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DESIGN METHODOLOGY IN MICRO TECHNOLOGY

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Abstract

In micro mechanics, there exist extensive activities making products and systems available according to customer's needs in large-batch and medium-sized production. The predominant research effort concentrates on the constitution and optimisation of the processes for production, manipulation and quality assurance. An aspect how to reach the optimal function of a product in compliance with the requirements is so far missing. The issue presented consecutively sets a first step to a specific penetration of the product development process for primary shaped micro components from metallic and ceramic materials with a high load carrying ability. The approach for influencing the required function by product design is subjected to an orientation to production based requirements. To transfer design relevant know-how derived from the production technologies into the early design phases corresponding design rules were defined. These design rules act as a methodological aid accompanying the product design. To demonstrate the performance of this methodological aid the development of a micro planetary gear was accompanied. Moreover, the design rules were computer-aided made available within a knowledge-based design environment divided into an information unit and an embodiment design unit.

Keywords: design methodology, micro technology, design rule, micro planetary gear, knowledge-based design environment

1 Introduction and objectives

Design methodology in micro technology necessitates a specifically adapted approach since it could not be derived straight from the experiences in the conventional product development. Looking at the correlation between function and embodiment design in the micro scale it is due to the increasing relation between surface and volume that scale-dependent phenomena and effects (e.g. anisotropy) become more important. For a specific application and manipulation of these properties it is necessary to adapt the product development process specifically for micro technology.

As far as customer oriented micro system products for large-batch and medium-sized production are concerned there is presently a lack of integrated technological process chains to be detected. In micro mechanics, an enormous potential exists for the miniaturisation of production techniques from precision engineering. The advantages are to get competitive three dimensional micro parts. Research for the „development, production and quality assurance of primary shaped micro components from metallic and ceramic materials" are the fundamentals of the Karlsruhe collaborative research center SFB 499. Besides the constitution and optimization of the production preparation, manufacturing and materials testing design methodology is an explicit discipline.

By a specific penetration of the product development process for primary shaped micro components and micro systems specifically adapted methods and tools for the effective product design will be constituted. One method out of these should enable the designer to retrieve know-how from the production and the molding technologies and to manage detailed instructions from the designer's point of view. Since the information is provided effectively and regardless of individual people the designer can access at any stage of the product design process. Furthermore, the embodiment design phase is supported by implementing the know-how into the CAD.

2 Design rules as an aid accompanying the process of product design

Since the development and the design of micro technological products and systems are to be mainly orientated towards production technology, design methodology aims not only at adapting the process-specific requirements and parameters of the production technologies in a way which is appropriate for the individual design engineer but also at providing this knowledge by means of suitable aids accompanying the design process. The method of design rules supports the product designer at different abstraction levels of the product development process especially during the embodiment design of systems and components in the three-dimensional CAD.

2.1 Restrictions of production techniques

In the field of micro technology especially boundary conditions concerning product technology have a considerable effect possible for creating the system components. In order to design an efficient micro part perfectly fulfilling the required function the product designer thus needs to be able to develop and design in a micro-production-oriented way.

As a first step technology specification sheets were created (figure 1) in order to systematically collect the characteristic geometrical dimensions and properties of the production plant tools as well as the manufacturing sizes (such as feature size, aspect ratio) achievable by using them. In this context production preparation and molding are the essential steps within the process chain for the manufacturing of primary shaped metallic and ceramic micro components.

<u>Restrictions of production preparation</u>

The process of primary shaping firstly requires the manufacturing of a mold insert. With the aims to establish an efficient process chain for industrial large-batch and medium-sized production and to provide heavy-duty micro system components by means of metallic and ceramic materials, abrasive and machining methods offer big advantages. Up to now the center of manufacturing mold inserts has been micro milling with micro end mill cutters.

The body diameter of the milling cutter as well as the length of the milling cutter's edge are process-specific characteristics, which have a restrictive effect on the part design. Apart from that also the tolerances of the machine tool, the tool and the process management are important. Moreover, phenomena such as formation of burrs and wear of tools are to be considered (as long as the latter cannot be compensated for by the process). Figure 1 shows an extract of the technology specification sheet for the micro milling process.

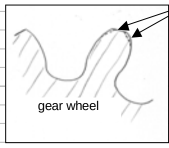
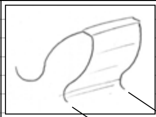
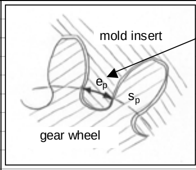
		technological parameter		design-relevant interpretation	influences
end mill cutter	1	diameter [mm]	d ≥ 0,10	 tip rounding so, that the milling cutter with the smallest body diameter can enter the mold insert's structures	-- loss of active flank length -- load-carrying capacity declines -- concentricity declined -- reduction of head width
		scaling [mm]	0,05		
	2	cutting depth		 maximum face width for a single-sided mold insert manufactured by micro milling	
		empirical formula	2-3 x d	2-3 x d = 2-3 x 0,1 = 0,2-0,3 mm	
		extended end mill cutter	~ 8 x d	8 x d = 8 x 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 in 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 ~ 2		
	6	formation of burrs			

Figure 1. Achievable manufacturing sizes in production preparation

Restrictions of molding

The molding processes include the micro casting as well as the injection molding of micro-powder (µPIM), which can be distinguished in CIM for ceramics and MIM for metal. The µPIM process is especially suitable for the aforementioned large-batch and medium-sized productions, since in these cases one can injection mold directly into the mold insert and at the same time manufacture a large number of micro components. The first thing required for the micro casting are models made of e.g. plastic, which one should be able to encapsulate. In this context dead-mold casting covers specific fields of application.

Boundary conditions from the µPIM derive from the necessity for runners, a sufficient number and size of part surfaces and points of attack for ejector pins used for demolding. The maximum yielding points and aspect ratios as well as sharp cross section transitions or bendings limit the mold-filling or the standard of the mold-filling technique. The shrinking, which occurs depending on the selected material, and which is almost linear during the sintering process, should be particularly taken into account.

If the influence of the up to now collected technology data on the part design is also known, it is still the product designer himself, who has to carry out the projection on structural characteristics at micro components by means of his awareness of problems and his experience. In order to include process data and information effectively and regardless of individual people into the design process, the restrictions have been interpreted relevant to design.

2.2 Design rules– an interpretation of restrictions relevant to design

Design rules are detailed instructions for micro-compatible part design. They derive from basic technological requirements.

Due to their level of abstraction design rules are especially suitable for the transformation of quantitative process parameters into geometric mathematical expressions. Thus, the data, which may be directly connected to the design system in order to support the embodiment design, can be managed in databases. Furthermore, by means of a hint to restrictive characteristics the designer can also be influenced in his decisions during the planning phase. Apart from the technology-related deducing especially the computer-aided availability of design rules accompanying the process has been taken into consideration.

<u>Classification of design rules</u>

In order to provide the required computer-aided illustration of the design rules a classification scheme for unambiguous identification has been developed. According to this scheme the presentation of design rules consists of a rule class and a number (figure 2).

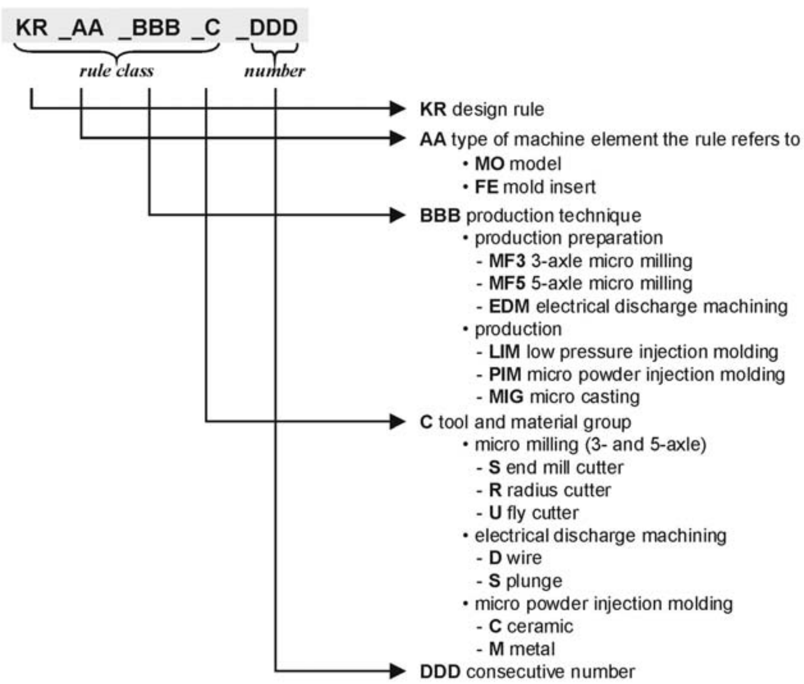


Figure 2. Classification scheme for the presentation of design rules

The rule class contains the type of machine element the rule refers to. Depending on the rule information concerning production technology and details about the tool and material group are given. If a rule can be applied to various production techniques or tool and material groups, the entries ”xxx” or “x” are made instead of the listed code letters. However, this is not possible for the machine element type, as the contents of the rule has to be clearly assigned to the mold insert or the model. Therefore, there are generally different records of design rules for mold and model, which are nevertheless clearly connected geometrically. Restrictions from the mold insert manufacturing automatically affect the model and vice versa. However, a difference can be found in the geometrical properties. The model is scaled down due to a sinter shrinking during the molding process. Moreover, complementary figures are developed since a drilling in the mold insert results in a cylinder of lower height and diameter in the model. Thus, distinguishing according to the machine element type leaves it up to the product designer if he wants to develop the model of the primary shaped part or the corresponding mold insert.

Examples of technology-related design rules

The design rule **KR_FE_MF3_x_002** is explained as an example.

It refers to the mold insert as machine element type (**FE**) and is valid for the production preparation technology of 3-axle micro milling (**MF3**). The entry „**x**“ shows its validity for several tool groups (end mill and radius form cutters). Apart from that it is the second of its rule class composition. Expressed in a mathematical relation the rule is as follows:

$$R_{\text{inner edge}} \geq d_{\text{milling cutter}} / 2 + T_{\text{mill}} \quad (1)$$

$R_{\text{inner edge}}$	radius of roundings of edges of the mold insert
$d_{\text{milling cutter}}$	body diameter of the milling cutter
T_{mill}	sum of tolerances (machine tool, cutter, process management)

Due to the circular cross section of the milling cutter no sharp inner edges or radii of the mold insert, which are smaller than the milling cutter’s radius plus its tolerances, can be manufactured. This fact as well as the influence of further design rules on the micro product design will be explained by means of the development of a micro planetary gear.

3 Design rules accompanying the development of a micro planetary gear

Planetary gears are typical mechanical systems of high power density in mechanical engineering and precision engineering. Thus, it is particularly suitable for the comparative investigation of the approach of product development in micro technology.

3.1 Problem of micro technical gearing

The main proposition for the development of the micro planetary gear was that all components of the micro system should be manufactured by the technological process chain and from a heavy-duty ceramic material.

In the early design phase of product planning the product designer had to face beside the distinct specification of the requirements for such a micro gear a multitude of open questions. Fundamental points to be clarified were for instance which kind of gearing would be producible in the microscopic scale at all and if there are any standards of dimensioning to fall back on. Moreover, the layout and dimensioning of basic machine elements like bearings or shaft-hub joints are relatively unknown. Already in this early stage, design rules gave important indications for the part design and thus predefined essential properties of gearing and characteristics of the whole gear.

As the subsequently most important restriction of production technology the circumstance described by the design rule according to equation (1) has turned out. Since micro end mill cutters are utilized for the manufacturing of mold inserts roundings occure on the inner edges of the mold insert and subsequently on the component’s edges. For the concrete geometrical layout of a micro gear tooth (figure 3) this leads to a tip rounding of minimum 50 µm for the up to now smallest for reproducible cutting results utilized micro end mill cutter with a body diameter of 100 µm. This causes a loss of active flank length resulting in a declined transverse contact ratio which is essential for function requirement fulfilment. It is obvious how a slight geometrical restriction affects a great deal of annoyance of function.

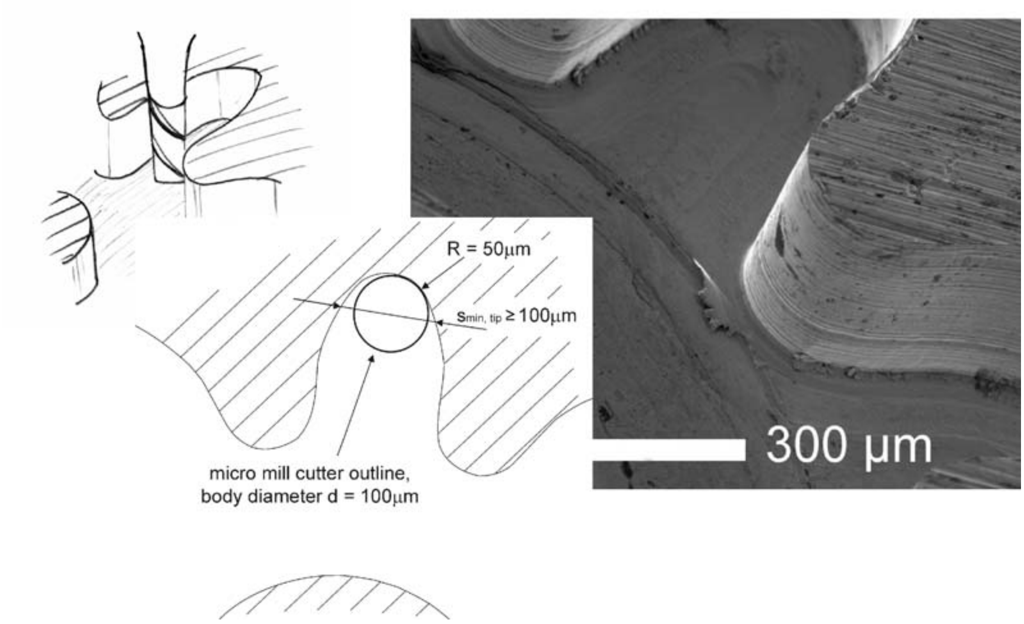


Figure 3. Rounding of component edges caused by the micro end mill cutter manufacturing the mold insert

Restrictions in the face width are based on a direct correlation between cutter's parameters, the realisable cutting depth being two times the body diameter. This circumstance is expressed by the design rule **KR_FE_MF3_x_005.**

$$t_{\text{cutting depth}} \leq 2 * d_{\text{milling cutter}} \tag{2}$$

$t_{\text{cutting depth}}$	cutting depth according to the length of the milling cutter's edge
$d_{\text{milling cutter}}$	body diameter of the milling cutter

The know-how relevant to design within the design rule on hand enters the much further step of the calculation of the carrying capacity of the gearing and therefore denies for example the determination of a requested safety factor by an increase of the face width.

This condition is even declined, since the micro parts are exposed to a sinter treatment shrinking almost linear in all dimensions. The shrinking of zirconium dioxide, the ceramic material applied in this case, is about 22 % with an additional tolerance of 0,4 %. By adding geometrical margin this phenomenon can be compensated. On the other point of view, the shrinkage implies the chance to increase the degree of miniaturization of the components with respect to the structural dimensions of the mold cavities placed on the mold insert.

Hence, by the discussed technological restrictions the approach in product design changed in comparison to macroscopic scale. The central design task expressed itself like this: "Constitute around a 50 µm tip tooth rounding a gear flank for a micro planetary gear of smallest size, complying the required gearing tolerances and sustaining a constant transmission rate."

3.2 Conceptual and embodiment design of the gear

Results in conceptual and embodiment design of the micro planetary gear are presented in [1] and [2] in detail. In these contributions different other methods and tools are successfully applied on the product development in microscopic scale.

Figure 4 shows the completely designed micro planetary gear:

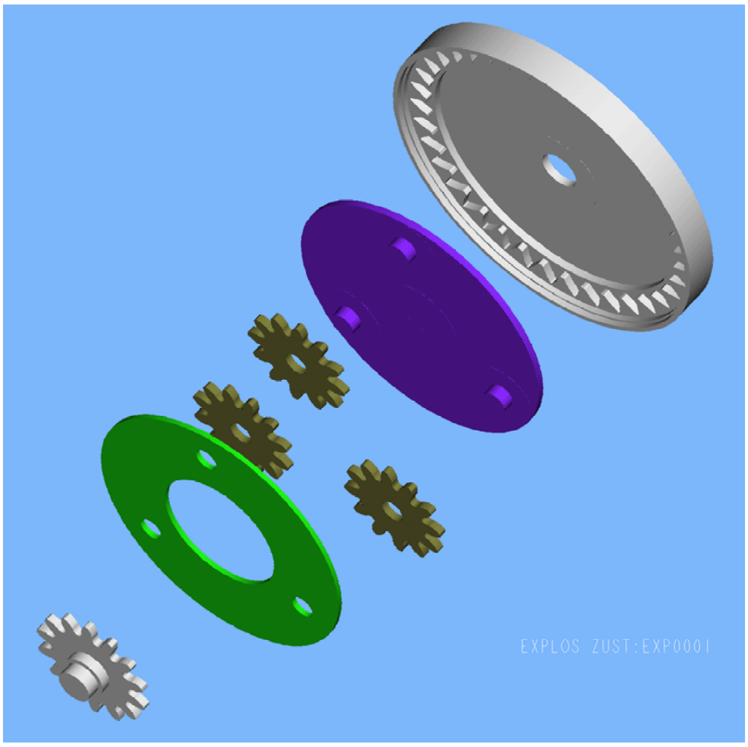


Figure 4. Completely designed micro planetary gear

4 Computer-aided availability of design rules

For a computer-aided availability of design rules the constitution of a knowledge-based design environment was approached. Both, an information unit and a three-dimensional CAD system with an application for knowledge-based engineering (KBE) are integrated, accessing the same data record.

4.1 Information unit: Design and Methodology Database (Konstruktions- und Methodikdatenbank) - KoMeth

“KoMeth” is an interactive knowledge portal which supports the product designer with specific design rules through different methods of access. For each design rule there exists an information site presenting the rule class and number, the title and the mathematical relation. Drafts, descriptions and pictures of virtual product models and manufactured components give illustrations (figure 5).

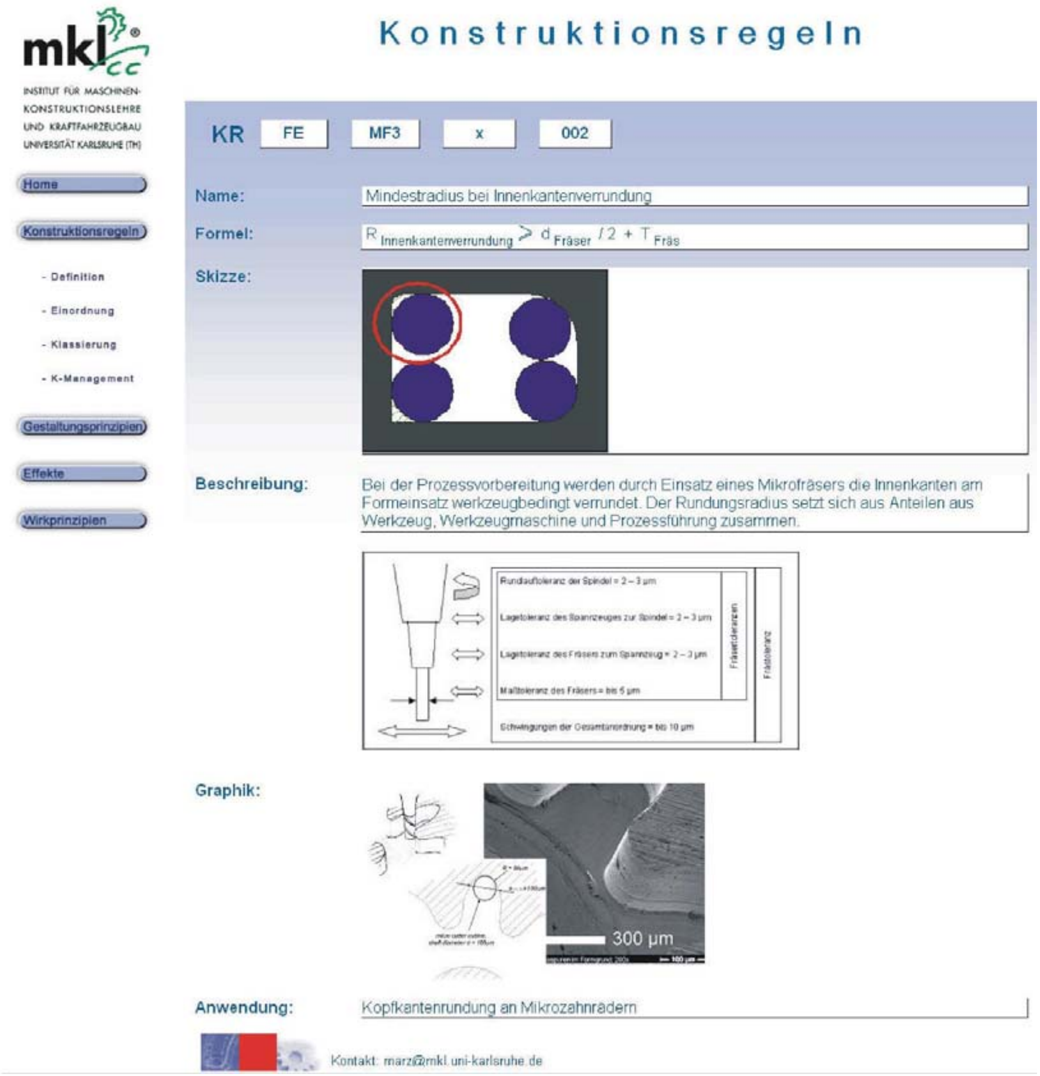


Figure 5. KoMeth – Design and Methodology Database

4.2 Embodiment design unit: application for KBE within the three-dimensional CAD system Unigraphics V18.0

To apply design rules during the embodiment design phase, the application for KBE within the three-dimensional CAD system Unigraphics V18.0 [5] had to be upgraded by a specific range of functions.

Starting a CAD session the designer is requested to define the type of machine element and details about the tool and material group. The programmed algorithm extracts edges and surfaces from the design draft with respect to the method of boundary representation – B-rep. [3] and relations between the boundary elements. The detected geometrical properties are connected together with the corresponding design rules, which have been concretised by parameters of the production techniques, resulting in elementary rules. These elementary rules represent mathematical relations that can be applied to the design draft by means of the application UG/KF (Unigraphics / Knowledge Fusion). [5] Any infringement of a rule is indicated in an interactive window (figure 6).

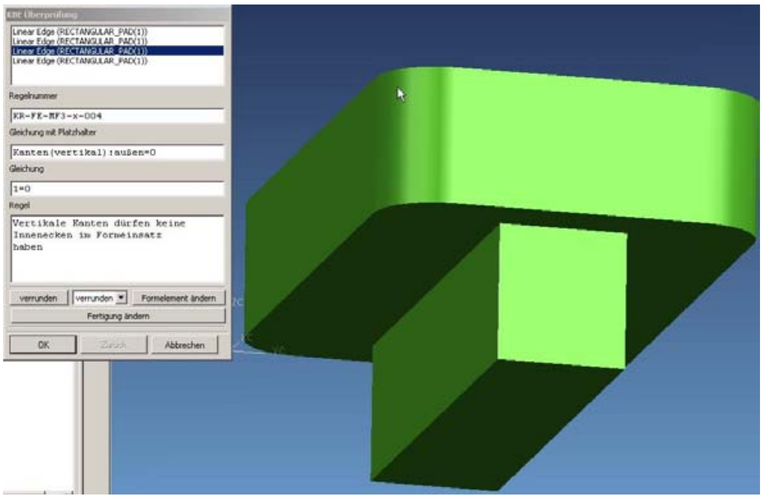


Figure 6. Knowledge-based embodiment design (interactive window with infringed rules)

5 Conclusions

Following the technological process chain for manufacturing primary shaped micro components from metallic and ceramic materials, the technological boundary conditions and restrictions of production preparation and molding, as well as material specific properties were collected. By the means of the method of design rules as an aid accompanying the process of micro product design, detailed instructions for the designer could be derived from the technological background. Accompanying the development of a micro planetary gear the potential of this method was revealed. Within a micro-specific adapted design environment the design rules could be accessed by an information unit on the one hand and by a three-dimensional CAD system with an application for knowledge-based engineering (KBE) on the other.

Drawing a conclusion, the available manufacturing technologies and materials in micro technology necessitate a different approach for the product development process. In the conventional process for mechanical and precision engineering almost each product design is producible, as long as it does not severely infringe to elementary design know-how, though it may involve high technological and financial efforts. In micro technology a lot of know-how relevant to design derives from disciplines subsequent and adjacent to the design process. Already in early phases of product design the possible design scope the developer can use to find an optimal way for fulfilling the design task is significantly limited. In a much more intensive way, going beyond any guidelines for embodiment design, the product design in micro technology is inescapably driven by technology.

6 Acknowledgement

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