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COMPUTER AIDED EVALUATION OF DESIGN RULES FOR MICRO PARTS

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1 Introduction

The embodiment design of micro parts is highly restricted by the available manufacturing technologies. Especially primary shaped parts are subject to a great number of limitations due to the complex production process. But not all of them are known yet and most are changing over time. Thus it is necessary to provide a set of so called design rules that describe these conditions and limitations. Further on, an automated way to check these rules within a CAD system is needed.

This paper presents a system to satisfy these needs with the main focus on an optimized design for manufacturing of primary shaped micro parts.

2 Knowledge Based Design

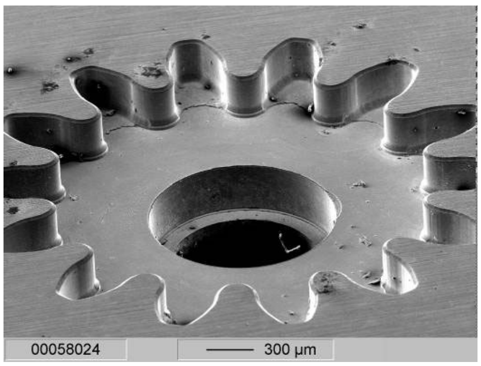
Knowledge Based Engineering (KBE) is an efficient tool for accelerating development processes and becomes more and more popular in the design process. Most CAD systems either include such tools or they are available as add-ons. These systems mostly use relations between dimensions of features in the digital model. They have to be defined for each feature of a model separately or for one kind of feature (e.g. all holes) in general. Both methods are little useful for really new designs but for modifications of existing designs since they have only few possibilities to define them in an abstract way.

Other systems have the possibility to build a whole technical system out of a functional structure. The engineer has to describe the technical function in a special language. The KBE system more or less automatically generates a design that fulfils these requirements. Of course, this is only possible for already known pairs of function and design. The system is able to adapt the dimensions of the design to the programmed conditions.

This paper describes a rule based system. The engineer still has to design his system in a conventional way in a 3D CAD system. The KBE system checks the design afterwards according to predefined abstract rules. If it finds a contradiction, different actions are possible: Either it is able to correct the problem by itself or it presents the user some solutions and asks which to use, or it informs the user about the rule. The advantage of this kind of KBE system is, that the rules are stored in a separate database, independent of the used CAD system or a special design. The same set of rules can be applied to every design and all CAD systems that have an appropriate interface.

3 Designing Micro Systems

The objective of the collaborative research center (Sonderforschungsbereich) ‘Development, production and quality assurance of primary shaped micro components from metallic and ceramic materials’ is to develop an industrial applicable process of product development, production and validation for micro parts. One aspect is to provide a methodology to design micro parts with respect to their production, usage, loading, measurement, test etc. These aspects of the development process have all special restrictions, boundary conditions or requirements. They depend on the used technology and thus the ability to manufacture e.g. required tolerances and surface qualities with respect to their function.



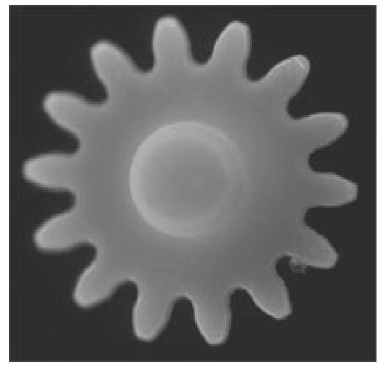


Figure 1. Milled mold insert (SEM micrograph, left) and molded part (right)

Mainly the production process chain of primary shaped micro parts is regarded. Hence, it must be considered that as the model (positive) is mostly created in the CAD, and the corresponding negative mold –the mold insert- is automatically generated. With parametric CAD systems it is possible to consider the sinter shrinkage in this process and thus to create a bigger mold insert. The production of the model is then carried out in two steps. Firstly, the mold insert (negative) is manufactured. The technologies currently available for this process are micro milling, micro erosion and laser ablation [8]. The second step consists of molding the model (positive) by means of ceramic or metallic micro powder injection molding or micro casting [6, 7].

On both process steps there are separately different restrictions, e.g. that it is not possible to mill a cavity, which is smaller than the milling cutter or that in terms of the micro powder injection molding a minimum wall thickness and a maximum flowing distance need to be observe

4 Design Rules

Knowledge and experience can be stored in so called „design rules“. They describe how a designer has to act in a special situation, e.g. if he has designed a slot and the part should be machined with an end mill, this slot must be minimum as wide as the diameter of the end mill. To apply these rules on a concrete CAD model, further information is needed. On the one hand, the system has to determine the width of the slot, on the other hand, it has to know the diameter of the end mill. Then it can compare both values and infer if the rule has been considered or not.

Thus a system to evaluate design rules automatic in a CAD system has to consist of three elements: the CAD-system with an access to the geometric data, the stored rule sets and information about the used process, materials, …

4.1 Geometric data in the CAD-system

Most parametric CAD systems use "features". A feature mainly is a (basic) geometrical element together with its dimensions and its placement relative to other features. Today, there are often more than 100 different features defined in a CAD-system. As they are not all absolutely independent of each other there are more ways to describe the same part. E.g. you get the same resulting geometrical part if you extrude a square with a circle in the middle and if you use a cube and place a hole in it. Thus you would have to describe each rule in a lot of different ways to regard all possible features and interaction of features.

Cherian and Midha presented in [3] a system to check if a part is injection-moldable and predict some mechanical properties of the molded part. They used boundary elements of the 2D cross sections (lines / curves and points) to analyse the geometry. The main advantage of this approach is that it is nearly independent of the history of the CAD model, it is even possible for imported CAD models from another system. If two models have the same shape, they also have the same boundary elements. It is only possible – depending on the CAD system – that e.g. a circle is divided into two concentric half circles.

This approach was extended to real 3d geometries. The boundary elements then become faces and edges (the intersection of two adjacent surfaces). Algorithms are needed that are able to calculate the geometric properties of this elements. They are defined for edges (e.g. angle), faces (e.g. height), two faces (e.g. gaps, free distance between the faces) or special groups of faces (e.g. notches).

4.2 Systematic storage of design rules

All rules are stored in a database independent of the CAD system. They are formulated as abstract as possible without any special process data. Such a rule consist of 6 parts:

- a brief verbal description of the rule
- eventually a picture
- a mathematical equation as a condition that refers to the part's geometry
- a unique key that identifies the rule and it scope
- instructions what to do if the condition is true
- instructions what to do if the condition is false

The knowledge-based design environment makes it possible to separately formulate the rules for different processes. However, it is necessary to unambiguously point out to which type of machine element the geometric quantities relate. This can be achieved by means of a so-called rule class, which indicates for which type of machine element a rule has been set up and to which production technologies and tools or materials it applies.

If a rule is applicable to all technologies or tools/materials the marking "xxx" or "x" can be observed instead of the special code. Due to an additional consecutive number an unambiguous rule code for each rule is derived.

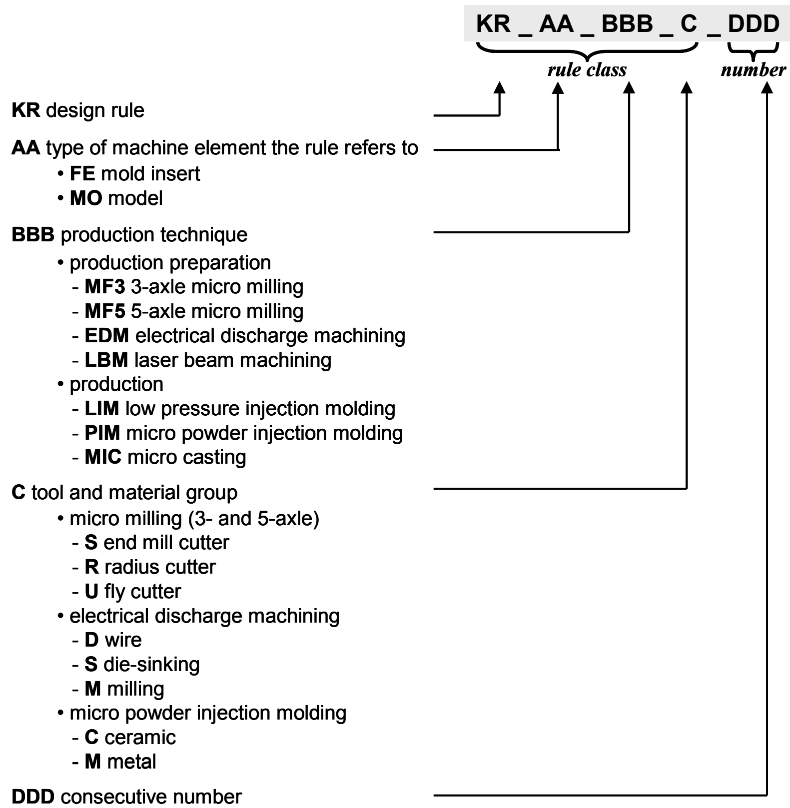


Figure 2. Rule key to identify each rule

4.3 Database with additional information on processes, materials etc.

The process specific data is stored in a separate database. It represents the current state of technology and thus changes over time. The data is stored in two hierarchical levels. The first represents the process (e.g. milling), the second an additional differentiation (e.g. a special end mill with d=100µm). Parameters can be defined on both levels. If the same parameters are defined multiple times it is possible to add them (e.g. tolerances of a milling machine and an end mill) or use the biggest, mean or smallest value (e.g. maximum part dimensions).

4.4 Examples for Design Rules

Process related design rule

In order to point out the relation to production technologies the design rule KR_FE_MF3_x_002 is explained as an example. It refers to the production technology of 3-axes micro milling preparing the process, which applies to various tool groups (end mill cutter and radius form cutter). It relates to the mold insert and is the second of this rule class combination. The corresponding mathematical expression is as follows:

$$R_{inner\_edge} \geq \frac{d_{milling\_cutter}}{2} + T_{mill} \tag{1}$$

Because of the circular cross section of the milling cutter no vertical inner edges or radii, which are smaller than the milling cutter's radius plus the milling tolerance, can be produced.

However, if the radius is as big or even bigger than the milling cutter, the tool can process to the geometry of the cavity. Applied to the geometry of a micro gear this implies a tooth tip rounding and thus a reduction of the effective transverse contact ratio. [1, 2]

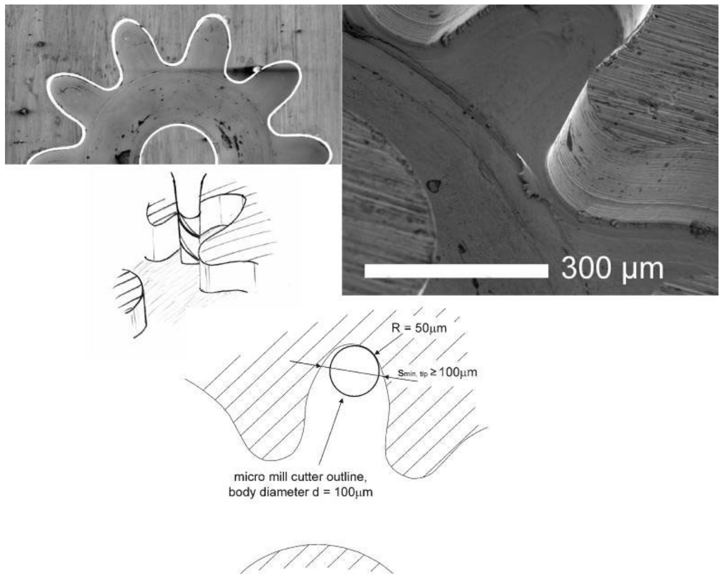


Figure 3. Milled mold insert (SEM micrograph) with rounded teeth caused by micro mill diameter

Load related design rule

According to the German standard DIN 743 [4] it is possible to calculate the maximum allowed load on a shaft depending on material properties and the geometry in some basic cases. In this standard some special geometric forms called notches are defined. They can be expressed and described with the corresponding boundary elements defined in 4.1.

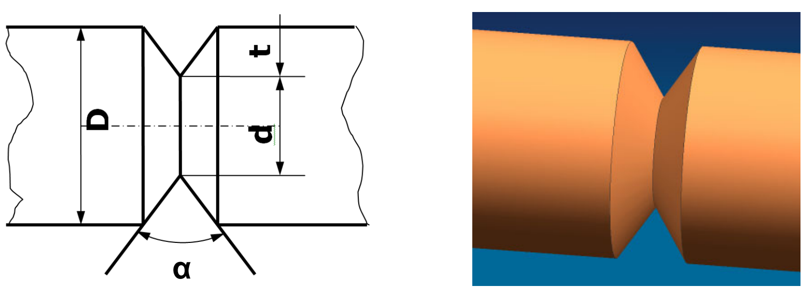


Figure 4. V-notch defined in DIN 743 [4] (left) and its boundary elements in a CAD model: cylinder – cone – cone – cylinder, connected with circular edges

Now you can formulate a design rule which states that the ratio of the yield strength and the maximum stress due to the notch effect must be bigger than a specified safety factor:

$$\frac{R_e}{stress\_v\_notch(D,d,\alpha)} \geq S \qquad (2)$$

The parameters D, d and α can be expressed as attributes of the boundary elements:

D = diameter cylinder
d = diameter circular edge between cones
α = 180° - angle of cone

5 Rule based design assistance in a CAD system

5.1 Integration in the CAD system

In general a system will only be used if it is no additional work and has an obvious advantage to the designer. Thus no new system besides the normal CAD tool should be introduced to the designer, but the rule based assistance system has to be integrated in the regular CAD system. The realized prototype extends the toolbar of the CAD system with new options: define parameters and rule check. Therefore it is possible the check all rules within the CAD system with only one action. The results will be printed on the screen and directly marked in the CAD model.

5.2 Scheme of rule check

The evaluation of the rules is made in several steps: First parameters have to be defined. Since a lot of design rules describe the primary shaping process used in the center of excellence the system is able to handle both, the mold and the part, and it is possible to define two subsequent manufacturing processes, e.g. milling of the mould and powder injection molding. These parameters – the two processes and whether it is a mold or a part – have to be defined prior to checking.

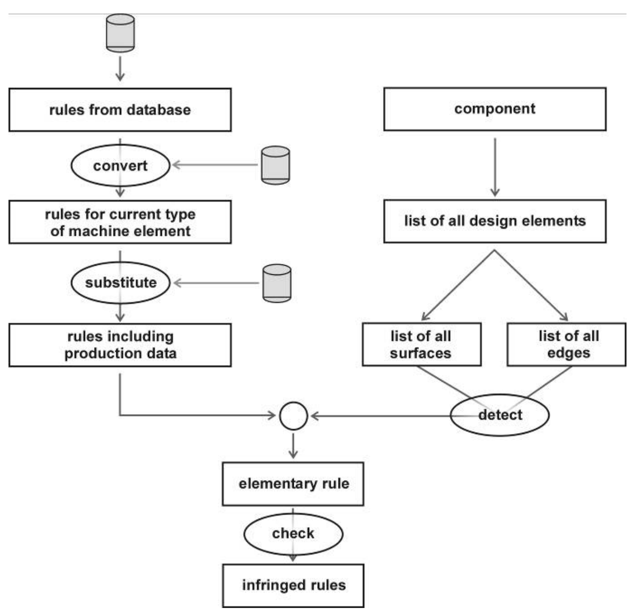


Figure 5. Process scheme of rule adaptation and evaluation

5.3 Adapting rules

By adapting the general rules of the database to the special geometry as well as to the currently used processes elementary rules are obtained. Consequently, they are not generally applicable anymore, but describe the concrete circumstances and can hence be evaluated by the computer. The preparation for this is carried out in two parallel steps: the adaptation and concretization of the rules and the analysis of the geometry. The processing of the rules as provided by the database until the time, when they can be connected with the geometric parameter, is carried out in three steps.

1. The rules are loaded from the database into a list corresponding to their rule key. Rules, which are not appropriate according to the process, tools or material are not considered.
2. Since rules can be defined for parts and for mold they have to be converted eventually. Although the part and the mold are different in their shape and dimensions, they are correlated in an exact way. A linear shrinkage assumed all dimensions have a defined ratio and the shape is inverted i.e. a cylindrical shaft becomes a hole with a smaller diameter and length. Thus if a rule is defined for the other part type (model or mold insert), it is “translated” by means of a transformation table, e.g. mold: bore diameter -> model: shaft diameter * shrinkage.
3. In accordance with the applied process chain the technological data is loaded from a separate database and placeholders in the rules’ formulas are replaced. If no equivalent for a placeholder can be found in the database, the value „0“ is assumed. E.g. if you have a process with no shrinkage, no shrinkage will be defined too.

5.4 Analyzing CAD part geometry

The evaluation of the geometry of the part is carried out in two phases. First all boundary elements from the database of the CAD system need to be read and secondly the corresponding properties of each of them are to be determined if needed by some rule.

Geometric properties can be defined for solid bodies (i.e. all surfaces of one part), single surfaces, pairs of surfaces, special groups of connected surfaces or edges (identical to the intersection of two adjacent surfaces). For the determination of geometric properties topologic information about the individual boundary elements are available within the CAD system from the part database, such as unit (normal) vectors, maximum width and height etc. Simple geometric parameter can be derived directly out if them. E.g. two surfaces are parallel if they have identical unit normal vectors.

Other parameter are more complicated to calculate, since there are various influencing factors or interdependence. One example is the angle of an edge, which is defined as the angle measured between the adjacent surfaces directly at the edge, with an angle $\alpha<180°$ for convex structures and $\alpha<180°$ for concave ones. This separation is possible since the normal vectors of surfaces of solid bodies point always outwards from the volume.

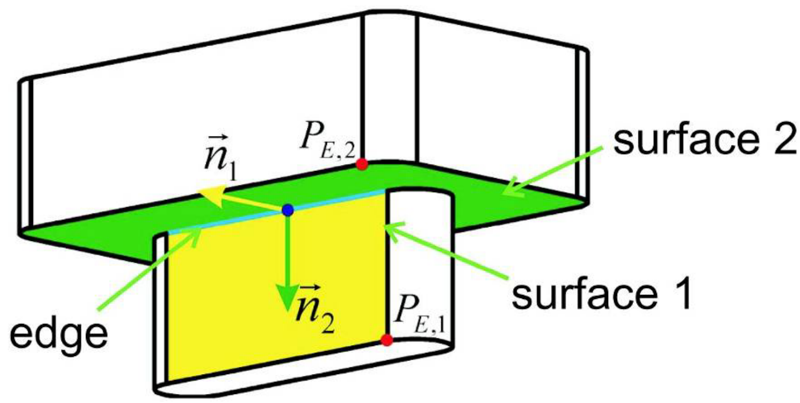


Figure 6. Boundary elements of a sample part used to calculate the angle on the marked edge

In particular it is calculated in the following steps:

1. Determination of the adjacent surfaces
2. Specifying a common point of both surfaces on the edge
3. Determination of the unit normal vectors of the two surfaces at this point
4. Calculation of the angle between the unit normal vectors

$$\cos\varphi = \overrightarrow{n_1} \bullet \overrightarrow{n_2} \tag{3}$$

5. Determination of the small angle between the surfaces

$$\alpha^* = 180° - \varphi \tag{4}$$

6. If the surfaces are parallel (α^*=0° or α^*=180°) the angle on this "edge" is $\alpha = \alpha^*$. Else it has to be determined if it is an "outer" or an "inner" edge.
7. Check if one of the surfaces exceeds the common edge in the direction of the other normal vector. This is done by determining the extreme point on the surface 1 in the direction of the normal vector of surface 2. To obtain an unambiguous point two further directions are needed, the first normal vector and the cross product of both vectors are used. This is of no importance to the angle but to the algorithm to work. The second point is determined analogous.
8. If one of these two points is on the common edge of the surfaces, it is an outer edge; if not, it is an inner edge.
9. Calculation of the angle: $\alpha = \alpha^*$ (outer edge) or $\alpha = \alpha^*$+180° (inner edge) respectively

5.5 Evaluation of the rules

A large set of elementary rules is created by combination of all adapted rules with all appropriate geometric elements. In this step the last placeholders (for the geometric parameters) are replaced by exact values. Finally these elementary rules are evaluated to a logic result (true or false). If the rule evaluates to "false" the system creates an appropriate message and proposals how to correct the CAD model. In some cases, this optimisation can be done automatically.

6 Realized prototype

The above describe system has been realised as a software prototype at the author's institute. It is based on the commercial available CAD system "Unigraphics" and its programmer interface "UG/Open API". The handling of the rules and the analysis of the geometry is performed by a program written in Visual C++. The evaluation of the elementary rules to logic results is done by Matlab and its C-interface. Therefore, all of Matlab's geometric functions can be used inside the rules as well as user defined functions. To extend to possibilities of the rule-based engineering system, new functions can be defined in Matlab without changing the core program. E.g. a set of functions to calculate the notch effect according to DIN 743 [4] is implemented in this way and allows to use load related design rules on shafts.

6.1 User Interface

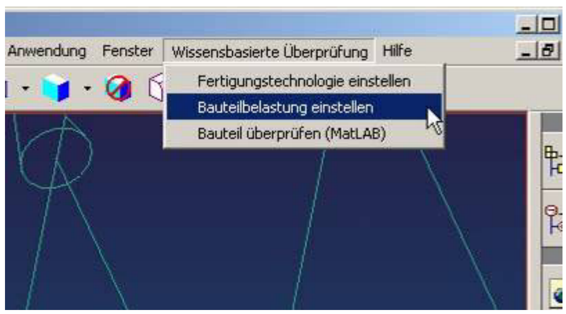


Figure 7. Extended Unigraphics toolbar for direct access to the knowledge based system

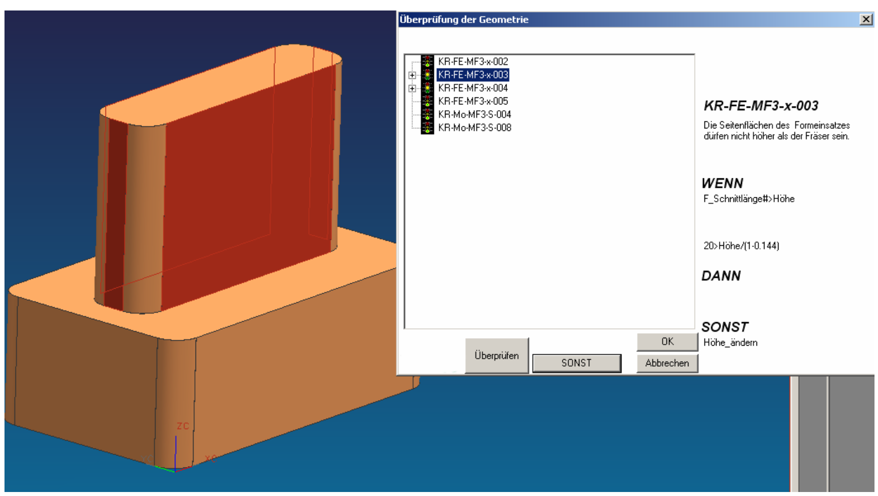


Figure 8. Dialog box with the results of the rule check. The boundary elements infringing the selected design rule are marked.

The user interfaces for setting up the parameters of a part and checking the rules are accessible by an extended toolbar within the CAD system. Thus the user can work regularly in the CAD system and activate the knowledge based system "by one click". The result of the rule checking is also presented in a dialog box. All rules that evaluated to false are marked. If the user selects a marked rule, the corresponding elements in the CAD model are highlighted. If an automatic correction is defined, the user can apply it.

7 Conclusion

For the development of micro parts much more restrictions compared to “normal sized” mechanical engineering need to be considered. Therefore, providing a system for checking the geometry of the micro parts concerning certain parameter as a knowledge-based support for the designer is useful and necessary. Since this system is based on the knowledge about manufacturing quantities, material parameter and design rules, about which up to now information is only partly available, the system also requires an open structure and the possibility to easily modify the data record. For this purpose, a program module has been implemented into the CAD system Unigraphics, which is able to carry out this checking. The entire data record has been filed externally in databases. Thus, it is accessible for the user as well as for other systems independently of the CAD system.

The geometry analysis is based on the so-called „boundary representation“ of the part [3], i.e. on the surfaces and edges (the boundary representations) of a solid. Hence, it is independent of the way how this solid has been generated and generally applicable for all CAD formats supporting this presentation (e.g. Parasolid, STEP) [5]. Although the analyse functions have been especially programmed for the demonstration objects they are universally applicable. Consequently, they also provide correct results for more complex parts, but do not nearly demonstrate all interesting geometric quantities. For this purpose, the set of functions needs to be extended.

The possibility to automatically carry out corrections in order to secure the production-compatible design of the micro part makes work easier for the designer. He is therefore able to concentrate on a function-oriented design as the system might automatically recognise and correct small deviations (e.g. roundings) which are less important for the function of the mechanical part but make production possible or clearly easier. As a result, unnecessary delays in the preparations or even deviations between the manufactured part and the drawing

References

[1] Albers, A., Burkardt, N., Hauser, S., Marz, J., „Prototyp einer wissensbasierten Konstruktionsumgebung für den Entwurf von Mikrobauteilen“, Konstruktion, 2005 (1/2), p. 76-81

[2] Albers, A., Burkardt, N., Marz, J., “Restrictions in the design of gear wheel components and drives for micro technology”, Microsystem Technologies, 9, 2003, p. 192-196

[3] Cherian, R. P., Midha, P. S., Smith, L. N., Pipe, A. G., (2001) Knowledge based and adaptive computational techniques for concurrent design of powder metallurgy parts”, Advances in Engineering Software, 32, 2001, p. 455-465

[4] DIN 743, “Tragfähigkeitsberechnung von Wellen und Achsen“, Beuth Verlag, Berlin, 2000

[5] ISO 10303-42, “Industrielle Automatisierungssysteme und Integration - Produktdatendarstellung und -austausch - Teil 42: Allgemeine integrierte Ressourcen: Geometrische und topologische Darstellung“, Beuth Verlag, Berlin, 2003

[6] Ritzhaupt-Kleissl, H.-J., Bauer, W., Knitter, R., Piotter, V., Ruprecht, R., Haußelt, J., „Fertigung keramischer Mikrokomponenten. 4. Statuskolloquium des Programms

Mikrosytemtechnik 30.-31. März 2000", Wissenschaftliche Berichte FZKA 6423, Forschungszentrum Karlsruhe, 2000, p. 45-50

[7] Ruprecht, R., Gietzelt, T., Guttmann, M., Hanemann, T., Heckele, M., Müller, K., Piotter, V. „Abformverfahren für mikrostrukturierte Bauteile aus Kunststoff und Metall. 4. Statuskolloquium des Programms Mikrosytemtechnik, 30.-31. März 2000", Wissenschaftliche Berichte FZKA 6423, Forschungszentrum Karlsruhe, 2000, p. 39-44,

[8] Schmidt, J., Simon, M., Tritschler, H., Ebner, R. „µ-Fräsen und µ-Erodieren für den Formenbau", wt Werkstattstechnik online, 91, 2001, p. 743-746

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