# Product Development Regarding Micro Specific Tasks
# –
# Challenges in Designing for Production and Assembly

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**Abstract**

Tolerances and the interaction of parts play a large role in the micro design process. The downsteam processes, e.g. production also play a major role. The main processes that have to be taken into consideration are because of the basic material used, circonium dioxide, design and production of the cavity, injection molding and sintering, decollating, quality assurance and at last the assembly of the different parts.

The different steps of the production process have certain restriction on the design. The restrictions delimit the shape of the parts and of the system as a whole. In many cases the matching of parts is evident to achieve a functional system, e.g. we would need to produce parts with a diameter of 1 mm with a maximum deviation of 1 µm to fulfill the function without searching a matching couple.

**Keywords**:

Design for Micro-Mechanical-Systems (DFX), Design Process, Micro Gear

## 1 INTRODUCTION

In the past ten years, the research on and the use of small sized parts and systems has increased. Everywhere around us, things are gettting smaller and smaller. This miniaturization generates a specific need of new design and production processes. Therefore the Institute of Product Development (IPEK) at the University of Karlsruhe does research not only in the classical field of product development but also in the field of micro systems design. Special interest is put on processes taking place during design and manufacturing.

The collaborative research center (SFB 499) at Karlsruhe deals with design, production and quality of primary shaped micro parts [1]. Hence, there are different domains to think of. One basic requirement for the research group is to be able to produce a large number of parts. For that reason the methods of primary shaping were chosen.

The physical outcome of the project is seen in **Figure 1** (a planetary micro gear).

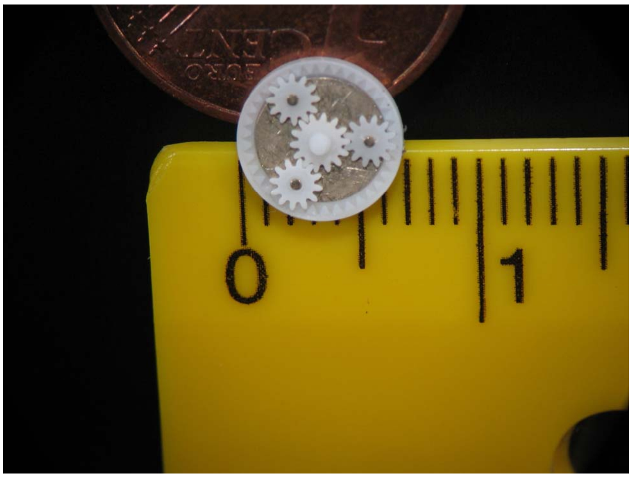

Figure 1: Micro Planetary Gear

Following the steps of the product development process the designer has to find the requirements, the first important thing to mention is the design of the mold insert. The designer needs to pay attention to different requirements, e.g. the milling of the mold is one way to be able to produce a constant quality. Nevertheless, the diameter of the milling cutter is limiting the minimum diameter of any detail in the mold [2].

The powder injection molding builds ub the next step of production process. Beside the typical limits of injektion molding (e.g. aspect ratio), there is a microspecific task in the design of the gate system.

The demolding also is a challenge for both, the designer and the production engineer. Ejector pins do not have as much space as they have in macro-systems. Therefore the designer has to arrange the pins very accurately.

After demolding, sintering is the next step of production. Here we generally have to meet two basic challenges. One is that there are different temperatures at differnt places in the oven. Because of this, the ceramic parts have variable shrink factors for indentical materials and therefore are of differnet sizes. The second challenge is, that non planar parts tend to deform tremendously. E.g. the planet carrier needs to be embeded in sand before sintering because otherways it would bend.

At the end the different parts must be assembled to a working system. In this case we have a micro planetary gear drive as seen in **Figure 1**.

Regarding these aspects we need to have a close look on existing design processes and on the new requirements.

## 2 DEVELOPMENT PROCESS MODELS

### 2.1 General Models of Product Development Processes

The guideline 2221 of the Association of German Engineers (VDI) describes a seven step process model for development and design tasks [3]. First of all, the design task has to be clarified. This step results in a list of requirements, i.e. engineering specifications, which accompanies the development process. Based on that, product functions are identified and structured. Then the designer has to look for working principles (e.g. physical effects) or combinations of these, which fulfill the desired functions. These principal solutions are combined to realizable modules. The decisive modular structures are the initial points for preliminary design. Then design of the product as a whole follows. Eventually, specifications for realization and operation, i.e. the product documentation, are elaborated. The iterative aspect is emphasized, i.e. the process stages are not rigidly coupled, but can be passed though repeatedly.

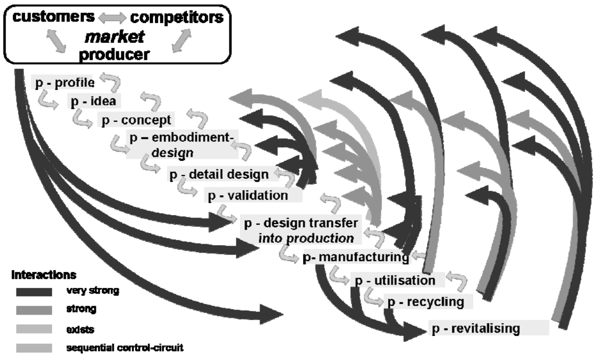

Figure 2: Process of product development, realization and utilization (Albers, 2004)

Pahl and Beitz (1996) describe a process model for developing technical systems, which consists of four stages [4]. The first step is planning and clarifying the task. Product ideas are generated or derive directly from a customer's order. Based on that, the specific task has to be clarified, i.e. information regarding customer demands and requirements has be gathered, weighted and concentrated in engineering specifications. The second step is conceptual design, during which principle solutions and solution variants are generated and evaluated. The one being most promising in consistence with the engineering specifications is elevated to the next level, embodiment design. Within embodiment design preliminary layouts are generated and evaluated according to technical and economical feasibility. The definitive layout is compatible to all requirements and has to be accomplished in a last step. In detail design, arrangement, dimensional, material and surface properties of components are finalized. Drawings and documentations are produced.

During the nineties it was recognized, that development processes do not proceed serially, but strongly parallelly or interlacedly. Within this such called integrated product development all groups being involved in the process cooperated profoundly. According to Ehrlenspiel (2003) integrated product development integrates personal, informational and organizational aspects [5]. The product life cycle is described by means of systems engineering, whereas each system can be subdivided into a system of objectives, an operation system and an object system. The influences of all systems, e.g. customer, product, production, human resources, methods etc., on the complete system are considered holistically.

The process model according to [6] represents the single life cycle stages, which partially might be overlapping or even parallelly arranged, and describes the strong interactive elements within the process (cp. Fig. 1). The market with its three players (customers, competitors and the producer himself) is the initial point for developing a new product.

Generally spoken, developing systems or products is problem solving. Observing a product life cycle from the detection of market demands to recycling and redesign, different stages can be distinguished. The VDI guideline 2221 defines six different stages, which are system study, system development, system production, system introduction, system operation and finally system replacement. Within each of those stages, different steps of problem solving have to be passed through.

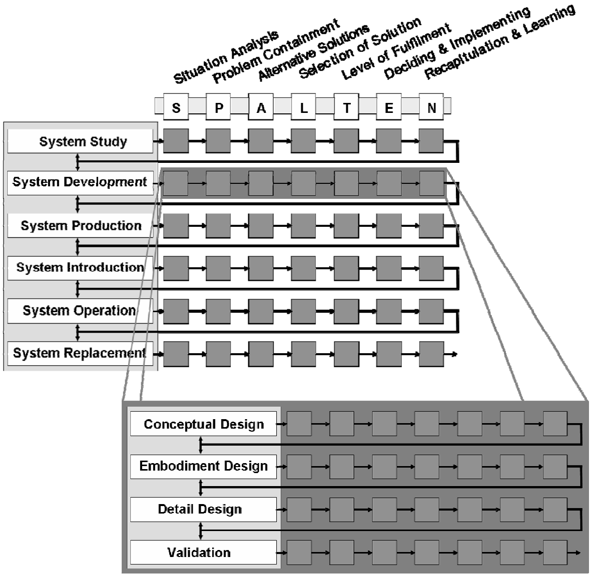

Figure 3: Problem solving process SPALTEN in a system life cycle context (cp. [5])

Using the SPALTEN method (German: spalten = to split, to decompose) [7, 8], these steps of problem solving are situation analysis, problem containment, finding alternative solutions, selection of solutions, analysing the level of fulfilment, deciding & implementing and finally recapitulation & learning.

The system development stage can be subdivided into clarifying the task, conceptual design, embodiment design and detail design. For each of those stages the fractal SPALTEN process can be applied again (cp. Fig. 2).

These basic proceedings can be universally applied when solving technical problems or designing technical systems – independent of designing a single-scale or multi-scale system, respectively product. However, on the one hand, today’s products are getting increasingly more complex and, on the other hand, demands regarding quality, time-to-market and costs come to the fore. A universal process model cannot satisfy these demands sufficiently. Thus, specific process models and design flows for single branches were developed.

## 2.2 Process Models for Microsystem Technology

The potential functionality and the development process of a microsystem are heavily dependent on its production technology. As a matter of principle, two areas can be distinguished. There are lithographic microtechnologies, e.g. silicon micromachining or LIGA (German acronym for lithography, electroforming, molding), which both are called mask-based processes, since substantial structuring steps are performed by exposure to radiation through a patterned mask, and there is tool-based microtechnology employing mechanical micromachining, i.e. miniaturized tools known from macroscopic technology, e.g. milling of molds and subsequent molding by thermoplastic injection (TIM) or powder injection (PIM) of ceramic or metallic materials.

*Mask-based Microsystem Technology*

For mask-based microsystem technology there are several models describing the design flow. Hahn (1999) adapted the aforementioned Y-model, whereas the evidently occuring difference can be found in the levels of abstraction, which are system, component and structural level [9]. While being consistent with the Y-model on higher levels of abstraction, divergence occurs close to the central vertex (production-related design). Not only the object of design itself has to be created, also production, i.e. the technological processing sequence, has to be developed parallelly, especially due to the fact that the latter is application-specific and heavily influences the later shape.

For the proceeding close to the vertex of the Y-model, [10] employ a highly iterative such-called “circle-model”, which is adapted to the requirements of designing microstructures. The model consists of four steps of layout design, process development, verification and process modification being arranged in a circle and especially considers the parallelism of developing mask layout and production process.

The “pretzel model” of [10] (2003) clearly shows the parallelism of developing behavorial design and processing sequence. On the one hand, based on a behavorial model and supported by a component library, a verifiable 3D model is synthesized. This 3D model comprises relevant information on design and structure of the single layers and the materials these are consisting of. Based on the known materials of the layers, process sequences and according process parameters are defined. On the other hand, when developing a new process sequence, analysis of this processing leads to mask properties and hence to a 3D model.

Another approach is the hierarchical process model of [11] (1994), in which a complete system is subdivided into a number of hierarchic levels with corresponding subsystems and components. The single completely developed and tested subsystems are implemented into the hierarchical higher subsystems and finally into the complete system. Regarding microsystem technology, the flow for designing the subsystems consists of several stages. In the beginning, requirements and specifications are defined. Then design, implementation and integration is performed in order to completely describe the system. The system is simulatively validated and eventually prototypes are set up and tested.

### *Tool-based Microtechnology*

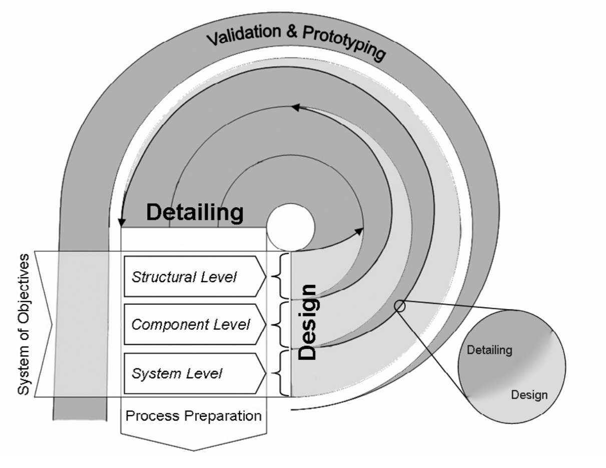

Figure 4: Design flow for tool-based microtechnology (sickle model, cp. Marz, 2005)

Considering tool-based microtechnology, there are technological conditions and restrictions, e.g. achievable flow lengths, minimum milling cutter diameter or minimum wall thickness. This results in a strong orientation in what is producible and therefore in a technology-driven design flow – in contrast to macroscopic product design, which is driven by market requirements. In order to achieve a design compatible to production, specific knowledge from process preparation (e.g. mold manufacture) and production (e.g. PIM) is required. The special aspects of designing tool-based microsystems are visualized by a model introduced by [2] (2005), which is called “sickle-model” (cp. Fig. 4) due to its sickle-shape transition from the design stage to the detail stage. The model represents the design stages conceptual, basic and detail design on system, component and structural level, i.e. on different levels of abstraction. The levels of abstraction are represented by three concentric rings, whereas the outermost ring is most abstract. The design flow itself runs counter clockwise from conceptual to detail design becoming more concrete. For system design, during the first quarter, conceptual design is performed, then in the second quarter the system is basically designed and finally detailed. The design activity is a superposition of a bottom-up design approach from structural level to system level and of a top-down design approach from conceptual design to detail design. When deciding on system level for concepts, on structural level, structures already have to be detailed due to the strong influence of technology. Visualization of this activity results in a sickle-shaped curve. For the transition from functional description to embodiment, the junction of design and detailing has to be considered. Therefore, a “methodological stage of transition” is introduced. The designer approaches this transition stage with the results of conceptual design on system level. Main functions and sub functions are extracted. Employing methodological means of support, e.g. effect catalogues, the designer finds effects, i.e. working principles that fulfill the sub functions. Conceptual design derives from the combination of these partial solutions and consists of functional items and basic shapes without any quantified dimensions or specified materials. The system itself is subdivided into components. On structural level, details for the functional items are designed with respect to technological conditions and restrictions. The latter are provided externally by a knowledge representation, for which design rules are used. These design rules represent knowledge from subsequent life cycle stages, e.g. process preparation in terms of realizable structural details, e.g. the minimum edge radius. Thus, while synthesizing, the transition stage is required to adhere to invariant structural details.

As an example, design of a micro gear is discussed: When beginning to concept the micro gear on system level, structural details like the tooth shape have to be considered. Assuming a PIM-process, for production a mold insert is required. The cavity has to be scaled up by a certain percentage (shrinkage) and has to be milled. Employing one of the smallest off-shelf end mill cutters (100µm diameter), the minimum edge radius within the mold is 50µm. This strongly affects the tooth shape and results in a shorter involute and therefore in a reduced contact length. At the same time the tooth width is restricted by the cutting depth of 200µm, which influences the transmittable torque and hence the conceptual design of the gear system. [2, 12]

## 3 THE PRODUCTION PROCESS

### 3.1 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.

*Restrictions of production preparation*

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 centre of manufacturing mold inserts has been micro milling with micro end mill cutters.

The body diameters 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).

*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, temperature and other process variables, and which is almost linear during the sintering process, should be particularly taken into account as discussed later.

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.

*Restrictions of sintering*

As explained above, there are many steps in the production processes that have restrictive character to the design of micro parts. For sintering these restrictive elements are the Therefore the designer has to consider these process steps in his design.

To understand the meaning of the production processes to design of micro parts, we need to have a close look on the next steps in the process.

Sintering too is restrictive to the design of micro parts. For the duration of the sintering process, the place of the part in the oven is of importance. Considering the scale of the oven and of the micro part this becomes easy to understand. The interior of the oven is orders of magnitudes larger than the micro part. The temperature distribution in the oven is inhomogeneous and therefore the sintering of the micro part is determined by the specific temperature at the specific place of the part.

As a result parts of one batch vary in size and other characteristic values.

Often it is necessary to integrate different functions in a single part. This results from an embryonic technique for joining micro parts. The result of these circumstances is complex forms.

The sintering of the planetary carrier shown in Figure 5 only works reproducible if the carrier is embedded in sand. The sand is needed because there is no plane area of support at the part itself. The three pins are the only available surfaces. The carrier twists during sintering that much, that it will not fulfill its function in the gear.

The positive aspects of the variation of the parameters will be considered in the next chapters.

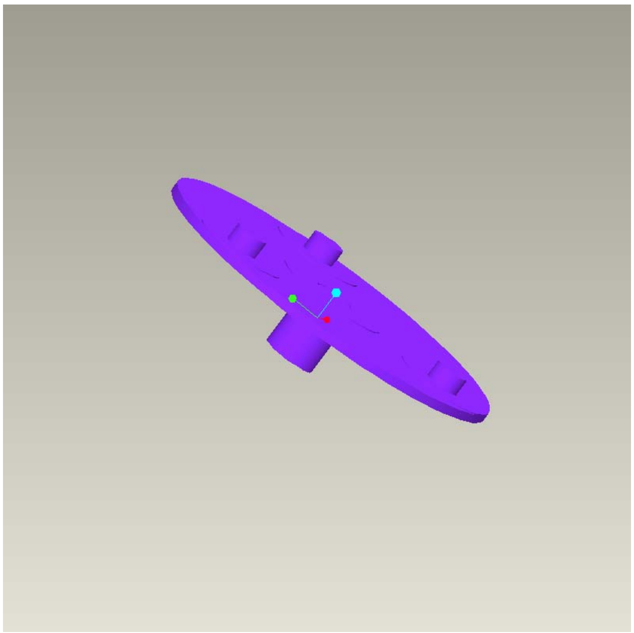

**Figure 5**: Design flow for tool-based microtechnology (sickle model, cp. Marz, 2005)

## 4 ASSEMBLY OF A MICRO PLANETARY GEAR IN PRACTICE

Function can be defined as the ability of a technical system to fulfill its means. A function can be divided into sub functions of which each must fulfill at least one aspect of the means of the whole system [13].

To fulfill a technical function it is necessary that at least two surfaces get in contact. These contacts can be seen in Figure 6 for the planetary gear.

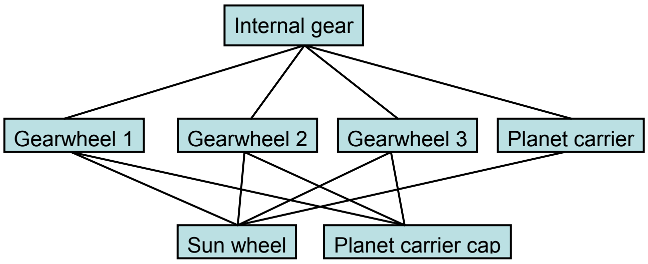

**Figure 6 :** Contact Structure of a simple planetary gear

Looking at Figure 6 one can see the complexity of the interdependencies of the system planetary gear. It is obvious that assembly is not trivial at all.

Micro systems are mostly assembled with the help of microscopes. In this special case it was not possible to use manipulators or something. The assembly was real handcraft.

This is because of the few pieces that were built up in laboratory tests and the economical restrictions that result from them.

As explained above, the assembly of a micro planetary gear is not simple. The previous processes have several inaccuracies that add up to a non working system.

Well, this is only part of the truth.

To achieve a working system other strategies are necessary. We learned about the inaccuracies of the previous processes.

As the process engineer is trying to control his production processes so that they always perform the same way, the assembly of micro parts does need a certain variation of the process until today. This certain variation of the processes generates a manifold of parts and this increases the chance that the assembler finds two and more pieces fitting together to a working system.

This is compulsory, because at the moment no manufacturing method comes up with an accuracy of micrometers in a reproducible and economical way.

Dimensioning of ordinary macro mechanical systems is done on a broad empirical basis. The lack of this basis in the micro world is obvious; therefore we need new strategies to build up micro systems that work.

## 5 CONCLUSIONS

Today’s measurement machines that can be used for micro parts have an accuracy of ~1 µm. Considering the required tolerances of these parts we recognize that often tolerances are in the same range of the measurement’s accuracy.

To meet with these facts and the demand for large number of pieces future processes must be designed for both, micro assembly and micro measurement.

All produced parts need to be measured or verified so that they can be arranged to groups of similar parts afterwards. Considering our planetary gear again this could mean that the planetary gear wheels make up a certain number of groups. Each, the carrier and the internal gear make up a number of groups too. The characteristic values of the groups are coordinated. For this reason the micro planetary wheels of one group will match with the carriers of the corresponding group. This way it becomes easy to find matching parts and it is less waste produced.

Hence, designing micro parts requires having a look on all steps of production, of assembly, quality assurance and at last on field testing.

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