Effective Stochastic Simulation for the Optimization of Time, Costs and Quality in Cold Forging

J. Koch[1], R. Völkl[1], U. Engel[1]

[1]*University of Erlangen-Nuremberg, Chair of Manufacturing Technology – Egerlandstr. 11, 91058 Erlangen, Germany*
URL: www.lft.uni-erlangen.de *e-mail: J.Koch@lft.uni-erlangen.de; R.Voelkl@lft.uni-erlangen.de; U.Engel@lft.uni-erlangen.de*

ABSTRACT: In cold forging tool life is limited in most cases by fatigue and characterized by distinct scatter depending on the scatter of the process parameters. This fact is also obstructing the production of net shape parts. Due to the scatter, a single simulation run with average values is known to be not appropriate to predict the desired output quantities. This paper describes an innovative method using a mathematical model of the forging process with a deterministic and a statistical component. According to the strength versus load concept (SVL-concept), a combination of the parametric and the statistical model leads to an integrated statistical process model which enables tool life prediction by taking statistical effects into account. In order to improve tool life an approach of avoiding tensile stresses and strains in the die has been successfully used for steel and cemented carbide tools.

Key words: Computer Aided Engineering, Cold Forging, Tool Life, Stochastic Simulation

1 INTRODUCTION

The main advantages of cold forging are a good surface finish quality, close dimensional tolerances and the possibility to obtain the required strength by work hardening. Despite these advantages cold forging tools have to resist highest cyclic loads because of the high flow stress of the workpiece material. Due to the cyclic loading of the tool during the forging process the main failure cause are fatigue cracks. Unfortunately if the tool breakdown is caused by fatigue cracks the tool life shows an extremely high scatter. The range of tool life values can vary by a factor of 10 which can be seen on many practical examples from industry. The characteristic scattering of the tool life itself is depending on the scatter of the process parameters [1]. This fact is also obstructing the production of net shape parts. Therefore it is meaningful to predict the tool life and workpiece accuracy already in the construction period. For this task the strength versus load concept (SVL-concept) has been developed using a mathematical model of the forging process [1]. The present paper is focussed on the possibilities how the SVL-concept can be effectively used in practice to predict tool lifescatter and optimize tool design. Their application will be shown by industrial case studies. To provide the methodology to the end-user a software program with a user-friendly graphical interface was developed.

2 STOCHASTIC FE-SIMULATION

It is state-of-the-art to use the FE-analysis for the calculation of the occurring tool-strain and stress during the forging process. Due to scattering influence parameters, a single simulation with average values is not appropriate to predict the deviation of the desired output quantities. New developments offer the possibility of taking stochastic influence factors into account [2]. There, a mathematical model of the forging process is introduced which contains two main components. The first one is the parametric process model which describes the influence of the process parameters on the forming process and is generated as a response surface by several FE-simulation runs with varying parameters. The second one, the statistical process model, represents the statistical distribution of the parameters by means of numerical combined probability density functions. The combination of both, the parametric and the statistical model leads to an integrated statistical process model which enables tool life prediction and also process optimization with the consideration of statistical effects.

3 IMPLEMENTATION OF THE METHODOLOGY

The particular steps of the stochastic FE-simulation will be discussed in detail in this chapter and enhanced by new approaches, enabling a robust and time efficient application. Furthermore, the methodology was approved in the industrial practice with the optimization of a tool for the production of bearing balls. The lifetime of this tool is controlled by fatigue and is observed to be in a wide range between 36,000 and 70,500 cycles.

3.1 Process simulation

To simulate the forging process and to calculate the tool load, a FE-Model was developed. The FE-Analysis (FEA) has been performed with MSC.Superform in an axially symmetrical, thermal-mechanically coupled analysis. Because stresses and strains in the die are essential for the tool life calculation, the tool was represented as a deformable body in the FEA (fig. 1).

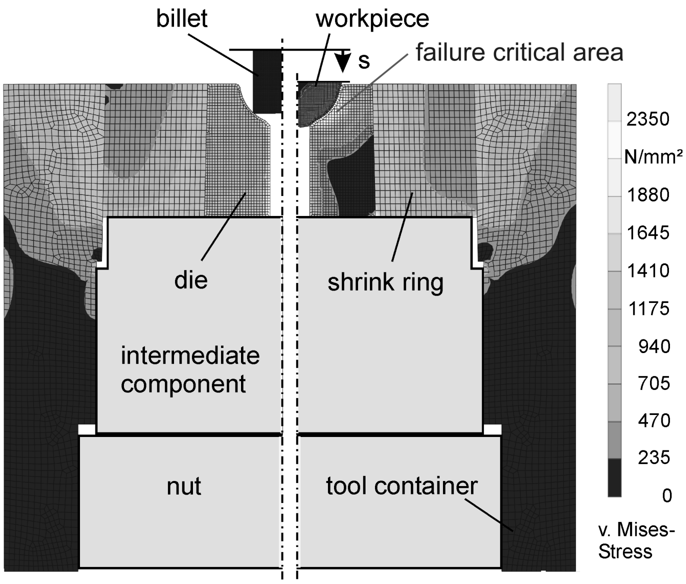

Fig. 1: FEM-model for the simulation of material flow and tool load (left: initial load, right: maximum process load)

In order to guarantee high simulation accuracy, which is necessary for a precise tool load calculation, several actions were taken. First, the yield stress of the workpiece material has been measured in compression tests and the friction factor has been identified by measurements of the height and diameter of the workpiece. Next, the FE-inaccuracies due to the discretization error of the mesh have been reduced with the use of the Richardson extrapolation system. By applying this method it is possible to calculate the convergence rate of the FE-model using several refinement levels and to estimate the exact results [3]. Finally, the output quantities process force and the radial strain of the tool were measured in production and used to validate the FEA.

3.2 Tool life calculation

To predict the tool life (N_f) from FEA-results, a damage concept is required. To calculate high cycle fatigue of cold forging tools the plastic strain component of the Manson-Coffin approach can be neglected which leads to the Basquin-Manson-Coffin-equation (eq. 1). It has been successfully used in many case studies [2,4,5].

$$2N_f = \left(\frac{2\varepsilon_a \cdot E}{2\left(\sigma'_f - \sigma_m\right)} \right)^{\frac{1}{b}} \tag{1}$$

In this concept the tool load is reflected by the strain amplitude ε_a and the static mean stress σ_m calculated by FEA. The tool strength is characterized by the fatigue parameters σ'_f and b. They have been measured for the die's steel S 6-5-2 with a hardness of 62 HRC in cyclic four-point bending tests [5].

3.3 Sensitivity analysis

The number of required simulation runs is growing fast with the number of considered process parameters. Therefore it is necessary to concentrate on the most significant parameters affecting the tool life. In this study the relevance of friction, geometry variants, shrink fit, billet volume and yield stress has been tested. For each parameter several FEAs with different settings have been performed to determine the parameter sensitivity on tool life. The shrink fit of the prestressing system and the yield stress of the workpiece material parameters have been identified as most significant and mainly responsible for the scatter in the tool life.

3.4 *Statistical process analysis*

According to the SVL-concept the scatter of the identified significant process parameters is responsible for the scatter in tool life. The required statistical analysis can be done either by analytical statistical methods (e.g. probability function systems) or Monte Carlo technique. Due to the fact that the Monte Carlo technique requires a high number of data points to obtain consistent results, its use in cold forging is practically not applicable since more than 1,000 complete FEAs would be needed. Therefore a system has been developed, which generates an integrated parametric and statistical process model. If these models are based on the same parameter field, they can be directly overlaid to an integrated parametric and statistic process model (fig. 2).

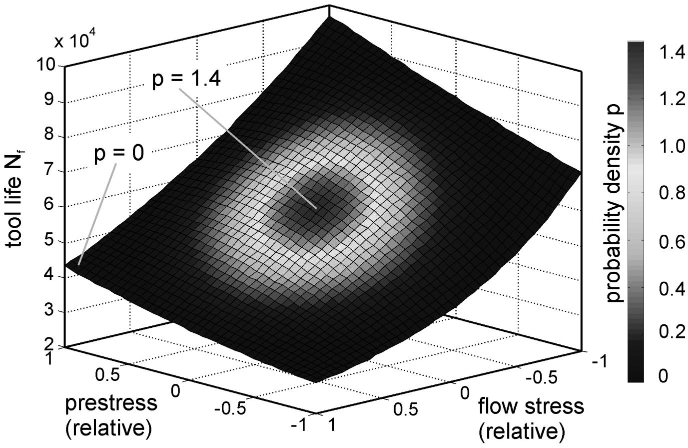

Fig. 2: Response surface of the integrated parametric statistical process model

The response surface is finally computed by using polynomial interpolation. The statistic process model describes the probability density p of each parameter.

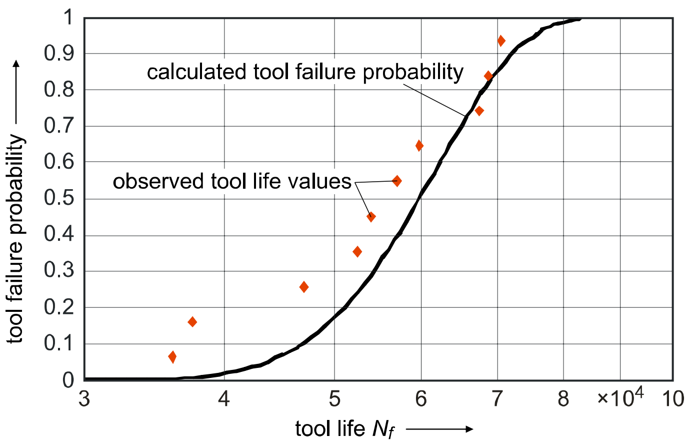

Fig. 3: Comparison of the observed tool life values in production and the calculated tool failure probability curve

The evaluation of the integrated model by counting the tool life values and adding up their probability leads to a tool failure probability curve (fig. 3). It shows a good accordance between the observed and calculated tool failure.

3.5 *Tool life improvement*

In cold forging applications the tool material is characterized by high hardness which means also high brittleness. Thus the basic aim during tool design is to avoid tensile stresses and strains in the critical die region. In this case study the prestress condition of the die has been improved by the use of FEA and the parametric process model. The FEA of the present tool construction shows strains of ε_{33} = 0.0037 at the critical die area (fig. 4, low prestress). In order to reduce tensile stresses and strains by enhancing the prestress an additional shrink ring was fitted into the tool. Furthermore the die diameter and the shrink fits of ring 1 and 2 were optimized by 27 FEA runs and the use of a parametric process model. This kind of optimization yields a tool layout that eliminates tensile stresses and strains compared to the initial one (fig. 4, high prestress). Practical tests showed a tool life improvement with cemented carbides at the suggested highest prestress conditions of about 250%.

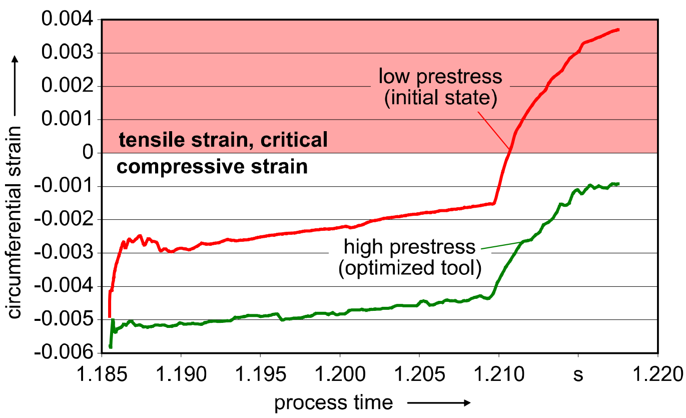

Fig. 4: Circumferential strain in the critical die area during the forging process

3.6 *Optimization of cemented carbide tools*

The transferability of the optimization strategy will be shown by the optimization of a cemented carbide tool for the production of welding screws. Due to unavailable characteristic values for cemented carbides a tool life calculation is currently still not possible. Focal point of the further case study is the life improvement of such tools using the FEA and the strategy developed and successfully tested for steel tools.

The cold forging process of the welding screw case study consists of five stages whereas stage four is the most critical. With the use of the FEA software MSC.Superform an axially symmetrical, mechanical model was developed to simulate the forging process and to calculate the tool load. In order to calculate the stresses and strains in the tool, the die and the shrink rings were carried out as deformable bodies in the simulation model (fig. 5). The yield stress of the workpiece material, a main influence parameter on tool life, has been measured in compression tests.

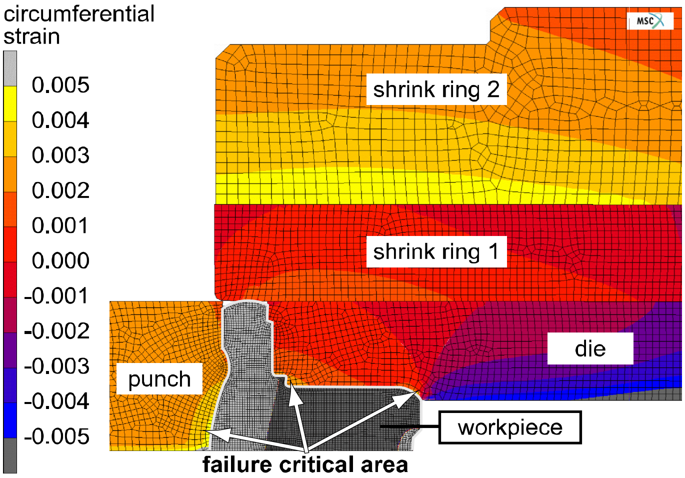

Fig. 5: FEM-model for the simulation of material flow and tool load at maximum process load (welding screw case study)

At maximum process load the initial tool construction shows strains of ε_{33} = 0.0006 (fig. 6). Due to the maximum stress in the outer shrink ring which is already at the flow limit, the interference between the die and the inner shrink ring was increased in order to enhance the prestress. The first optimization state already eliminates tensile strain for mean process parameters.

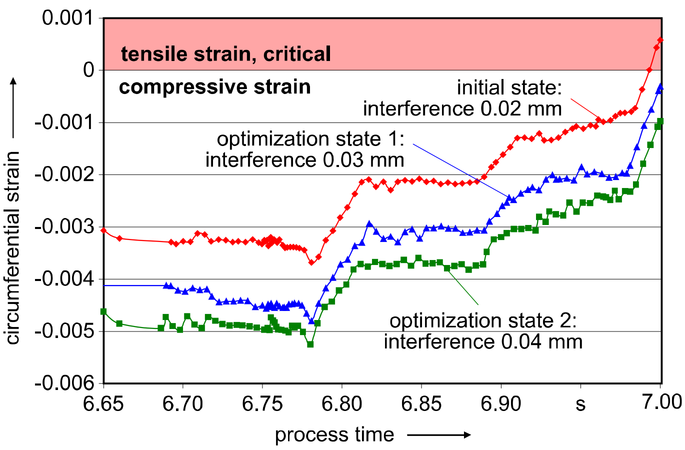

Fig. 6: Circumferential strain in the critical die area during the forging process, welding screw case study

The second optimization state completely eliminates tensile strain compared to the initial one. A primary tool at the suggested highest prestress condition showed a 10-fold life improvement in practical tests. Due to long-term usage of tools with the improved design a statistically approved value is currently not calculable.

4 CONCLUSIONS

The present paper describes a method which facilitates the consideration of parameter scatter in practice to calculate the tool failure probability curve characterizing the tool reliability. The FEA enables the modeling and investigation of the forging process including the tool behavior, mainly characterized by the occurring strains and stresses. The subsequent tool life calculation is performed by local strain approach which is currently not feasible for cemented carbide tools due to missing characteristic values. It could be demonstrated that the prestressing condition is also a main parameter for the tool life improvement of cemented carbide dies. To provide the methodology to the end-user a software program with a user-friendly graphical interface was developed. It facilitates the utilization of the method without the need of fundamental mathematical or statistical knowledge.

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