Shape Optimization of Polycrystalline Micro Mechanical Components

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Abstract
DFG’s Collaborative Research Center 499 (CRC499) aims for establishing production processes of primary shaping, i.e. micro powder injection molding (µPIM) and micro casting (µCast), to the medium and large-scale production of highly loadable, three-dimensional micro mechanical components made of metal and ceramics [1]. As in most modern product development processes, it is necessary to use simulation and optimization methods to predict, analyze and improve the behavior of components and systems.

Within dimensions of micro technology, effects occur that can be neglected in the macroscopic world. In the case of macroscopic components, material behavior within finite element (FE) analyses is usually assumed to be isotropic. When simulating micro components this assumption does not apply necessarily. This is due to the fact that—depending on the chosen material and the small size of the components—micro mechanical components may be made up of only a few grains. Since these grains behave anisotropically the behavior of the components is affected in some cases.

1 Influence of the grain structure
In order to ensure a robust dimensioning of micro components, methods for modeling components including their grain structures and possible defects such as pores have been developed and implemented in a software tool [2]. Studies that have been conducted using a planetary gear drive developed within the scope of CRC499 show that with decreasing size of a component its material anisotropy and grain structure gain more and more influence on the stress distribution and flow of forces. Due to the grains’ anisotropy and porosity, significant scatter in components’ behavior could be shown [3]. These methods make the first step for a dimensioning process of micro mechanical components and systems.
2 Adapted shape optimization

The second step is based on the previously mentioned methods for modeling the grain structure. They are used within an iterative shape optimization approach allowing a robustness based optimization of components with respect to these aspects. As shown before, in micro dimensions a component’s behavior in some cases cannot be assumed to be constant. Therefore, a stress-based optimization algorithm, implemented in FE-DESIGN’s TOSCA Structure.Shape [4], is being adapted.

On the basis of an already given geometry, multiple stress analyses with stochastically generated component properties including grain structure and porosity are conducted. For modeling the grain structure the above mentioned methods are used. Statistical data such as standard deviation or coefficient of variation are calculated. It is assumed that the stress in each node is normally distributed. After the central limit theorem (CLT) this means that analyzing one discrete point within an unlimited number of specimens with respect to the local stress would lead to a Gaussian distribution. The normally distributed variable is described by variance $\sigma^2$ and mean value $\mu$.

Since in reality it is not possible to analyze an unlimited number of specimens and therefore exactly determine these parameters, they are estimated using a limited number of them and an interval estimation. For each of the parameters a confidence interval is determined. For a shape optimization with respect to robustness, node displacement is based on the respective determined standard deviation. Further steps to enhance the method to a shape optimization with respect to reliability and both robustness and reliability are currently being taken. Within a subsequent shape optimization iteration these data are considered and the surface geometry of the component is modified to improve its robustness.

The modified geometry is processed again with respect to grain structure and porosity to calculate the new statistical data. That data is used for the next optimization iteration. The iterative process is performed until a stop criterion such as a maximum number of iterations is reached.

Thus, the component’s surface geometry is modified iteratively using multiple FE analyses and statistical data. The process has been automated and implemented in a software tool.
3 Test case

The process is validated by means of the optimization of a micro turbine rotor blade’s shape. The turbine rotor is part of an air pressure driven turbine developed within the scope of CRC499. It is used as an actuator of a micro planetary gear. The turbine rotor is connected to the sun gear of the planetary gear by a shaft. The turbine rotor model has been reduced to two dimensions and to one single blade due to symmetry. The original design takes into account manufacturing restrictions, i.e. a predefined minimum cutter radius. Load is applied on one side of the blade while the other side can be modified during optimization. Each iteration of the optimization bases on 200 specimens with individual grain structures.

By means of these proposals derived from the optimization the design of the turbine rotor has been adapted. Figure 1 shows a comparison of the original design and the optimized shape. Figure 2 shows that the standard deviation of the stresses could be reduced homogenized using the new shape optimization approach.

Figure 1: Original (left) and modified design (middle and right) [CRC499]

Figure 2: Standard deviation of von Mises stresses at the design nodes
4 Conclusions
Depending on a component’s size and material a micromechanical simulation model should take into account its grain structure. Studies show that the grain structure may heavily affect both a component’s and therefore the system’s behavior.
An iterative approach allowing a robustness based shape optimization of components with respect to these aspects has been introduced. By means of this approach the component’s surface geometry is modified on the basis of multiple FE analyses and statistical data. The process has been automated and implemented in a software tool.
Studies have been conducted using a turbine blade as a demonstrator system. The optimized component shapes show a higher robustness, i.e. a lower and more homogeneous standard deviation than the initial designs despite of the grain structure. Both steps—methods for simulation of components in consideration of the grain structure and methods for optimization with respect to its influence—make a contribution to the dimensioning of molded micro components and systems.

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References: