced material spectrum. Totally new applications arise from it, making it necessary to characterize the materials with respect to their microstructures and properties. This is an important input for product development.

1.2.1.7 Emphasis on Actuators
Since the LIGA process and mechanical microproduction technologies do not rely on silicon as base material, there is enormous potential to develop actuators using a multitude of effects. Integrated in a superior system or as an integrated self-sufficient microsystem, actuators offer particularly energy and material interfaces to the macroscopic world. A microspecific design methodology has to be directed on methods and processes to calculate and design the relevant interface machine elements.

1.2.2 Microspecific Design Flow

Each design process starts with a definition of the target system. The target system definition is developed with the involvement of the customer and determines requirements and boundary conditions for the product that is to be developed (Fig. 1-1).

The target system definition helps to concretize the task and to clarify vague and unexpressed demands on the object system – the subsequent microproduct – prior to the beginning of the design. Along with the customer, a requirements list is generated, which describes the target system by quantitative and assessed criteria. To ensure that a fundamental criterion is not forgotten, checklists with main headings exist for drawing up a requirements list [13, 14]. The requirements list represents a dynamic document, which has to be examined continually with respect to up-to-dateness and inconsistencies during the design process. Moreover, the risk exists of specifying the task in an unchallenged or in an overextended way. An unchallenged specification might lead to a product ahead of schedule but without matching the real performance characteristics. On the other hand, an overextended specification might limit the solution space in such a manner that no solution could be developed [3]. For the target system definition of microelectronic circuits, hardware description languages are standardized. The microsystem technology of primary shaping concentrates on energy- and material-converting microsystems with integrated information flow and with single functions from different physical, chemical and biochemical domains, so no formal methods and target system definition languages are available.

When conventionally developing products and systems of mechanical engineering and precision engineering [13–16], a conceptional phase would follow, in which basic partial solutions for functionally organized subsystems would be developed and systematically combined to the optimum basic solution with consideration of evaluation techniques. When developing microsystems, the approach is 'technology driven'. At the same time, the technology term describes all of those scientific disciplines as a whole that contribute to the product development process. This especially applies in production engineering and material sciences. Among material sciences, also research on new or specifically formed

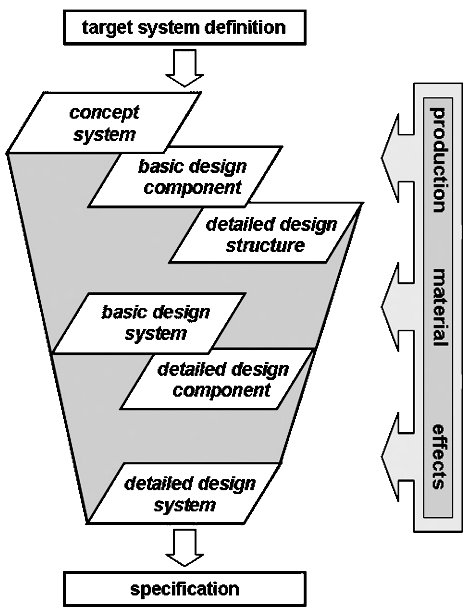


Fig. 1-1 Microspecific design flow

physical, chemical and biochemical effects has to be itemized. Effects are comprehended as both those which are intentionally used to transfer the target system into the object system by effects and active principles in order to fulfil a function (e.g. shape memory effect) and those which inevitably result from phenomena such as friction and wear.

Because of being driven by technology, parallelization of stages of conceptual and embodiment design occurs, which exceeds different levels of abstraction. While making conceptual decisions on system level related to function in a top-down approach, simultaneously structural details conditional on technology are being designed in a bottom-up way. In between, single components are preliminarily drafted (basic design). These structural details can be entirely finalized and annotated with all tolerance data and information relevant for production preparation. Already during the subsequent design stage, a complete component can be constituted in its final shape (detail design). The system comes to the stage of basic design. Eventually the system itself is finalized and refined into a detailed design documentation for transfer to production preparation. In doing so, the approach constantly changes between the view on the complete system and the smallest structural element ('meet-in-the-middle') [17], wherein the design space is restricted for the designer through boundary conditions and restrictions of the production processes. However, features that cannot be described as easily as geometric quantities also have an influence. These are characteristics of the materials themselves such as microstructure or mechanical properties and physical, chemical or biochemical effects made accessible by them. The latter can develop into disturbing effects when the dimensions become smaller, they can become less important or even emerge and therefore open up completely new applications. All of these 'technological' aspects therefore have to be integrated into the microtechnological design of structures, components and systems [18].

Therefore, it is necessary to make the multi-technological knowledge from the above-mentioned technologies directly available to the designer in the design process. This is achieved via the methodological aid of design rules.

1.3 Design Rules

1.3.1 Basics

1.3.1.1 Definition

Design rules are instructions derived from technological restrictions which have to be followed mandatorily for a realizable design.

Technologies embrace all processes and methods of production preparation, production and material science including effects which are adjacent or subsequent to the design process. Restrictions describe all boundary conditions, requirements and constraints that influence the design embodiment of the product with respect to the entire product life cycle. A realizable design is a design that is completely specified in detail (CAD–CAM suitable 3D CAD model, drawings) ready for production.

Owing to their mandatory character, design rules are an explicit part of the conceptional and embodiment design activities. Disregarding the knowledge about restrictions leads to a design that only inadequately fulfils the function or is even not able to be manufactured, assembled, dimensionally characterized and so on.

Design rules are mandatory instructions to be followed by the designer!

1.3.1.2 **Derivation of Design Rules**

Design rules begin by *detecting* potential influences that a technology could have on the microtechnological design. The features and parameters of this technology are quantifiably taken over in an *extraction step*. Then these properties will be projected to existing and possible components and system structures and marginal analyses of still realizable manufacturing sizes will be made, i.e. *interpreted relevant to design* [19, 20].

Only a methodical trained product development engineer can carry out this interpretation and raise technical facts via suitable query techniques (interviewing techniques, e-mail query via special forms, so called 'technology specification sheets'; see, for example, Fig. 1-5). Now these 'raw data' need to be transformed via creativity methods or with experimental knowledge into a methodical knowledge that can be used by the designer. Knowledge from individual disciplines – from the designer's view this is data and information – is raised to a higher level of knowledge and made available mono-disciplinarily, i.e. from the designer's point of view (Fig. 1-2).

According to a specially developed classification scheme, the interpretations are formulated as generally applicable rules. The classification scheme that is introduced here models itself on the technologies for mold insert production and replication that are a part in the production process. The nomenclature is as as shown in Fig. 1-3.

These different process steps are formulated separately for the further application of the design rules in a knowledge-based design environment. It has to be clearly determined to which type of part the geometric sizes refer. This is carried out via a so-called rule class. It indicates for which type of part the rule was formulated and to which manufacturing technologies and tools or materials it applies. The letters 'AA' describe the type of part to which the rule refers, i.e. 'mold insert' or molded and sintered 'model'. Then follows the information about the production technique with a more detailed specification of tool group and material group. When a rule is applied to different production techniques or tool groups or material groups, the entries 'xxx' or 'x' are indicated. The rule ends with a consecutive number for the respective rule composition.

Different rule sets exist for the mold insert manufacture and molding process of parts explained above. However, they can be geometrically connected. Hence

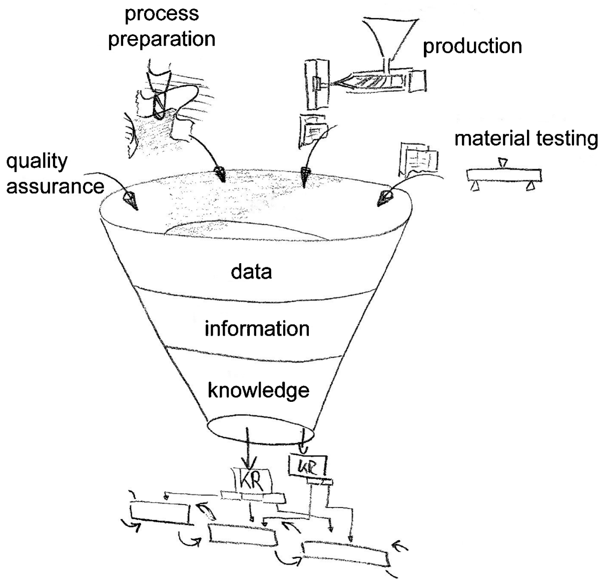


Fig. 1-2 Knowledge transformation by interpretation relevant to design

the structure details of the mold insert that are influenced by the manufacturing restrictions can also be found at the molded part, where the geometry sizes scale around the sinter shrinking and complementary structures are developed.

The following section explains the design rules of the single technologies (especially of process preparation and production) that are connected to process chains for replication processes. A distinction is made between two large process chains, 'micropowder injection molding' and 'microcasting'.

1.3.2
Design Rules Derived from Restrictions of Production Technology

Design rules are a methodical aid for achieving a knowledge transfer from technological facts (see, e.g., Fig. 1-5), especially from the operation system of production technology to the operation system of product development. This is demonstrated by the flow arrow in Fig. 1-4.

Fig. 1-4 demonstrates that not only are there indications regarding manufacturing aspects passed on to the designer via guidelines for embodiment design and rules, as in mechanical engineering or precision engineering, but that it is also mandatory to employ the requirements and restrictions relevant to design that are included in the design rules. Without the active design that includes the knowledge facts in the rules, an effective and successful synthesis is not possible in primary-shaping microtechnology.

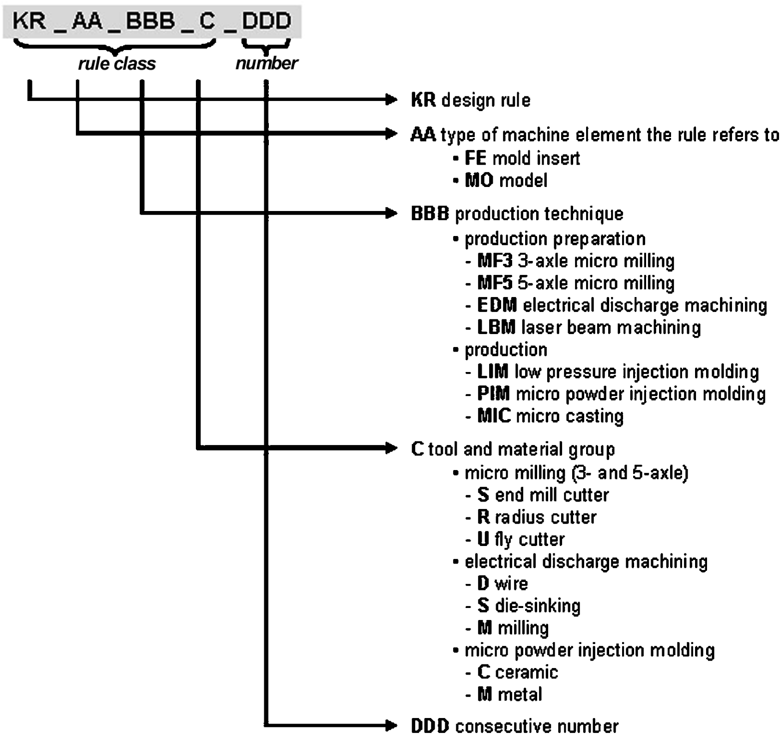


Fig. 1-3 Classification scheme for design rules

The rules used at present refer exclusively to the production process chains for primary-shaped microcomponents. It has to be considered that most of the time the model is created in the CAD and from there a negative form – the mold insert – is generated. In the case of parametric CAD systems, the sinter shrinkage can also be considered in this process and the mold insert can be designed correspondingly larger. The manufacturing of the model is done in two steps. First, the mold insert (negative) is manufactured. The technologies available here are machining and abrasive processes (see Fig. 1-3 and Chapters 4–7). The second step is the molding process of the model (positive) by means of ceramic or metallic micropowder injection molding (Chapters 10–12) or microcasting (Chapter 13).

To each of the two process steps different restrictions apply, e.g. it is not possible to mill a cavity that is smaller than the milling cutter. Also, micropowder injection molding requires a minimum wall thickness and a maximum flow length. However, both parts are geometrically unambiguously connected, i.e. restrictions of the mold insert manufacturing automatically apply also to the molded part and vice versa. Here it has to be considered especially that the geometric properties of both parts are not identical. First, the part is scaled during the molding process because of the sinter shrinkage and then a negative is cre-

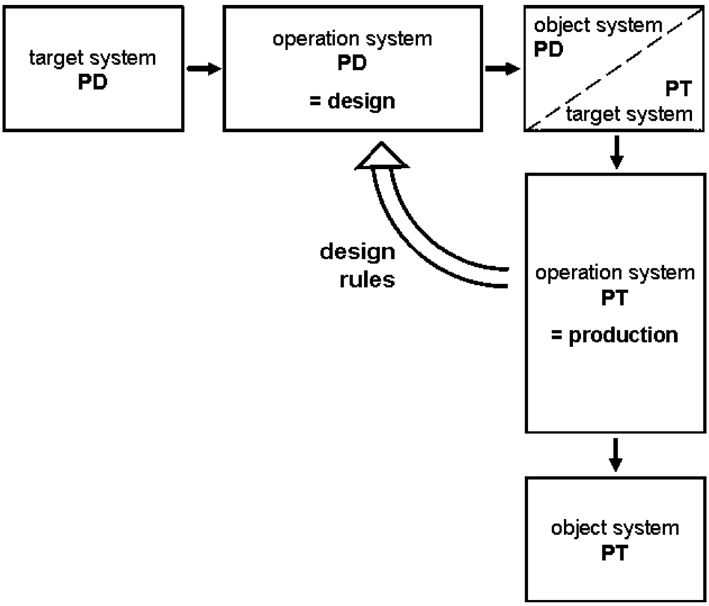


Fig. 1-4 Flow of knowledge from production technology (PT) to product development (PD) by design rules

ated, so that, for example, a hole in the mold insert is converted into a cylinder with a decreased height and diameter.

1.3.2.1 Design Rules for Mold Insert Manufacturing

Replication processes require as a first step the manufacture of a form – the mold insert. To achieve the aim of a cost-effective, medium-sized and large-batch production of microcomponents from metallic and ceramic material, abrasive and machining processes of the mechanical microproduction are more advantageous than processes based on lithography. For the majority of applications in the Collaborative Research Centre 499, micromilling has been used for the manufacturing of mold inserts so far.

Among others, micro end mill cutters are employed here in order to manufacture 2.5- and three-dimensional microstructures. Process-specific parameters that have to be extracted are, for example, the body diameter of the tool and the length of the milling cutter's edge that is linked to it. If interpreted with relevance to design, this implies that it is not possible to manufacture mold insert structures that are smaller than the milling cutter diameter plus the milling cutter tolerance or deeper than the maximum cutting depth. Owing to the circular cross section, vertical inner edges are also impossible, i.e. all mold insert edges – equivalent to outer edges of the final part – have to be provided with a minimal rounding radius.

All these parameters and properties are collected in so-called technology specification sheets and are interpreted with relevance to design (Fig. 1-5) [21].

In systematic scenarios, the determined technological facts are now projected on to potential geometric structures or functional influences on the microparts. The results are descriptions and mathematical connections that correlate machine tool and tool parameters with design parameters. With the presentation of the design rules, the designer is provided with abstract and descriptive, but also concrete and computer-aided information about the same knowledge fact. Fig. 1-6 shows a design rule for three-axis micromilling that applies both to the end mill cutter and to the radius cutter.

Various other design rules exist in addition that name the technological restrictions of three- and five-axis micromilling, and also rules for microelectrical discharge machining and for laser machining.

1.3.2.2 **Design Rules for Replication Techniques**

The replication of microcomponents is done by micropowder injection molding (μPIM) and by microcasting. Micropowder injection molding as a replication technique for microcomponents differentiates between metallic and ceramic injection molding depending on the material to be molded. The μPIM process uses the mold inserts in order to mold the metallic or ceramic feedstock directly into these molds.

The microcasting process is based on the lost-wax lost-mold technique, so as a first step models have to be manufactured. These lost models, mainly made from polymers, are mounted on a gate and feeding system made of wax. This assembly is completely embedded in a ceramic slurry. After drying, the ceramic is sintered, resulting in a ceramic mold with high mechanical strength. Simultaneously during the burning process, the polymer model is molten and burnt out. After the subsequent casting process, the metallic microcomponents can be taken out of the lost mold.

Micropowder injection molding

Boundary conditions of the μPIM process result from the necessity to attach runners in a sufficient number and size to the part's surface and to provide a surface for the ejector pins contacting the molded part for removal. The maximum achievable flow length and aspect ratios, and also sharp cross section transitions and cross section bendings, limit the mold filling behavior and the molding process quality. Especially the shrinkage of the material during sintering has to be considered. Therefore, taking into account the sintering shrinkage, it is possible that smaller structures may result compared with the dimensions of the mold insert, but shrinkage tolerances of ±0.4% have to be considered at the same time (Fig. 1-7).

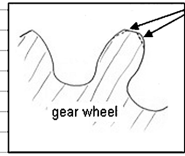
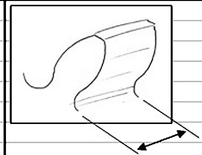
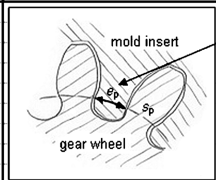
		technological parameter		design-relevant interpretation	influences
end mill cutter	1	diameter [mm]	$d \geq 0.10$	 tip rounding so that the milling cutter with the smallest body diameter can enter the mold insert's structures	→ loss of active flank length
		scaling [mm]	$\Delta = 0.05$		→ load-carrying capacity declines
					→ concentricity declines
					→ reduction of head width
	2	cutting depth		 maximum face width for a single-sided mold insert manufactured by micro milling	
		empirical formula	$2\text{–}3 \times d$	$2\text{–}3 \times d = 2\text{–}3 \times 0.1 = 0.2\text{–}0.3$ mm	
		extended end mill cutter	$\approx 8 \times d$	$8 \times d = 8 \times 0.5 = 4$ mm	→ milling cutter with body diameter greater than 0.5 for the planned degree of miniaturization
	3	tolerances [mm]			
		shank	+0 /–0.006		
		cutting edge	+0.01 /–0.01		
	4	minimum wall thickness	still to be investigated	 possibly required: minimum space width between the teeth	→ tooth pitch and relation space width e_p : tooth thickness s_p possibly to be adapted
	5	surface roughness [µm]	$R_z \approx 2$		
	6	formation of burrs			

Fig. 1-5 Achievable manufacturing sizes in production preparation by means of three-axis micromilling [21]

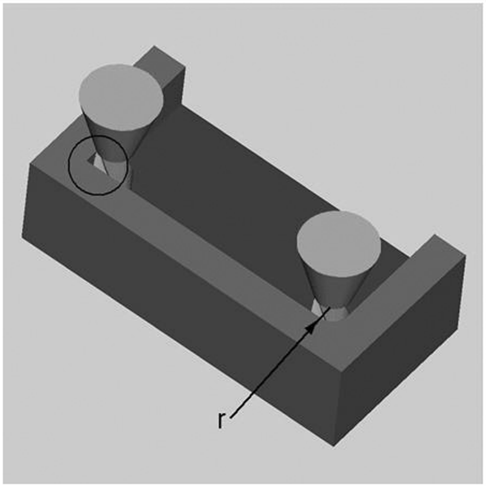
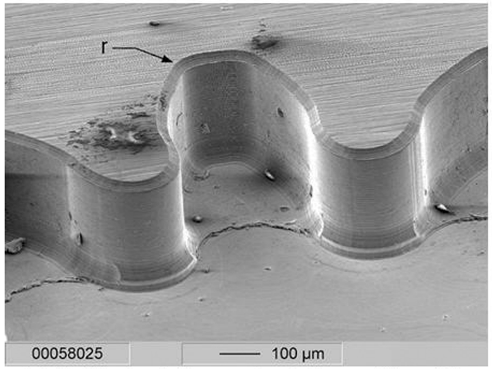
classification	KR_FE_MF3_x_001
name	Minimum radius for vertical inner edges
description	All vertical edges parallel to the milling cutter's axle have a minimum radius due to the tool's shape. The value of the radius consists of the milling cutter's body diameter plus the tolerances from the machine tool and the process control. Strictly speaking, this rule is only valid for end mill cutter and radius cutter, as fly cutter does not allow one to manufacture vertical inner edges
formal specification	$r_{\text{inner edge}} \geq r_{\min} = \frac{1}{2} \cdot (d_{\text{milling cutter, min}} + T_{\text{milling}})$
parameter	$d_{\text{milling cutter, min}}$ = 100 µm (smallest body diameter of a commercially available milling cutter for reproducible results) [32] T_{milling} = 10...12µm (sum of concentricity tolerance, positional tolerance, dimensional tolerance)
illustration	  detail of the tooth tip rounding in the mold insert for the part sun wheel for a micro planetary gear

Fig. 1-6 KR_FE_MF3_x_001 – Minimum radius for vertical inner edges

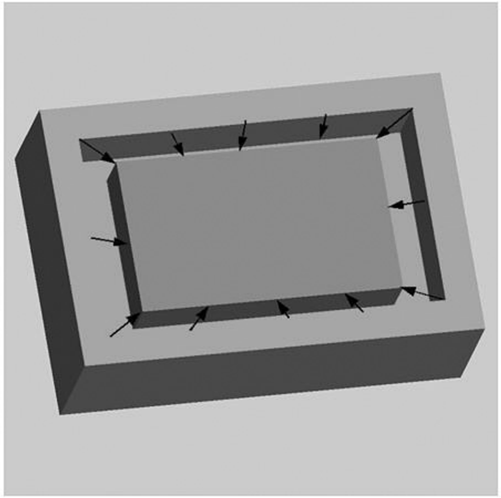
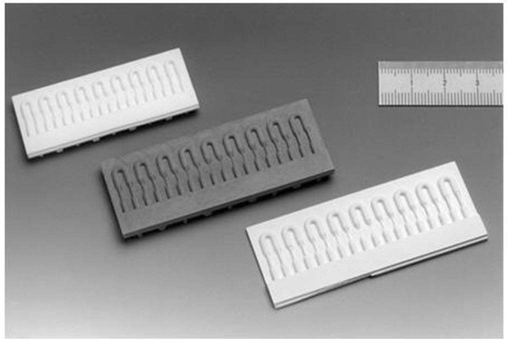
classification	**KR_MO_PIM_x_001**
name	**Dimensional margin**
description	Green compacts produced by µ-PIM shrink (*s*) linearly when subjected to debinding and sinter treatment. As a result, a dimensional margin has to be provided for mold insert manufacturing with respect to the determined component dimensions
formal specification	$s_{mold\ insert} = (1 - \gamma_{shrinking})^{-1} \cdot s_{component}$
parameter	$\gamma_{shrinking}$ = 16 ± 0.4% (Al_2O_3) [31] $\gamma_{shrinking}$ = 22 ± 0.3% (ZrO_2) [31] $\gamma_{shrinking}$ = 18 ± 0.4% (17-4PH) [31]
illustration	  sintered component, brown compact, green compact

Fig. 1-7 KR_MO_PIM_x_001 – Dimensional margin

Microcasting

To come to a design compatible with microcasting, several technological circumstances have to be taken into account. Compared with micropowder injection molding where the green compact and brown compact are intermediates on the way to the final sintered microcomponent, in microcasting more and versatile preparation and intermediate steps exist that influence the result. Depending on the manufacturing process for the lost models, different concepts for casting-compatible positioning of gates are necessary (model on substrate or single injection-molded models with gate and feeding system). The attainable surface roughness of the microcomponent is determined by the embedding mass employed and ranges down to $R_a = 0.5$ µm for Stabilor G. In addition, the attainable dimensional accuracy should be pointed out to the designer. By varying the expansion ratio of the embedding mass, the dimensional accuracy is adjustable within a few microns. In microcasting, small structures within a few 10 µm in wall thickness with at the same time high aspect ratios are processable. On falling below a specific structural diameter, the filling pressure rises in a hyperbolic manner, resulting in a more complicated form filling. This phenomenon is expressed by the design rule in Fig. 1-8, which consequently has an influence on the dimensional conception and the embodiment design (see Chapter 13) [22, 23].

1.4 Design Environment

The filing of rules in a database is important for the applicability of the rules for the designer and implementation in computer-based systems. The design rules can be provided over an interactive knowledge portal and/or directly with an application in 3D CAD.

The design environment is planned in a way that supports the designer with respect to the product development phase in which the design is at that moment, by means of the design rules that are correspondingly altered with the abstraction level. In the early stages, the general comprehensive information about the production processes and the material properties are the interesting aspects. In the embodiment design phase, quantified values about realizable manufacturing sizes have to be provided for a detailed design draft. Here, concrete instructions are required that must be followed to realize a production-compatible and functional part design.

According to these different representation forms of the knowledge content of design rules, the design environment itself has to be planned to be flexible and application specific. Therefore, an information component, i.e. a web-based interactive knowledge portal, and an embodiment design component that is directly integrated into the CAD system as a working environment for the designer were developed for the product development of primary-shaped microcomponents. Both units access the same data of a database [24, 25].

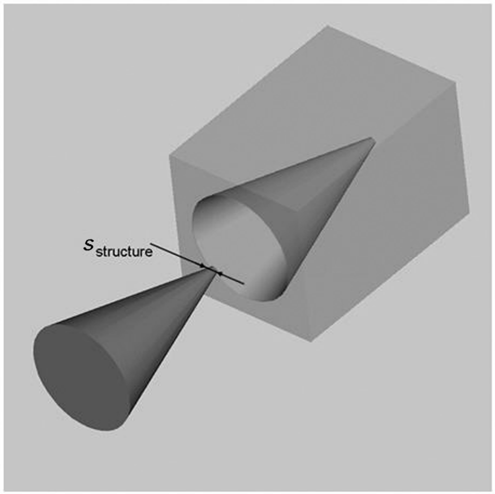
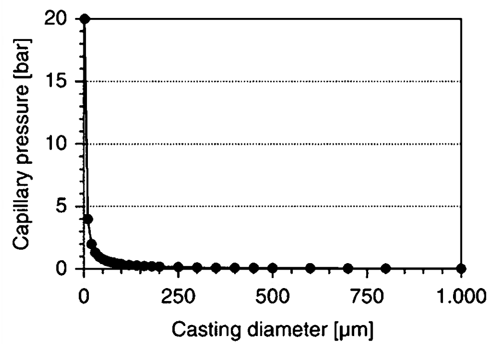
classification	**KR_MO_MIC_x_003**
name	**Minimum structure width**
description	The minimum structure width is determined by the casting diameter just to be filled by the given filling pressure. The theoretical filling pressure has to be loaded for compensation of the capillary pressure. Moreover, additional effects have to be compensated: the influence of the flow length due to the pressure decrease in the channel and the alternating viscosity of the melt with increasing cooling all along the flow path. Moreover, the counter pressure due to the enclosed gas can cause an even higher filling pressure
formal specification	$s_{structure} \geq s_{structure,\,min}$
parameter	$s_{structure,\,min}$ = 20 µm (Stabilor G) [22, 23]
illustration	  theoretical filling pressure (simplified) [23]

Fig. 1-8 KR_MO_MIC_x_003: Minimum structure width

1.4.1
Information Unit

A 'design and methodology database' (KoMeth), which supports the designer as an interactive knowledge portal via different access possibilities with design rules, serves as an information component. The access page offers different selection fields that permit, according to the classification scheme (Fig. 1-3), the search for rules for a specific manufacturing technology, for specific part types or specific tools and materials. The rules that were found are displayed systematically in a hit list according to their rule class and name. If the designer is already familiar with the production process chain, a direct search over the list of existing rule classes and names is also possible. When selecting a rule from the hit list, an information page is displayed which shows the rule class, the numbering, the rule name, a prosaic description, an algorithmic–mathematical formula (if available) and sketches of geometric dimensions and illustrations of real manufactured microstructures (Fig. 1-9).

In the course of product development, the abstraction level decreases and more and more technological restrictions have to be considered. Especially at the stage of realizing the embodiment design, the shape and dimensions of realizable structure details are not easy to comprehend any longer. In addition to the significance of errors and the inefficiency, these details deviate too much from the original design work. Therefore, the so-called design rule checker was established in mechanical engineering, microelectronics and mask-based microtechnology. This approach is also used for rule-based embodiment design of primary-shaped microcomponents.

1.4.2
Embodiment Design Unit

In addition to the presented qualitative and descriptive content, the knowledge base of the database also includes concrete values of single manufacturing technologies and knowledge about connecting these data with geometric characteristic values in the form of rules. These are formulated separately because both are independent of each other and subjected to permanent changes. The information and parameter values are derived from the state of the microproduction technologies and the material sciences. The rules are derived from the expertise and the experience in the design process, process preparation and production, and also from the part testing and material testing. Therefore, they are also subjected to permanent development and completion. All information and knowledge have to be saved independently of the CAD system. This offers the advantage that the same information and knowledge data can be used for different CAD systems and can be maintained without CAD.

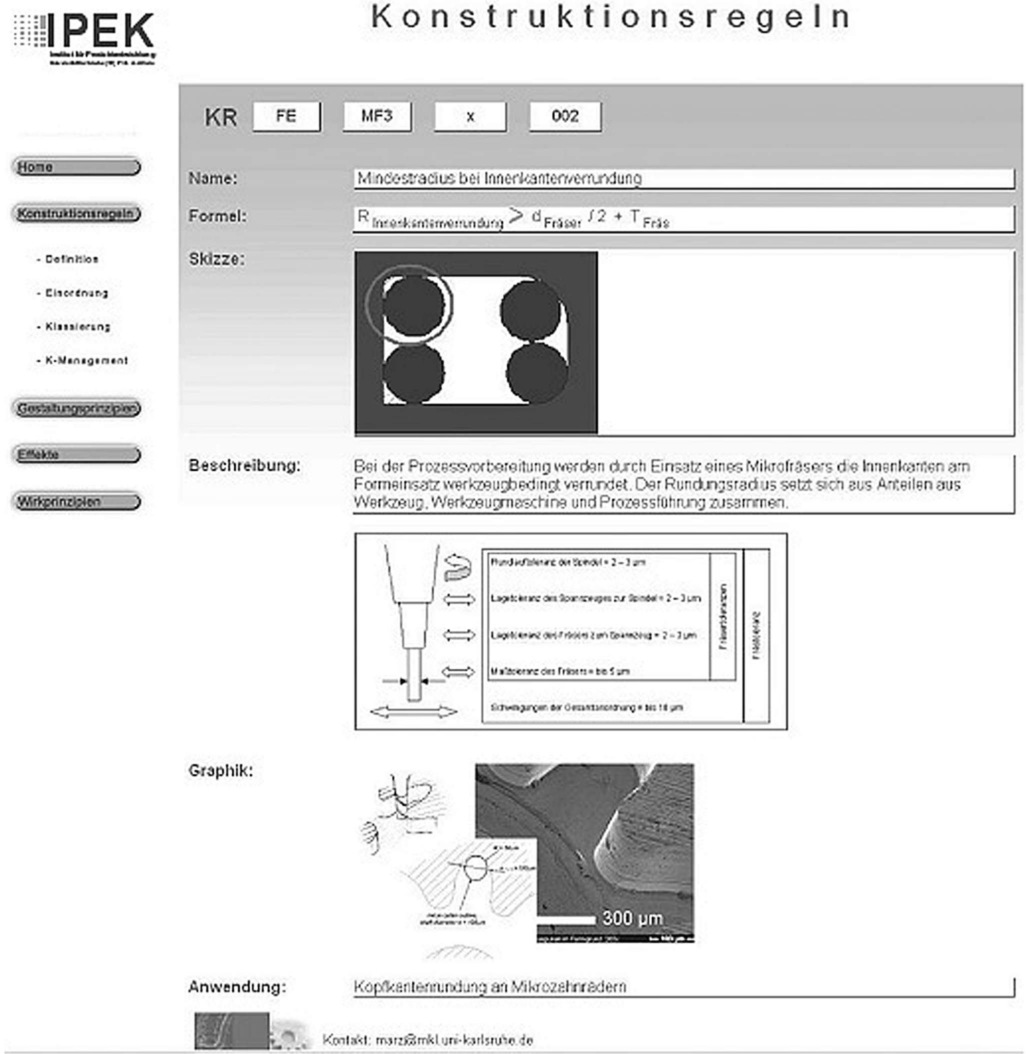


Fig. 1-9 KoMeth – Design and methodology database

1.4.2.1 **Preparing Elementary Rules for Computer-aided Design Rule Check**

With the application at hand, it has to be examined whether the designed geometry can be manufactured by means of the production technologies and materials selected. Therefore, the necessity to focus only on geometry is obvious, i.e. on the individual surfaces and edges. As a result, a description by means of boundary representation (B-rep) [26] has been chosen as the geometric model. In addition, many common transfer formats for CAD data such as STEP [27] or IGES support this description model.

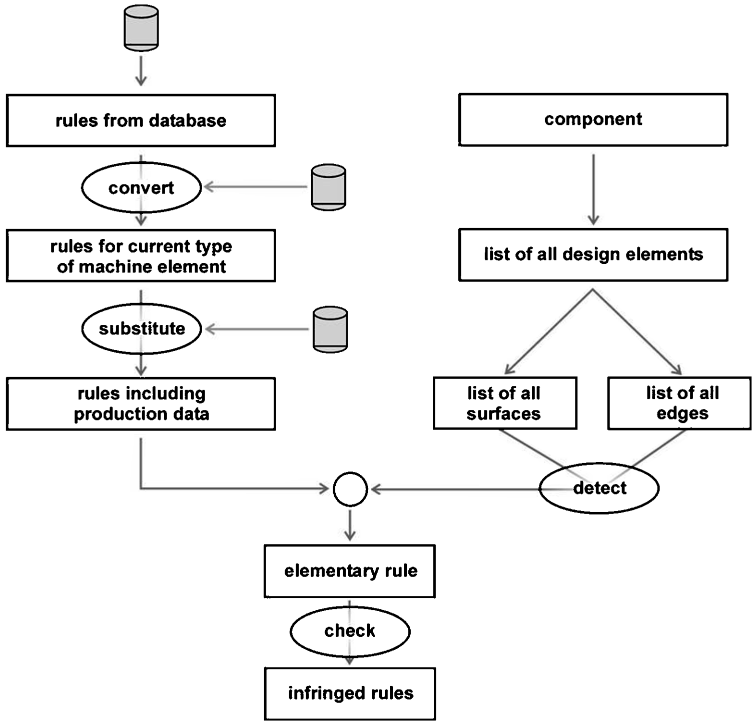


Fig. 1-10 Preparing elementary rules from general design rules and the geometry of the component

The task of a programmed algorithm is thus to derive geometric parameters from the three-dimensional geometric model and connect them by means of rules with the production technological parameter.

By adapting general rules to the special geometry and to the individual production process, elementary rules are obtained. Consequently, they are not generally applicable any longer, but describe concrete circumstances and can hence be evaluated by the computer. As can be seen in Fig. 1-10, the preparation for this is carried out in two parallel paths: the adaptation and concretization of the rules and the determination of the geometric parameters.

Application- and process-specific adaptation of the design rules

The processing of the rules as provided by a database until the time when they can be connected with the geometric parameters is carried out in three steps (Fig. 1-10, left path):

1. The rules are loaded from a database into a list corresponding to their rule code. Rules which are not appropriate according to the technology or the tool/material are not considered.

2. If a rule is defined for another type of machine element (model ↔ mold insert), it is 'translated' by means of a transformation table. In doing so, certain key words are replaced by others (e.g. inner diameter → outer diameter)
3. In accordance with the applied production process chain, the production technological data are loaded from a separate database, after which the respective placeholders in the rules are replaced. If no equivalent for a placeholder can be found in the database, the value '0' is assumed.

Determination of the geometric parameters by means of the boundary representation method

The evaluation of the geometry of the machine element is carried out in two phases (Fig. 1-10, right path). First, all boundary representations from the database of the CAD system need to be read, and second, the corresponding properties of each representation are to be determined.

In the first phase:

1. a list of all solids of the machine element;
2. a list of all surfaces and edges of the solids from (1) are detected.

Geometric properties can be defined for solids, individual surfaces, two surfaces or edges (Fig. 1-11). For the determination of a property, geometric information about the individual boundary representations from the machine element database is available, such as unit (normal) vectors, fulcrum, limiting or proximate elements, etc. From this geometric information, simple geometric parameters can be derived. Two surfaces, for example, are parallel when they have identical unit normal vectors.

For other parameters, the calculation is more complicated, since there are various influencing factors or interdependences. One example is the angle α of an edge, which is defined as the angle measured by the part between the adjacent surfaces directly at the edge. For the determination of this quantity, the fact is used that normal vectors are always indicated outwards from the volume solid of the CAD.

In particular, the calculation runs through the following steps:

1. Determination of the adjacent surfaces.
2. Specifying a common point of the surface on the edge.
3. Determination of the unit normal vectors of two surfaces at this point.
4. Calculation of the angle between the unit normal vectors:
   $cos\varphi = \vec{n}_1 \cdot \vec{n}_2 \,.$

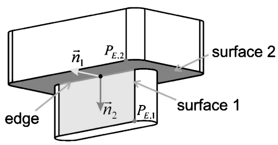


Fig. 1-11 Determination of the boundary elements and their interrelations

5. Determination of the small angle between the surfaces:
   $\alpha^* = 180^\circ - \varphi$.
6. Adjustment of nonparallel surfaces ($0^\circ < \alpha^* < 180^\circ$), if it is an inner edge ($\alpha > 180^\circ$) or an outer edge ($\alpha < 180^\circ$).
7. Check if one of the surfaces exceeds the common edge in the direction of the other normal vector. This is possible by determining the turning point $P_{E,1}$ on the surface F_1 in the direction of the normal vector $\vec{n}_2$ of the other surface F_2. To obtain an obvious point, two further directions need to be defined. For this the cross product $\vec{n}_1 \times \vec{n}_2$ and the first normal vector $\vec{n}_1$ are used. The point $P_{E,2}$ is determined analogously.
8. Adjustment if one of these two points is on the common edge of the surfaces; if yes, then it is an outer edge, if not, it is an inner edge.
9. Calculation of the angle:
   with an outer edge: $\alpha = \alpha^*$
   with an inner edge: $\alpha = \alpha^* + 180^\circ$.

The detailed rules obtained by means of the steps listed above are now combined with all applicable boundary representations and their geometric properties in order to determine elementary rules. The latter consist only of numbers and mathematical operations and can be evaluated by an appropriate commercially available program [28, 29].

1.4.2.2 **Design Rule Check**

The 3D CAD System Unigraphics for Knowledge Based Engineering (KBE)
For realizing the knowledge-based design environment, commercially available system components are used to a great extent. Unigraphics (UG) V18 [30] is employed as a CAD system as it offers the possibility of a full parametric design. Furthermore, since version 17, a knowledge-based module (UG/Knowledge Fusion) (UG/KF) and a programmable user interface (UG/Open API) have been provided. The advantage of directly using a CAD system with an integrated knowledge-based module is that no neutral interface formats are required. As a result, costs and effort can be reduced and a loss of information (e.g. parametric or attached attributes) due to several format conversions can be averted.

Indication of the production process chain with associated technological specifications
Before it is possible to check the microcomponent, the designer needs to indicate the production technologies used and the type of machine element of the product model that is to be designed. For this purpose, in a pop-up window a question on whether the mold insert or the model is involved and a question concerning the techniques and tools planned for the production are displayed. As a consequence, the corresponding rule classes can be derived.

Via the chosen rule classes, a database is addressed from which the applicable design rules on an abstract level are read out. In a further step, the parameters within the rules are replaced with concrete quantities from the production technologies, e.g. by the tool diameter or the process tolerances.

A great advantage is that the production technological parameters are filed in a separate database. Especially in the microdomain they change permanently as there are always new process alternatives available or existing ones are improved. The filing is carried out separately for the production preparation and the production. In the production preparation not only the process but also the tools are distinguished. For each of these any properties can be defined, which are filed in a separate, connected database table. Hence new properties can be introduced via the database only by means of modifications.

In a rule database all defined design rules are filed. They are contained in the form of an explanatory text, which is also displayed in case of a rule infringement, as well as in the form of an 'IF – THEN – ELSE' condition. The 'IF' part is formulated as a mathematical equation with placeholders for production technological and geometric parameters. If the described equation is correct, the 'THEN' part is carried out or, if not, the 'ELSE' part, which may be e.g. an automatic correction.

Design Rule Check (DRC) process

The checking is to a great extent carried out by means of a C++ program, which has been written exclusively for this task. In this program, the CAD data and databases are read in and elementary rules are created. These elementary rules are checked in the UG/KF module and rule infringements are presented in a pop-up window.

In order to demonstrate functionality, a micromechanical component has been defined, with the aid of which many production restrictions can be presented. It is a short T-piece at which the web has been shortened slightly and the vertical edges are rounded so that the mold insert can be manufactured by micromilling. The mold insert is to be milled with an end mill cutter (diameter 200 μm, length of cutting edge 400 μm) on a three-axis micromilling unit. To induce a rule infringement, the edges of the web are not rounded.

After the adjustment of the production technology and the type of machine element, the checking is started and the result is later presented in a dialogue box (Fig. 1-12 a). When an infringed rule is selected, the matching geometric element is marked in the CAD model and additional information concerning the rule is displayed. In this case (not rounded edge) also an automatic correction is possible. If this is carried out for all four edges, the program does not display an error message any longer (Fig. 1-12 b).

If the corrections are acceptable for the designer, drawings for the mold insert and the model can be generated for production and quality assurance. Alternatively, it might be possible to transfer the design data directly via a CAD–CAM interface to the production preparation.

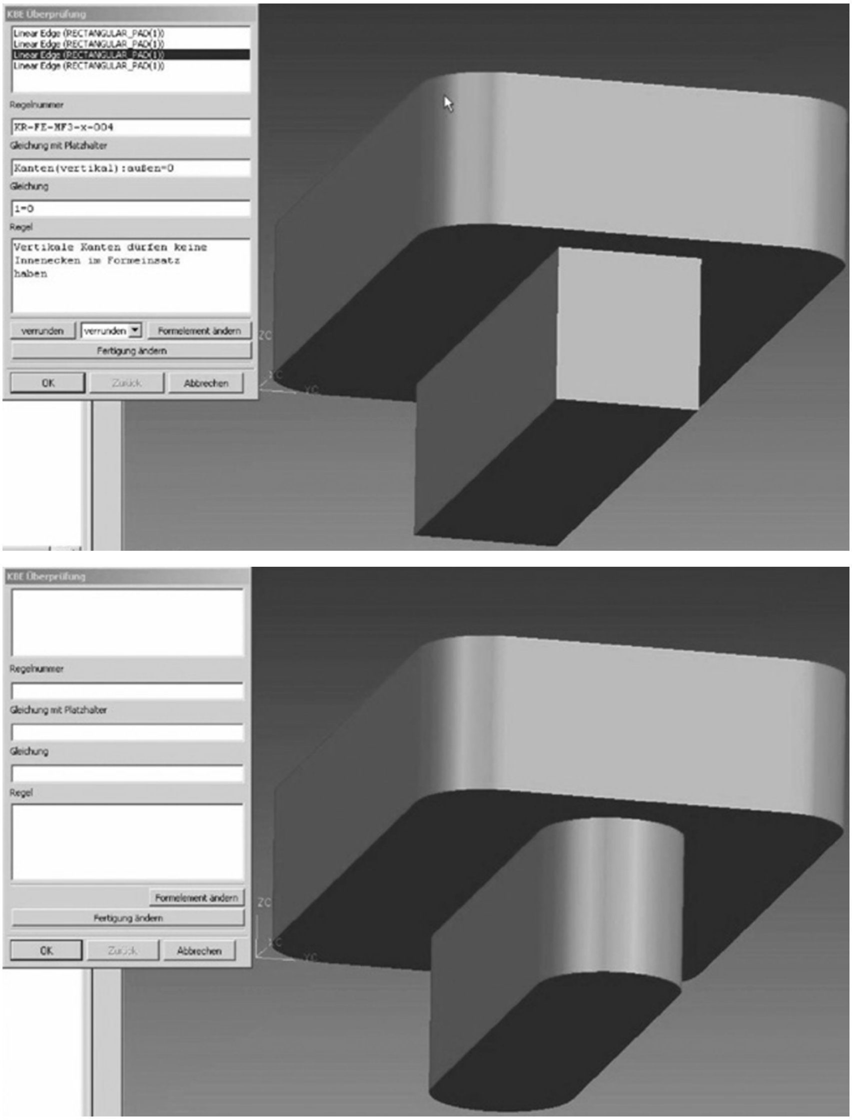


Fig. 1-12 (a) Interactive window with infringed rules; (b) manufacturable part after automatic correction (rounded vertical edges)

1.5
Conclusion

The approach presented here for the design of primary-shaped microcomponents and microsystems was defined and validated by developing and designing a microplanetary gear. Therefore, a tolerance concept for generic and gearing tolerances was established and implemented in the gear unit. By manufacturing and measuring single components of the gear, perceptions are iteratively integrated to the tolerance concept. Subsequently, our Institute will introduce a microgear test rig in order to test the components of microgears. The goal is to obtain information regarding the transmission behavior of high-strength microcomponents that are in contact within the system. In combination with the dimensional measurement of single components, microsensitive features and properties of microgears are deduced with consideration of their effects on function. Moreover, the development of a new VDI guideline is being directed by the Institute owing to its activities within the domain of microgears.

1.6
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