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PROCESS-ORIENTED TOLERANCING - A DISCRETE GEOMETRY FRAMEWORK

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ABSTRACT

Since the requirements on technical products steadily increase, there exists a growing need for considering all effects which may lead to reduced product quality in engineering design. Geometric variations are a main contributor to malfunction and decreased product quality and have thus to be limited by geometric tolerancing. However, geometric tolerances are a source of disharmonies since manufacturing requires loose tolerances for realizing low manufacturing costs whereas design tends to choose tight tolerances for ensuring the product quality. This paper focuses on an integrated view on process-oriented tolerancing considering information from all stages of the product origination. After highlighting barriers for process-oriented tolerancing, a framework is proposed, which integrates process information in a skin model inspired tolerance analysis approach. This framework takes all sources of geometric deviations into account when evaluating their effects on the product quality. Thereby, manufacturing and assembly aspects can be considered in tolerancing during engineering design, which helps to reduce disharmonies, save manufacturing costs, and increase the product quality.

Keywords: robust design, design for X, computer aided design, computer aided tolerancing

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1 GEOMETRIC VARIATIONS MANAGEMENT DURING PRODUCT DEVELOPMENT

Geometric variations of workpieces strongly decrease the function and quality of technical products (Wartzack et al. 2011). These variations are observable on every manufactured part since every manufacturing process is inherently imprecise and every measurement process involves uncertainties (EN ISO 17450-1). Geometric variations management and geometric tolerancing during product development, thus, aim at ensuring the product function by limiting these observable geometric deviations. These limits are depicted as geometric tolerances and have huge influences on the incurring manufacturing and inspection costs since tight tolerances require cost-intensive manufacturing steps and additional measuring routines (Shin, Kongsuwon and Cho 2010). However, the required tolerances often depend on the chosen product concept. Therefore, geometric tolerancing should be performed as early as possible during the product development process. This helps to predict possible design issues from a tolerancing view in time and to finally avoid preventable high manufacturing costs.

Various approaches for the integration of geometric variations management and geometric tolerancing in engineering design starting from the conceptual design phase have been proposed. Some of these approaches are the Design for Tolerancing Process (Roy et al. 2001), the Integrated Tolerancing Process (Dantan, Anwer and Mathieu 2003) and a top-down method for integrated design (Mathieu and Marguet 2001). These processes aim at integrating the tolerancing activities into the early engineering design context. However, there exists a lack in considering and integrating manufacturing process information and process capability knowledge in these tolerancing activities during engineering design (Stockinger and Meerkamm 2009). Thus, the problem is, that product developers quite often choose tighter tolerances than necessary in order to assure proper product functioning. In contrast to that, manufacturing requires loose tolerances for realizing competitive manufacturing costs. These contradictory tolerance requirements may lead to disharmonies and conflicts between manufacturing and engineering design. By the application of manufacturing process-oriented tolerancing, these disharmonies can be reduced and the mutual understanding can be increased. Furthermore, the tolerancing activities in engineering design can be simplified and finally manufacturing costs can be reduced.

The aim of this paper is identifying barriers and requirements of process-oriented tolerancing and naming main challenges and future possibilities of integrating process knowledge in computer aided tolerancing during early engineering design. Furthermore, a framework for process-oriented tolerancing in engineering design is proposed, which is also applied to a case study. The structure is as follows. In the subsequent section, an overview over process-oriented tolerancing is given and the main idea behind is explained and enhanced. Thereafter, current barriers for an integrated tolerance analysis framework are highlighted. Following that, the integration of process information in a skin model inspired tolerance analysis approach is explained. Furthermore, the prerequisites of this approach are highlighted and it is applied to a simple study case. Finally, a conclusion and an outlook are given.

2 PROCESS-ORIENTED TOLERANCING IN ENGINEERING DESIGN

Tolerancing was historically understood and conducted as tolerancing for assembly as this is a straightforward geometric task (Voelcker 1998). In this regard, geometric tolerances are set to ensure the assemblability of workpieces to assembly groups enabling interchangeability of workpieces and manufacturing process independency. However, since geometric deviations also affect the product quality and function during use, there is a growing trend for taking into account not only manufacturing deviations but also deviations brought in by fluctuating operating conditions during use in tolerancing. For example, various researches have been focusing on the integration of deformations due to operating forces and models for computer aided tolerancing enabling at least 2D tolerancing have been developed (Armillotta and Semeraro 2012; Schleich, Stockinger and Wartzack 2012; Walter and Wartzack 2012). These efforts are depicted as functional tolerancing and aim at allowing a comprehensive view on the product and the various contributors of geometric deviations during manufacturing, assembly, and use. However, both tolerancing for assembly and functional tolerancing are product oriented since they focus on the *effects* of geometric deviations on the assemblability or the functional behavior of the product, respectively, disregarding the *sources* of geometric deviations which lie in fluctuating process parameters.

In contrast to that, following the current understanding, process-oriented tolerancing aims at allocating these product-oriented tolerances to process variables such as for example the locator dimension (Ding et al. 2002). Many concepts for the integration of manufacturing and assembly process information in process-oriented tolerancing exist. For example, Ding et al. (2002) propose a method for process-oriented tolerancing for multi-station assembly systems, Huang, Shi and Yuan (2003) introduce an approach for simultaneous tolerance synthesis by variation propagation modeling of multistage manufacturing processes, Chen et al. (2006) try to integrate process-oriented tolerancing and maintenance planning in the design of multi-station manufacturing processes whereas Abellan-Nebot, Liu and Subiron (2011) employ the extended stream of variation model for process-oriented tolerance allocation. These approaches aim at allocating a given design tolerance to geometric process parameter tolerances for different manufacturing and assembly fixture systems by variation propagation modeling and optimization techniques. However, a comprehensive view on the design tolerances, which are for ensuring the product function, on the one side and the manufacturing process parameters, which are the main source of geometric variations, on the other side can hardly be found in the literature. Furthermore, most of the employed techniques only consider geometric manufacturing process parameter tolerances for fixture systems in machining and assembly and are not applicable for other manufacturing processes such as forming or molding.

However, in fact, the current understanding of process-oriented tolerancing as allocating product-related tolerances to manufacturing process variables is arguable. By considering manufacturing and assembly process information in product development and engineering design, product-oriented tolerancing can highly be simplified and improved. The knowledge about typical geometric deviations caused by manufacturing processes or assembly forces and its integration in product development holds the chance of product quality improvement and cost reductions. Therefore, both the mere product-oriented view and the process-oriented perspective should be considered corporately in computer aided tolerancing and geometrical variations management. This leads to an integrative tolerance simulation process during product development (Wartzack et al. 2011). Thus, process-oriented tolerancing is understood as the consideration of manufacturing and assembly aspects in product-oriented functional tolerancing in the following.

The idea of an integrated tolerance simulation framework requires the integration of information from all levels of the product life-cycle. Figure 1 shows the different kinds of information from the various steps of product origination to be integrated in computer aided tolerancing during product development for enabling modern process-oriented tolerancing.

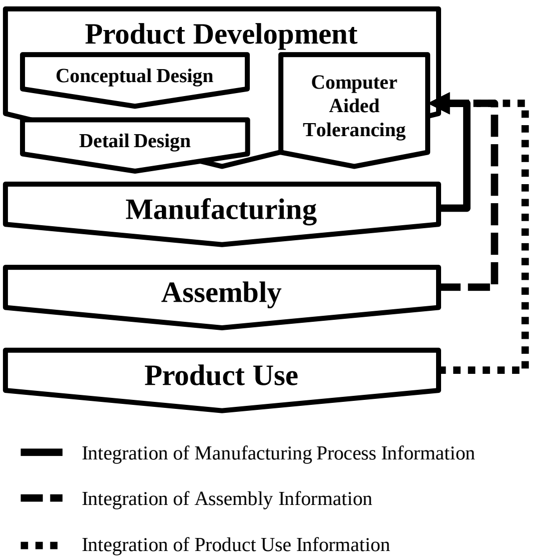

Figure 1. Integration of Information from the Product Origination Process into Tolerancing

The main design activities in tolerancing are the tolerance specification, the tolerance allocation, and the tolerance analysis (Armillotta and Semeraro 2011). During tolerance specification, part features, which have to be tolerance, as well as relevant datum features have to be identified. Numerical values for these tolerances are then set either by adjusting some initial values or by optimization. This step is referred to as tolerance allocation. Finally, the chosen tolerance values are verified by calculating the effects on the functional key characteristic whenever required. This last step is depicted as tolerance analysis. If the assigned tolerance values do not ensure the requested product quality, then the tolerance allocation and even the tolerance specification have to be repeated. This is an iterative process. Figure 2 shows the different tolerancing activities to be conducted during the tolerancing process in product development.

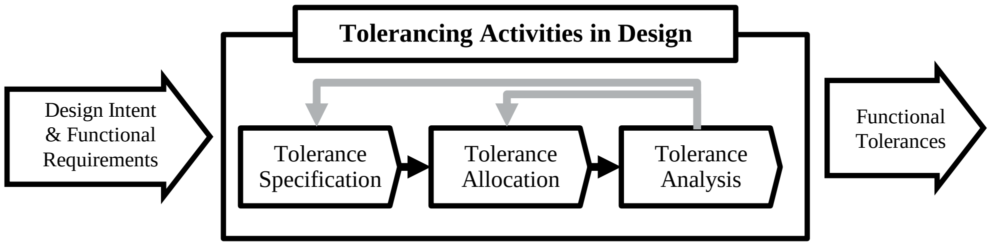

Figure 2. The Tolerancing Activities in Engineering Design

However, the tolerance specification is mainly conducted based on the functional relationships between different part and workpiece features and is only little depending on the employed manufacturing processes. Therefore, this step can be regarded as a product-oriented tolerancing activity. In contrast to that, the tolerance allocation is highly dependent on the manufacturing processes and often constrained by the process capabilities. This is because these processes determine the possible manufacturing precisions with respective tolerance ranges and have specific influences on the incurring manufacturing costs (each manufacturing process may have a characteristic cost-tolerance relationship (Yeo et al. 1997) which may lead to different manufacturing costs under equal tolerance ranges). Therefore, specific knowledge about manufacturing and assembly processes has to be considered during the tolerance allocation. Furthermore, the employed tolerance analysis model has huge impacts on the capability of considering process-oriented knowledge about expected observable geometric deviations. This is highlighted in the next section.

3 BARRIERS FOR PROCESS-ORIENTED TOLERANCING

The integration of various kinds of information from different manufacturing and assembly processes as well as the product use is crucial for enabling process-oriented tolerancing. Figure 3 shows these different kinds of information, which have to be considered. Manufacturing process information usually includes information about process setup and process variables as well as observable and expected geometric deviations, which may be classified into systematic and random deviations (R. P. Henke et al. 1999). Assembly sequence and applied assembly forces as well as processes (such as clamping, welding and screwing) are pieces of typical assembly information. Furthermore, geometric deviations can also be brought in by assembly processes and therefore have also to be considered. During product use, different ambient parameters and usage variables have an influence on the product function and the perceived product quality. Also in this stage of the product life-cycle, geometric deviations, for example caused by operating forces, hinder the product function and are therefore to be respected in an integrated tolerance simulation framework. In summary, the adequate integration of geometric deviations and their sources, which lie in variations of process and operating parameters, is crucial for an integrated product- and process-oriented tolerance analysis framework. However, a main barrier for process-oriented tolerancing is gathering, storing, processing and handling all these different kinds of information.

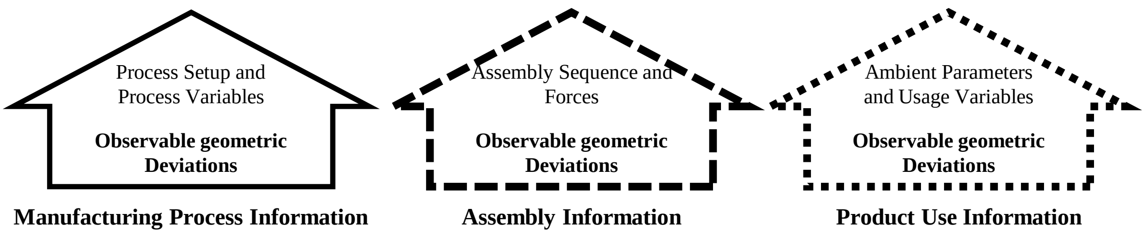

Figure 3. Integrated Tolerance Analysis: different kinds of Information

Furthermore, the integration of required information about geometric deviations in process-oriented tolerancing during engineering design is limited by modern geometry schemes employed in computer aided tolerancing and current tolerancing standards, which is a further obstacle. Various models for the representation of geometric tolerances can be found, such as the Direct Linearization Method (Marler 1988), the model of Technologically and Topologically Related Surfaces (TTRS) (Desrochers and Clement 1994) or the Deviation Domain based on the Small Displacement Torsor (SDT) (Giordano, Samper and Petit 2007). These models reduce geometric deviations to rotational and translation defects of workpiece features since they are to model geometric *tolerances* instead of geometric *deviations* in a true sense. Hence, they make severe assumptions and abstractions about the observable geometric deviations (Hong and Chang 2002; Ameta, Serge and Giordano 2011; Charpentier, Ballu and Pailhes 2012). As a result, the effects of geometric manufacturing deviations on the product function can only be considered approximately. Due to steadily increasing requirements on the quality of technical products, this fact is not acceptable. Therefore, the integration of deviation information stemming from different manufacturing processes can hardly be performed employing these models.
These simplifications motivate current research to develop a tolerance analysis approach based on the skin model concept. Details about this concept as well as the current state of affairs in this research context are given in the next section.
Furthermore, the integration of manufacturing information in engineering design and especial in tolerancing is an organizational challenge for modern quality-aware companies because of competing responsibilities between manufacturing engineers and engineering designers. These tensions may lead to disharmonies and may finally even decrease the product quality. Therefore, research and development is usually structured by a matrix organization. However, this problem is not addressed in this contribution.

4 INTEGRATION OF PROCESS INFORMATION IN A SKIN MODEL INSPIRED TOLERANCE ANALYSIS APPROACH

The standards for Geometrical Product Specification and Verification (GPS) offer a unified language for geometrical variations management as well as a toolbox for performing the tolerance activities during engineering design. The skin model concept, however, is a basic concept within these standards (EN ISO 17450-1). It is a model of the physical interface between the workpiece and its environment and is intended to support the designer in imagining allowable geometric deviations as well as predicting their effects on the product function and quality. The skin model concept is not related to any geometry or tolerance representation scheme. Current research, however, tries to develop a discrete geometry tolerance analysis framework based on this skin model idea (Zhang, Anwer and Mathieu 2011; Schleich et al. 2012). In this regard, the workpieces are represented by discrete geometry elements such as clouds of points or surface meshes as illustrated in Figure 5. These geometry representation schemes are straightforward since most tools for computer-aided engineering build up on similar geometry models. For example, reverse engineering applications usually ground on pointclouds gathered from measurements and the finite element method, widely used for structural analysis, is based on a volume discretization from which a surface mesh can be derived easily.

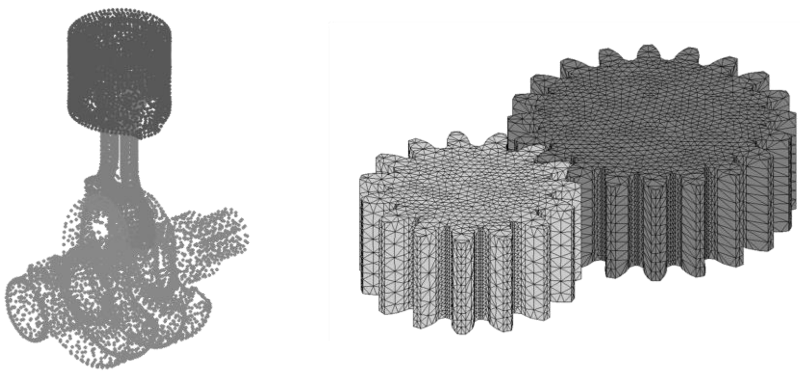

Figure 5. Pointcloud Representation of a Crank Gear and Surface Mesh Representation of two Gear Wheels

The mentioned approaches aim at delivering a realistic view of the product behavior considering geometric deviations of workpieces to the engineering designer. However, the integration of manufacturing process information in the tolerancing activities during engineering design employing such a skin model inspired tolerance analysis theory has not been considered yet.
As mentioned earlier, there are various kinds of information besides the expectable geometric deviations caused by employed manufacturing processes that have to be taken into account in functional process-oriented tolerancing such as assembly and usage information. For example, different assembly processes and varying operating conditions such as fluctuating operating forces or thermal effects may have a negative effect on the functional behavior of the product. A discrete geometry skin model inspired tolerance analysis approach, however, builds a suitable basis for the integration of such. This is because information about expectable geometric deviations can be integrated easily based on discrete measurements or results of manufacturing process simulations. Furthermore, information about assembly processes and operating conditions can be respected in discrete geometry tolerance simulation models for assembly and use.
The main idea behind a skin model inspired tolerance analysis approach is to perform tolerance analysis employing various simulation tools, such as for assembly and use, based on skin model shapes. These skin model shapes are part representatives comprising geometric imperfections within tolerance zones. They can be obtained based on manufacturing process simulations, measurement results or by applying suitable mathematical models for modeling expectable geometric deviations (Zhang et al. 2011; Schleich et al. 2012). In this context, manufacturing process simulations, for example for molding or sheet metal forming processes, can help to identify critical process parameter combinations and to predict expectable systematic geometric deviations. For this purpose, also measurements of real workpieces and prototypes can be performed if no powerful simulation models are available. Furthermore, the expectable geometric deviations can be modeled employing adequate mathematical approaches, such as quadric surfaces, since most systematic deviations can be reproduced by a combination of quadric shapes. However, these methods allow the integration of manufacturing process information such as process parameters, the process setup, and characteristic geometric deviations of manufactured workpieces. Figure 6 shows the framework for the generation of skin model shapes, which can be divided in a prediction stage and an observation stage depending on the available information about expectable geometric deviations in virtual product development (Schleich et al. 2012).

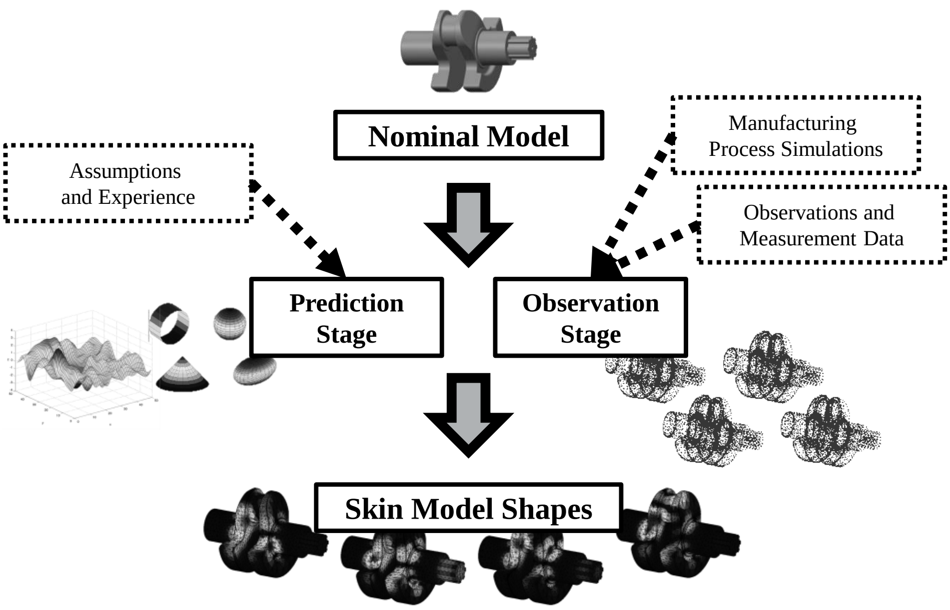

Figure 6. Generation of Skin Model Shapes following Schleich et al. (2012)

After the skin model shapes have been generated, simulation models are employed to determine the effects of geometric deviations on the assemblability and the product behavior during use. For this purpose, various simulation models, which are capable of processing the deviated part representatives,

have been developed. For example, Samper et al. (2009) and Stockinger et al. (2010) proposed approaches for the assembly simulation of deviated workpieces whereas Schleich, Stockinger and Wartzack (2012) took geometric deviations into account in the structural performance analysis. Since the capability of modern simulation tools steadily increases, it can be expected that the consideration of geometric deviations in computer aided engineering tools for tolerancing and robust design will gain more and more importance. In this regard, the integration and consideration of assembly and usage information, such as the assembly sequence and operating conditions, will become a common feature of modern CAE-tools. The application of these highlighted tools for engineering simulations enables the engineering designer to draw a realistic image of the product behavior during use considering geometric deviations and other quality-relevant fluctuations as well as their interactions and to identify design and tolerancing problems early.
After simulation models for assembly and use are applied to the skin model shapes, a comparison for conformance between the simulation results and the design intent can be performed in order to check if the tolerance specifications set during tolerance specification and tolerance allocation ensure the required product quality. This check for conformance is also part of the ISO standards for Geometrical Product Specification and Verification. If it can be found that the specified tolerances do not ensure the required product quality, then the tolerance specifications have to be adjusted and the procedure is repeated. As mentioned earlier, this is an iterative process. An overall framework for the integration of process information in a skin model inspired framework for computer-aided tolerancing (Schleich and Wartzack 2013a) is illustrated in Figure 7.

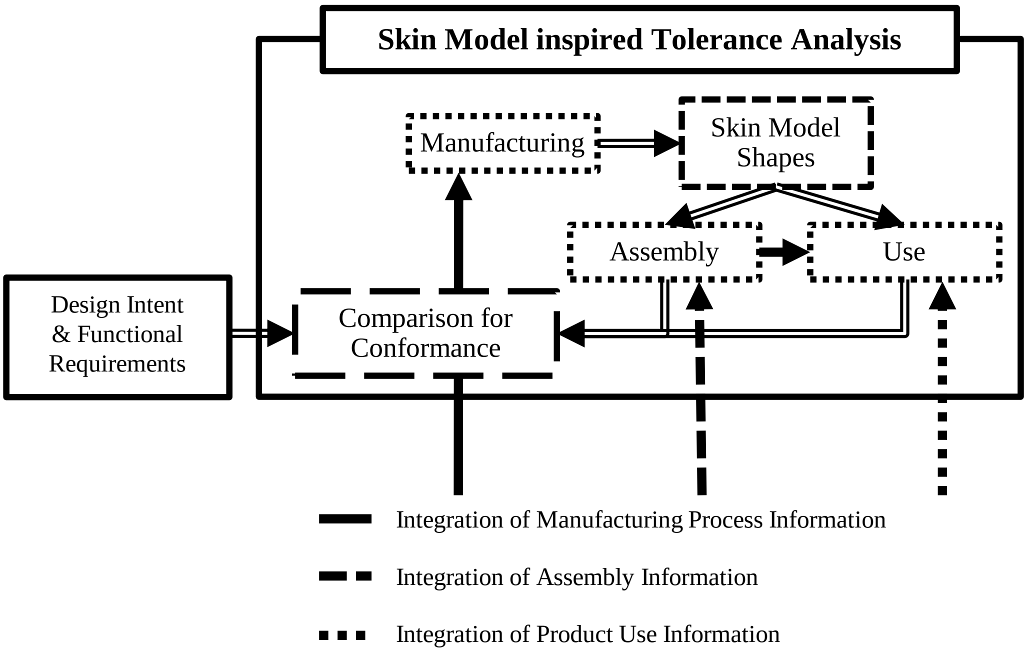

Figure 7. Integration of Process Information in a Skin Model inspired Tolerance Analysis Approach

It is worth mentioning, that the skin model in the strict sense is an infinite model and does not allow for any identification or simulation (Charpentier et al. 2012). Therefore, we denote the proposed discrete geometry tolerance analysis framework as a skin model *inspired* approach and the workpiece representations as skin model *shapes*.
The proposed framework for process-oriented tolerancing in product development is thus based on the application of computer-aided engineering tools which are applied not to the nominal workpiece and product models but to their respective non-ideal representations denoted as skin model shapes. However, in this regard, the connection between these simulation tools has an influence on the ease of use for the engineering designer as well as on the obtained result validity. A discrete geometry framework for skin model simulation and tolerance analysis holds the chance of a simple and sufficient information exchange from subsequent steps of the product lifecycle into computer aided tolerancing. This is because these geometry representations allow an easy and straightforward consideration of geometric deviations.

5 PREREQUISITES FOR MODERN PROCESS-ORIENTED TOLERANCING AND BENEFITS FOR VIRTUAL PRODUCT DEVELOPMENT

Even the best framework for integrated tolerancing is spare if responsible engineering designers do not make use of it. Therefore, the benefits of process-orientation for functional tolerancing have to be acknowledged and enforced in engineering design, manufacturing, and assembly to deploy all relevant resources and to convince important knowledge carriers. Furthermore, product developers have to be skilled in various engineering fields in order to assure an effective and efficient modern process-oriented tolerancing process. Moreover, in the context of integrated geometric variations management, also the needs and restrictions of manufacturing and inspection have to be considered during tolerancing. Thus, a coherent and complete tolerancing process with a unified language for geometrical variations management gains more and more importance. For this purpose, GeoSpelling has been proposed, which offers important advantages for a unified description of geometrical specifications (Mathieu and Ballu 2007; Dantan, Ballu and Mathieu 2008).

In summary, the main prerequisites for integrated process-oriented functional tolerancing, beside the technical issues regarding adequate simulation and validation models, are a company-wide consensus about the importance of geometric deviations and their effects on the product quality, the professional training of engineering designers as well as the implementation of a company-wide understanding of geometrical specifications and a unified GPS-language.

Once these prerequisites are fulfilled, the proposed framework for process-oriented tolerancing supports product developers in specifying dimensions and geometric tolerances. In this context, the main benefit lies in the concurrent consideration of product-related tolerances on the one hand and process-oriented scatter of process-parameters on the other hand. This helps to minimize tolerance-related costs by giving indications for optimized process parameter windows.

6 APPLICATION

The study case for the demonstration of the process-oriented tolerancing framework is a simple assembly group consisting of two flat plates with a change in the wall thickness manufactured by a molding process (Schleich and Wartzack, 2013b). In the nominal state, the two plates fit together perfectly. However, a gap between the plates can be observed when considering geometric deviations (see Figure 8). For this plate, a molding process simulation with varying process parameters, such as the melt temperature, the dwell pressure, and the dwell time, has been performed following a Latin Hypercube Sampling design plan. Thereby, the resulting workpiece geometries respecting shrinkage and warpage can be exported as surface meshes, which serve as skin model shapes. After applying an assembly simulation to these skin model shapes, the length l_{ges} of the assembly group can be measured. Hence, the tolerance analysis comprises the generation of skin model shapes based on manufacturing process simulations and their processing employing simulation models for the assembly.

As a result of this procedure, the effects of manufacturing process parameters on the product properties after assembly can be evaluated. The application of a sensitivity analysis to the results reveals the process parameters with the main contribution to the scatter of the assembly length. In this example, the melt temperature in the molding process has the highest effect on the length of the assembly, which can be seen from Figure 9. This information can now be used for the specification of admissible process windows.

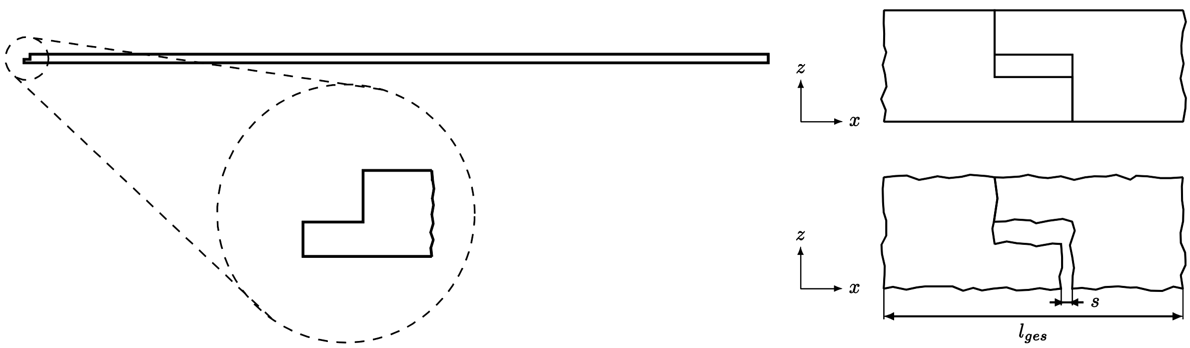

Figure 8. Study Case: Reference Part and Assembly Group of two Reference Parts

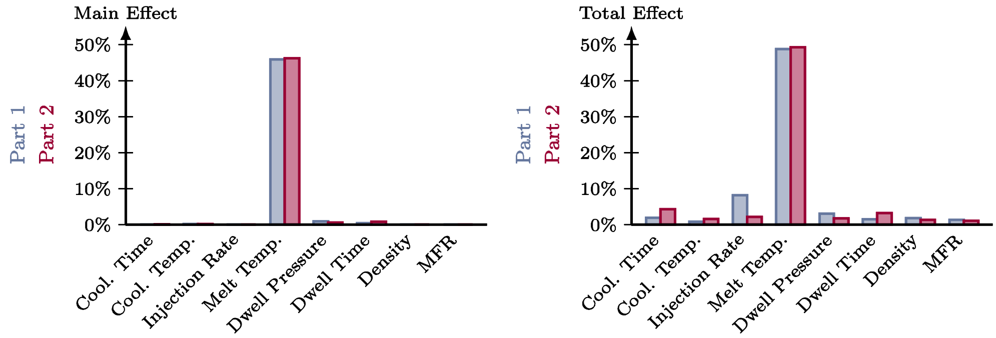

Figure 9. Results of the Case Study – Main and Total Effects

7 CONCLUSION AND OUTLOOK

This paper proposes a modern definition for process-oriented tolerancing as considering process knowledge in product-oriented tolerancing and gives an overview over possible chances of process-oriented tolerancing in engineering design. Furthermore, the barriers and restrictions of modern simulation techniques and geometry representation schemes used in computer aided tolerancing limiting process-oriented tolerancing in engineering design are identified. By integrating the information from subsequent steps of product origination, the tolerancing activities in product development can be highly improved and simplified. Furthermore, tensions between engineering designers and manufacturing engineers can be reduced since knowledge and restrictions from manufacturing and assembly are considered already in tolerance design. Therefore, the proposed approach for an integrated view on tolerancing in engineering design is a step towards a harmonic design of technical products. By applying various computer-aided engineering tools, the product developer can be supported in tolerance analysis which is an important step in all tolerancing activities during design. Moreover, the product quality can be improved since all sources of geometric variations as well as their effects on the product function are considered.
However, more versatile and accurate simulation models have to be developed in order to enable skin model inspired tolerance analysis. This opens a wide field for future research.

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