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OPTIMIZING THE FORGING OF CRITICAL AIRCRAFT PARTS BY THE USE OF FINITE ELEMENT COUPLED MICROSTRUCTURE MODELING

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Abstract

The near-net-shape forging of high strength nickel base superalloys 718 and 720 for aircraft parts requires the usage of finite element simulations to ensure a proper thermo-mechanical treatment. Because of the high mechanical requirements and narrow specifications of such parts not only a correct, defect free final geometry is necessary, but also a defined microstructure. The crucial point is therefore, to control all process parameters in a way to achieve the demanded properties.
The typical forging processes like hydraulic, screw press and hammer forging imply a broad spectrum of strain rates. The influence of these different strain rates as well as forging temperature and strain on dynamic and post-dynamic recrystallization have been examined experimentally. Annealing tests at various temperatures and time periods have been performed, to investigate static recrystallization and grain growth behavior as well as dissolution processes during heating periods. The obtained data was used to build phenomenological models, which were implemented into a finite element code of a commercial special purpose finite element program.
2D and 3D Simulations of multiple step thermo-mechanical processes are compared with microstructure examinations of forged parts to show the usability and accuracy of such models as a tool to optimize complex forging processes of critical aircraft parts. In combination with systematic process data collection during production a stable processes and satisfactory mechanical product properties are guaranteed.

Introduction

One of the main focuses of Bohler Schmiedetechnik is the development, production and sale of closed die forgings for the aircraft industry. Many of the key products in this business are made of high strength nickel base superalloys such as Alloy 718 and 720. The narrow process windows and the high flowstresses of these alloys as well as the demanding requirements regarding the mechanical properties of the forged parts are a big challenge for the process engineers. Due to the increase in affordable computer power as well as the development of accurate special purpose finite element programs a detailed simulation of the whole thermomechanical treatment can be performed. Therewith it is possible to recognize potential forging problems such as insufficient die filling, folds, to high forces, etc. previous to the production. Additional to these commercially available finite element codes, the usage of microstructure models, which are coupled with these programs, give the possibility to design and optimize the process in consideration of the customer microstructure requirements and allows an estimation of the mechanical properties in the final part.

Modeling of Microstructural Changes During the Forging Process

Modeling of microstructural changes during thermomechanical treatments implies the mathematical description of process relevant physical phenomena such as grain growth and recrystallization. These changes influence the mechanical properties, but also significantly affect the forging process itself. A change of the mean grain size leads to a change in the strain hardening and softening behavior of the material, which is visible in the different flowcurves as plotted in Figure 1. This fact forces the use of a fully coupled model including the calculation of the flowstress in dependence of strain, strainrate, temperature and of course the mean grain size. On the other hand the use of the fully coupled model slows down the simulation by a factor of nearly ten and leads to a certain numerical instability. Therefore a solution in between is used for process design at Bohler Schmiedetechnik, which means that necessary parts of the flowstress model are used for microstructure simulation. But for deformation calculation in the finite element program a database of experimental data is used. Details to these semi empirical flowstress models can be found in [1, 2].

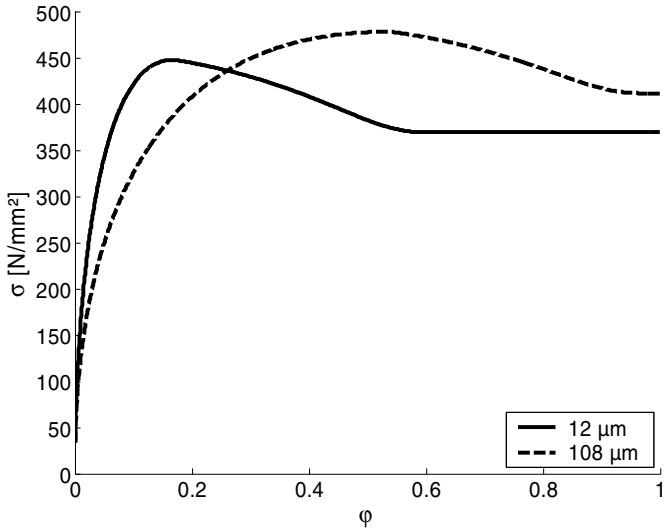

Figure 1. Influence of the average grainsize on the flowcurve (alloy 718, modeled at temperature 1000 °C and strainrate 5 s^{-1}).

As mentioned before recrystallization is the most important mechanism for the deformation behavior of these low stacking fault materials. But the possible grain refinement is of similar relevance regarding the recrystallization process, because of its significant effect on the mechanical properties of the material. In order to model these physical processes a classification of the different phenomena is necessary and commonly used e.g. [3, 4]. The time and deformation conditions of nucleation and growth of recrystallized grains are parameters to distinguish the different recrystallization processes from each other. Dynamic recrystallization is therefore defined as the process where nucleation and growth of the nuclei happen during the deformation. If the nucleation took place during the deformation and the growth subsequently without further deformation, the recrystallization is called meta-dynamic or post-dynamic. The third kind of recrystallization is the static, which is commonly well known as the one where both nucleation and growth happen past the deformation during an annealing process.

In the following the modeling of dynamic and meta-dynamic recrystallization, as the two important phenomena regarding grain refinement during hot deformation of nickel base alloys, should be described. At the beginning of deformation the dislocation density constantly rises. Due to the typical forging temperature and the low stacking fault energy of the alloys, dynamic

recovery can be neglected. Therefore, up from a critical dislocation density (ρ_c), which is proportional to a critical strain (φ_c), the forming of recrystallization nuclei starts [4, 5]. This critical strain can be modeled as a function of the peak strain (Eq. 1), which is the strain corresponding to the peak stress of the flowcurve, and itself is dependent of the initial grain size D_0, the strainrate and the Zener-Hollomon parameter Z (Eq. 2, 3). Values for material parameters a_i and further explanations can be found in [2, 5, 6, 7].

$$\rho_c \sim \varphi_c \approx 0.8 \cdot \varphi_p \,. \tag{1}$$

$$\varphi_p = a_1 \cdot D_0^{a_2} \cdot \dot{\varphi}^{a_3} \cdot Z^{a_4} \,. \tag{2}$$

$$Z = \dot{\varphi} \cdot e^{\frac{Q_{def}}{R \cdot T}} \,. \tag{3}$$

For the characterization of recrystallization kinetics two characteristic strain values are necessary. One is the before mentioned critical strain φ_c, the other must be an experimentally determinable value usually the strain, which corresponds to 50 % recrystallized volume fraction, $\varphi_{0.5}$ (Eq. 4). The kinetics can than be well described by an Avrami equation (Eq. 5).

$$\varphi_{0,5} = f\left(\dot{\varphi}, T, D_0\right). \tag{4}$$

$$X_d(\varphi) = 1 - e^{\ln(0.5)\left[\frac{\varphi - \varphi_c}{\varphi_{0.5} - \varphi_c}\right]^{a_5}} \tag{5}$$

The average grainsize of the recrystallized grains D_d can be modeled as a function of the temperature corrected strainrate the so called Zener-Hollomon parameter (Eq. 6).

$$D_d = a_6 \cdot \dot{\varphi}^{a_7} \cdot Z^{a_8} \,. \tag{6}$$

Meta-dynamic recrystallization occurs, if the recrystallization process is initialized during the deformation but not finished, thus the main part of the recrystallization takes place after the forging. As there is no further supply of deformation energy the kinetics of the process slows down, but can also be expressed with an Avrami type equation (Eq. 7). The main difference to the dynamic recrystallization is that because of no further strain changes time becomes the actuating variable. To consider temperature changes during cooling or reheating processes a temperature corrected time is used in the Avrami equation (Eq. 8 – 10) [2, 5].

$$X_m(t) = 1 - e^{\ln(0,5) \cdot \left(\frac{W(t)}{W_{0,5}}\right)} \,. \tag{7}$$

$$W_{0,5} = a_9 \cdot \varphi_m^{a_{10}} \cdot Z^{a_{11}} \,. \tag{8}$$

$$W(t) = \sum_{i=1}^{n} W_i \,. \tag{9}$$

$$W_i = t_i \cdot e^{\frac{-Q_m}{RT}} \,. \tag{10}$$

The calculation of the average grainsize of the meta-dynamic recrystallized grain D_m is similar to the dynamic recrystallized but dependent on the strain at the end of the deformation φ_m [6, 7].

$$D_m = a_{12} \cdot \varphi_m^{a_{13}} \cdot \dot{\varphi}^{a_{14}} \cdot \left(e^{\frac{-Q_m}{RT}} \right)^{a_{15}} . \tag{11}$$

The effect of static recrystallization, which is often neglected in high temperature closed die forging simulations, shows a significant influence on the microstructure in Alloy 718 forgings. Up from a critical strain φ_{cs} (Eq. 12), which is approximately 40 % of the peak strain φ_p, enough energy is stored in the deformed material to enable a nucleation and growth process during a subsequent reheating or solution annealing process. Because of the lower amount of nuclei formed during this physical process static recrystallization, unlike to the other recrystallization processes, usually result in a coarsening of the mean grainsize.

$$\varphi_{cs} \approx 0.4 \cdot \varphi_p \tag{12}$$

The equations (Eq. 13, 14) [6, 9] for the static recrystallization are very similar to the meta-dynamic one. The main differences are the lower amount of nuclei and the kinetic of nucleation and growth, which is much slower in case of static recrystallization.

$$X_s(t) = 1 - e^{\ln(0,5) \cdot \left(\frac{t}{t_{s0,5}} \right)} \tag{13}$$

$$t_{s0,5} = a_{16} \cdot \varphi^{a_{17}} \cdot e^{\frac{Q_s}{RT}} \tag{14}$$

The mean size of static recrystallized grains can be calculated according to Eq. 5, which is a modified version of Zhao et al. in [9]. It shows that the grainsize is dependent of the temperature T, the lower temperature limit for static recrystallization T_s and time on temperature but not of the strain.

$$D_s = a_{18} \cdot \left(\frac{T}{T_s} \right)^3 \cdot e^{a_{19} \cdot (T - Ts) \cdot t} \tag{15}$$

Grain growth as the second physical process which influences the microstructure and mechanical properties of the material has to be modeled as a function of time and temperature. Differing to usual expressions in the literature e.g. [3, 8] the influence of second phase particles on the kinetics is considered in the following equations.

$$D^{a_{20}} - D_o^{a_{20}} = h_k \cdot t . \tag{16}$$

$$h_k = f(Q_k, X_K) . \tag{17}$$

$$X_k = 1 - e^{\ln(0,5) \cdot \left(\frac{t_e - t}{t_e - t_{0,5}} \right)^{a_{21}}} . \tag{18}$$

Eq. 16 shows the typical semi empirical expression for grain growth with the grain growth exponent a_{20} and the energy term h_k, which is a function of the activation energy for grain growth Q_k and the relative fraction of the second phase X_k. X_k itself is dependent on the temperature corrected time for complete and 50 % dissolution (t_e, $t_{0.5}$) of the precipitate and the actual temperature corrected time t. [2, 10]

Experimental Examination of Microstructural Changes During the Thermomechanical Treatment

A broad experimental program and an accurate analysis of the microstructure parameters are necessary for the evaluation of all material parameters in the microstructure models. Tensile tests at constant temperature and strainrate were performed on a Gleeble 1500 servo hydraulic testing machine. Tests were interrupted and water quenched at different strains to examine the dynamic recrystallization status by the use of digital image analysis and microscopy. An example for this experimental evaluation is plotted in Figure 2.

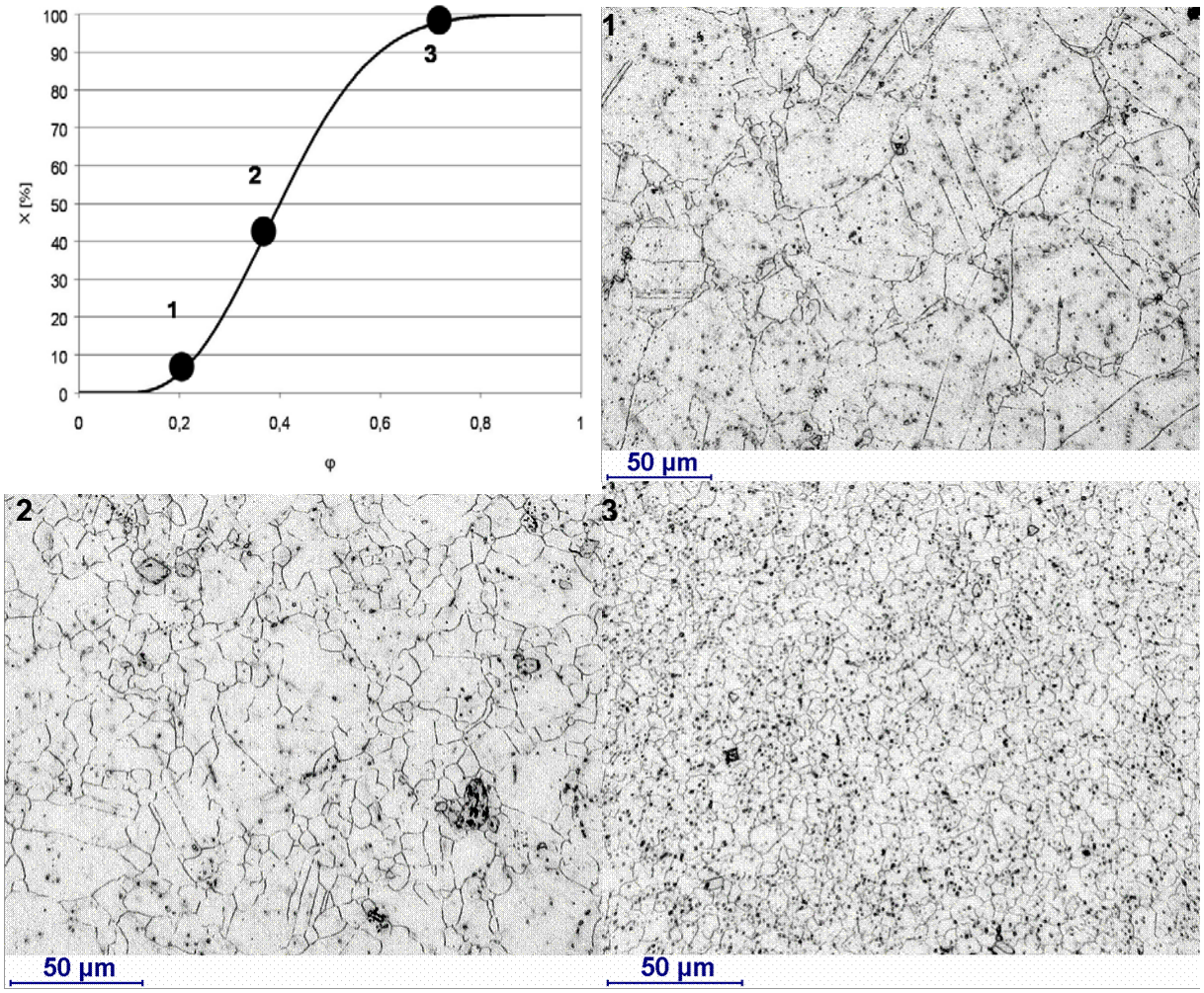

Figure 2. Alloy 718 recrystallized fraction and microstructure of water quenched Gleeble specimens deformed at a temperature of 1050 °C with a stain rate of 5 1/s to different strains.

Similar experiments with different holding times after the interrupted deformation where used to determine the parameters for the meta-dynamic recrystallization model. The influence of the static recrystallization on the microstructure was investigated on forged and annealed pancakes as well as on complex forgings. Due to the narrow bandwidth of strains where static recrystallization occur, regions of static recrystallization are very local and thin. Also the

transitions between regions of static and regions of dynamic or meta-dynamic recrystallization are very sharp (figure 3).

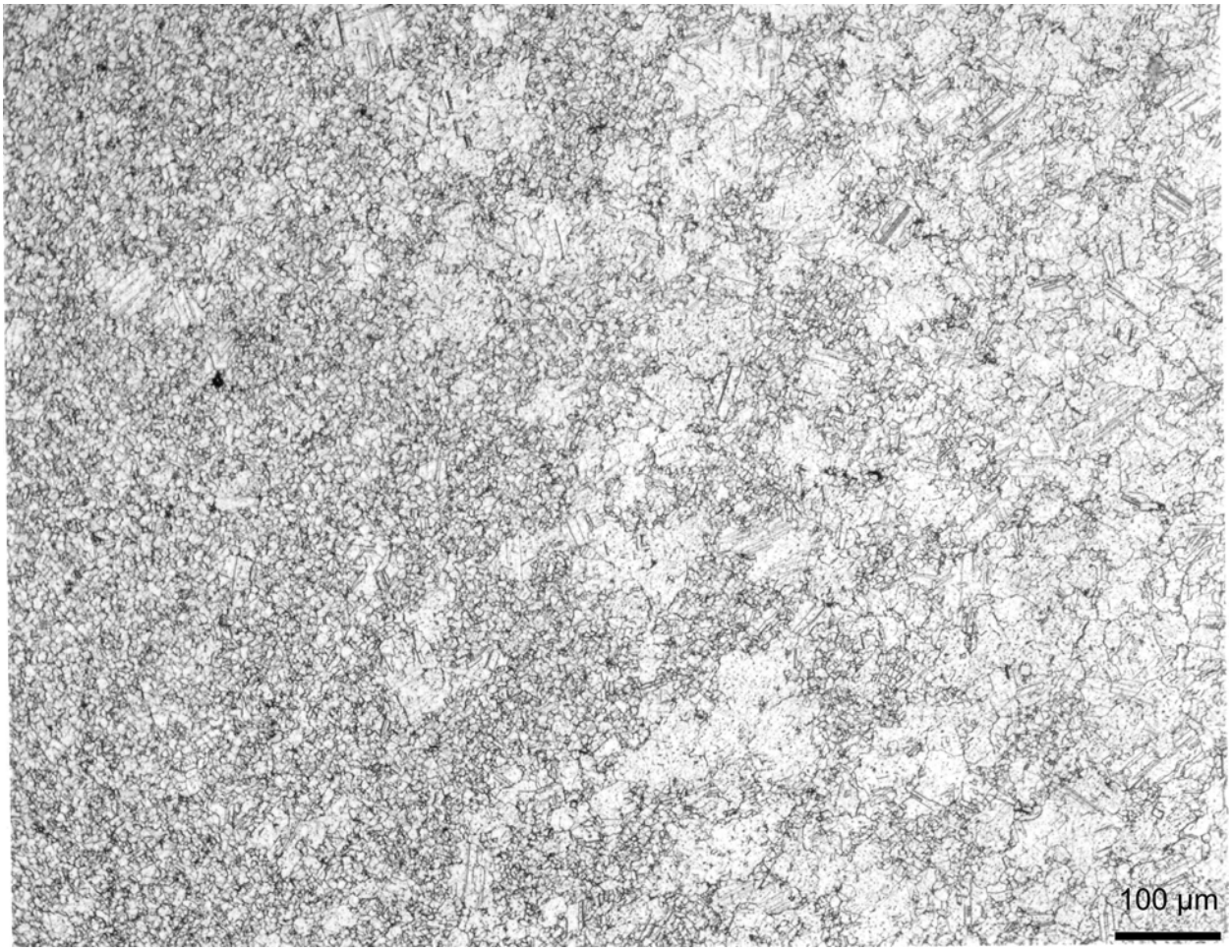

Figure 3. Sharp transition area between fine dynamically or meta-dynamically recrystallized grains and coarse static recrystallized ones.

For the examination of the grain growth behaviour annealing experiments at different temperatures and for various holding times were necessary. Mean grainsize and fraction of precipitated phases, primarily δ (Ni_3Nb) in Alloy 718 and γ' (Ni_3Al) in Alloy 720, were analyzed in the microstructure images [10]. All experimental results as well as data out of literature were used in nonlinear regression analysis to get the accurate values for the material parameters.

Results and Practical Application of Microstructure Simulations

To use microstructure modeling for the simulation of thermomechanical processes, the models must be coupled with commercial finite element codes. Therefore the models were programmed as so called user-routines in FORTRAN code, compiled and linked to the special purpose program DEFORM™. The routines are executed once for every element of the mesh during each time step. A flowchart of the whole simulation process is plotted in figure 4.

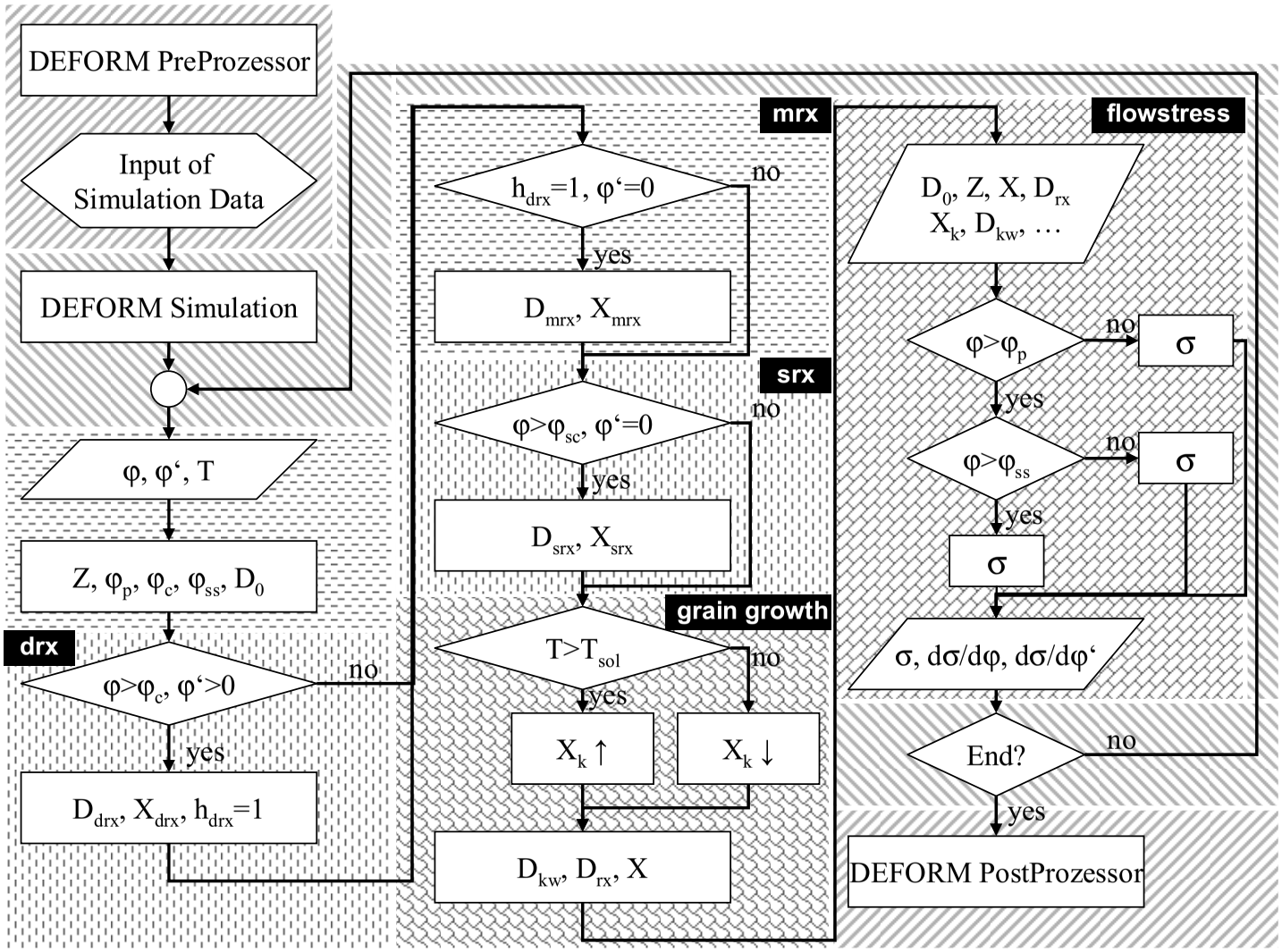

Figure 4. Flow chart of the simulation process (drx, mrx and srx means dynamic, meta-dynamic and static recrystallization).

The planning and optimization of a typical forging process starts with a backward design of all necessary forging steps. After this initial procedure the thermomechanical process is simulated again in forward direction. The targets, like die filling, folds, a specified minimum strain, microstructure properties and grainflow are compared with the simulation results. If they do not meet the requirements some of the input parameters of the process have to be changed and the cycle starts again. An example for this optimization process is the design of an alloy 718 forging for aircraft industry. As these forgings are axisymmetric the simulation can be performed in DEFORM2D™. The chosen example is a massive disc made of alloy 718 which is produced on a 315 MN screw press. A two die forging process is necessary to achieve the final geometry. To fulfill the requirement of a uniform fine grainsize as well as the before mentioned general targets a simulation of the process including microstructural simulation was necessary. Forging temperatures must be chosen below the δ-solvus to inhibit grain growth during heating and reheating processes. In the first design, as visible in figure 5, large regions of the cross section remain unrecrystallized. This means that these regions still show the original but deformed grain structure, which can lead in a coarse grain in the final forging. To prevent this unfavorable status a change of the blocker geometry was necessary. The optimized design leads to a minimum of unrecrystallized regions (figure 5 right).

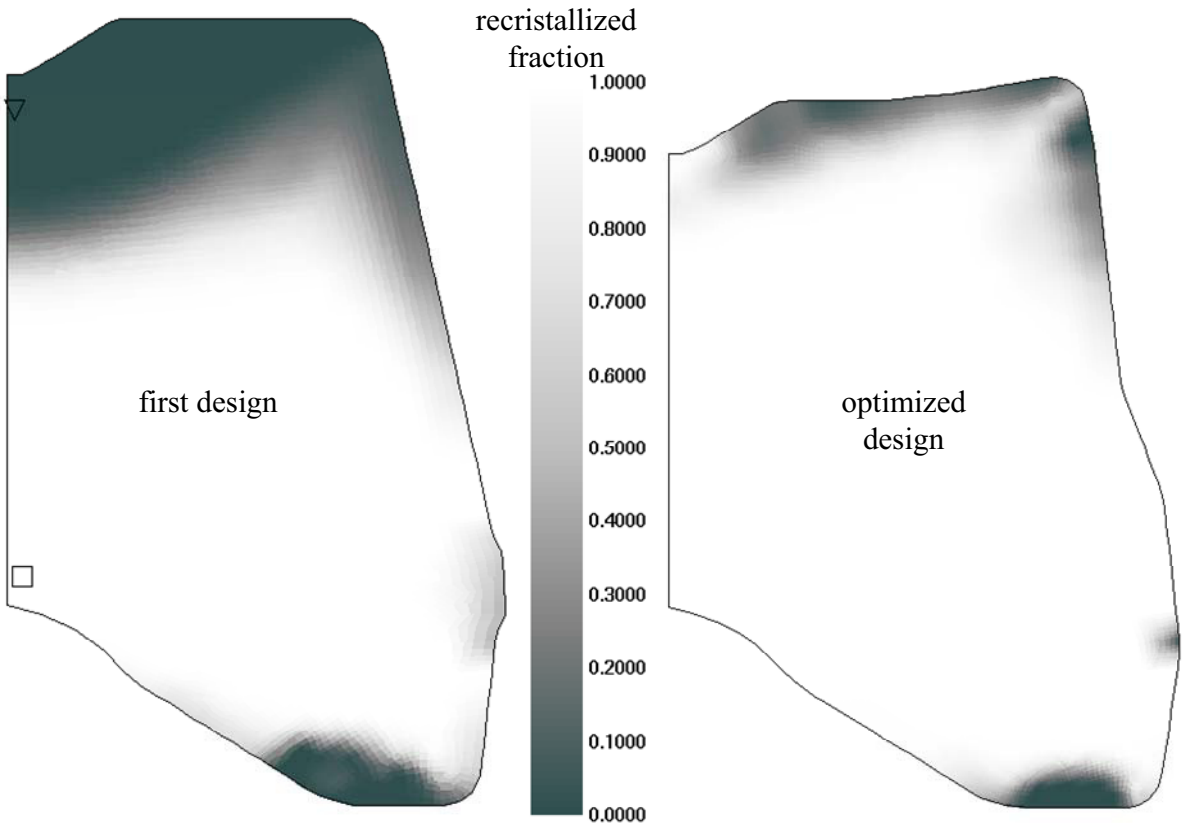

Figure 5. Optimization of the blocker design due to minimize unrecrystallized regions.

After the second forming step almost every part of the forging is recrystallized dynamically respectively post-dynamically, which leads to the favored uniform fine grain structure. In figure 6 a comparison of simulation and microstructure analysis on a forged part is presented. As visible the conformance between the calculation and the reality is pretty good. An example of a 3D-forging will be presented at the conference, because of the necessity of a color-plot.

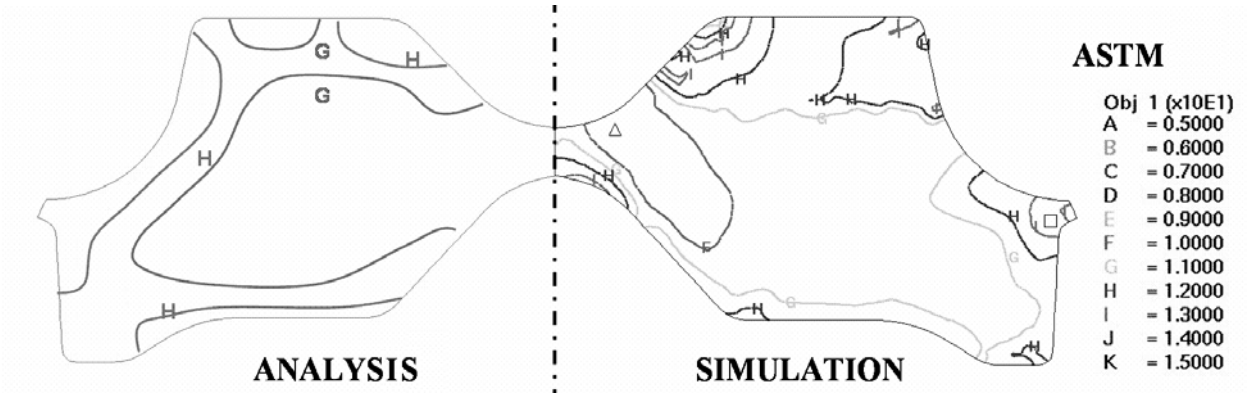

Figure 6. Comparison of simulation and microstructure analysis on a forged alloy 718 part.

Conclusions

The aim of the present work was to show that the use of modern special purpose finite element programs in combination with semi empirical microstructure routines gives the opportunity to plan and optimize thermomechanical processes more effective. Not only faultless parts can be guaranteed without trial forgings but also the meet of specific microstructural specifications. A basic requirement for the later modeling is a fundamental and proper experimental investigation of the physical processes like recrystallization and grain growth during the thermomechanical treatment. With respect to this fact an accurate simulation of the microstructural changes during the forging process is possible and shown in the above example.

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