Simulation of Recrystallisation and Grain Size Evolution in Hot Metal Forming

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Abstract. The paper presents an approach that combines the simulation of technological processes on two levels. One of them is the finite element model that predicts material flow and temperature distribution in the workpiece during any multi-stage deformation where forming steps can be separated by heating/cooling of the billet. The second level is a semi-empirical microstructural model that simulates static and dynamic recrystallisation and grain growth during deformation or dwelling time. The background of the microstructural model is Sellars formulation. The model parameters are derived by parameterization of the experiments done with the material specimens for a wide range of strain, strain-rate, temperature variation and pause time. This model has been integrated in QForm3D software and tested for several practical cases of open and closed die forging. The case studies have shown good agreement between the simulation results and practice that have opened the way for its implementation in industry.

Keywords: Metal forming, FEM, simulation, microstructure, recrystallisation, nickel alloy.

INTRODUCTION

These days the development of a metal forming processes is hardly imaginable without FEM simulation. The capabilities of simulation extend from prediction of material flow and tool stress analysis to overall optimisation of the technological processes including providing required distribution of the mechanical properties in the finished product. The latter task requires including metallurgical models into the finite-element metal forming simulation code. The presented paper is dedicated to this task that has been accomplished for the needs of aerospace industry where the requirements to guarantee product properties are the most critical.

MICROSTRUCTURAL MODEL DESCRIPTION

The present work is based on Sellars formulation that includes semi-empirical models of dynamic and static recrystallisation and grain growth [1]. Some practical implementations of this approach have been already published in our previous works [2-6]. The model is based on the following assumptions. Firstly, it is supposed that dynamic recrystallisation in the deformed material starts when the effective strain exceeds a certain critical value ε_c that can be expressed as follows

$$\varepsilon_c = a_1 \cdot D_0^{a_2} \cdot Z^{a_3} \tag{1}$$

where D_0 is the initial grain size, Z is the Zener-Hollomon parameter, $a_1 ... a_3$ are the material dependent parameters. The strain value $\varepsilon_{0,5}$, at which 50% of the grains are recrystallized is to be determined as follows:

$$\varepsilon_{0,5} = c_1 \cdot D_0^{c_2} \cdot \dot{\varepsilon}^{c_4} \cdot e^{\left(\frac{c_3}{T}\right)} \tag{2}$$

where $\dot{\varepsilon}$ is the strain-rate, T is the temperature, $c_1...c_4$ are the material dependent parameters.

The dynamically recrystallized share of the grains X_{dyn} is to be calculated as follows:

$$X_{dyn} = 1 - e^{e_1 \cdot \left[\frac{\varepsilon - \varepsilon_c}{\varepsilon_{0,5}} \right]^{e_2}} \tag{3}$$

where e_1.and.e_2 are material dependent parameters.

A very high grain refining can be obtained with the dynamic recrystallization. The actual grain size D_{dyn} depends on the activation energy of the material, process strain-rate and temperature. It can be expressed by the following relation:

$$D_{dyn} = d_1 Z^{d_2} \tag{4}$$

where $d_1...d_2$ are the material dependent parameters. Thus all parameters mentioned above ($a_1...a_3$, $c_1...c_4$, d_1, d_2, e_1, e_2) are to be determined experimentally.

The static recrystallisation can be specified by the time $t_{0,5}$ when 50% of the grains are statically recrystallised. Thus total share of statically recrystallised grains can be expressed as:

$$X_{stat} = 1 - e^{-h_1 \cdot \left[\frac{t_p - t_o}{t_{0,5}} \right]^{h_2}} \tag{5}$$

where

$$t_{0,5} = f_1 \varepsilon^{f_2} D_0^{f_3} \left[\dot{\varepsilon} \cdot e^{\frac{Q_{st}}{RT}} \right]^{f_4} \cdot e^{\frac{f_5}{T}} \tag{6}$$

and t_p is the pause time, t_0 is the time till the beginning of the static recrystallisation, D_0 is the initial grain size before starting of static recrystallisation, Q_{st} is the activation energy for the static recrystallisation and h_1, h_2, $f_1...f_5$, $g_1...g_4$ are the material dependent parameters. The average diameter of statically recrystallised grains can be calculated as following:

$$D_{stat} = g_1 \varepsilon^{g_2} D_0^{g_3} Z^{g_4} \tag{7}$$

where h_1, h_2, $f_1...f_5$, $g_1 \ldots g_4$ are the material dependent parameters of the model and D_0 is the initial grain size before starting the static recrystallisation.

After primary recrystallisation the microstructure is not yet in the state of equilibrium. Further reduction of the grain surface energy is reached through the grain growth:

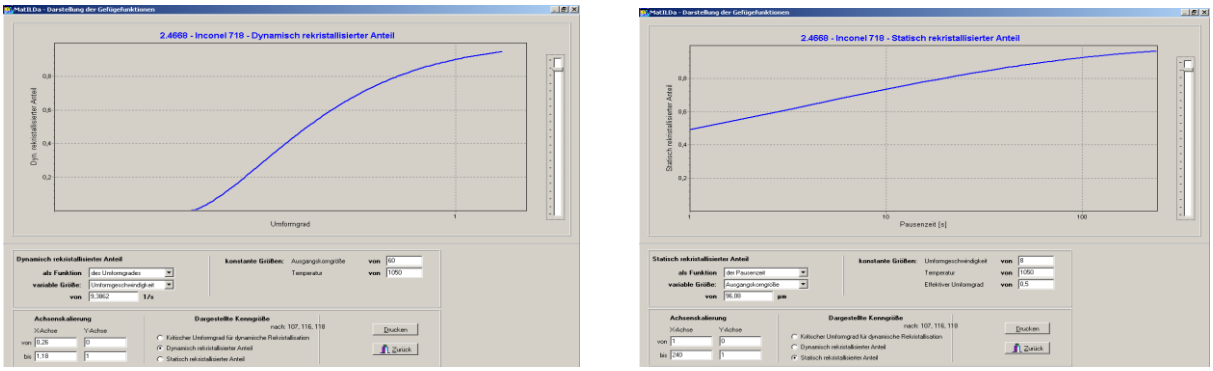
$$(\Delta D)^n = \lambda \cdot t \cdot e^{\frac{-Q_{KW}}{RT}} \tag{8}$$

where t is the time, ΔD is the grain size variation, Q_{KW} is the activation energy for the grain growth, λ and n are material dependent parameters.

PARAMETERS OF THE MODEL FOR INCONEL 718

The model specified above requires experimental determination of the material dependent parameters. It can be done by series of torsion and compression tests within the working ranges of the temperature T=950-1100°C and the

strain-rate $\dot{\varepsilon} = 0.1\text{- }10\ s^{-1}$ that corresponds to the most typical process conditions. Such tests have been done for Ni-based alloy Inconel 718. Using these experimentally determined parameters the material model behavior can be visualised and verified by the program MatILDa (Material Information Link and Database service) developed by GMT-Berlin. Fig. 1 demonstrates the possibilities of this tool. Any parameter of the process (strain, strain-rate, temperature or pause time) can be continuously varied by means of the "slider" control while the other parameters are kept constant at certain levels.



(a) (b)

FIGURE 1. The share of dynamically (a) and statically (b) recrystallized grains displayed in MatILDa program as function of the strain and the pause time respectively.

The results of predicting the grain size after the deformation at different values of the deformation and the temperature have been compared with experimental observations and they have shown good correspondence with practical observation as shown, for example, in Fig. 2.

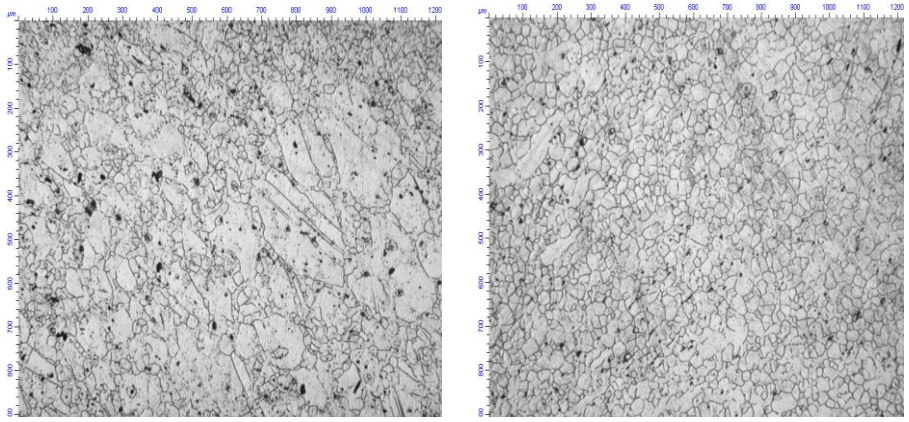
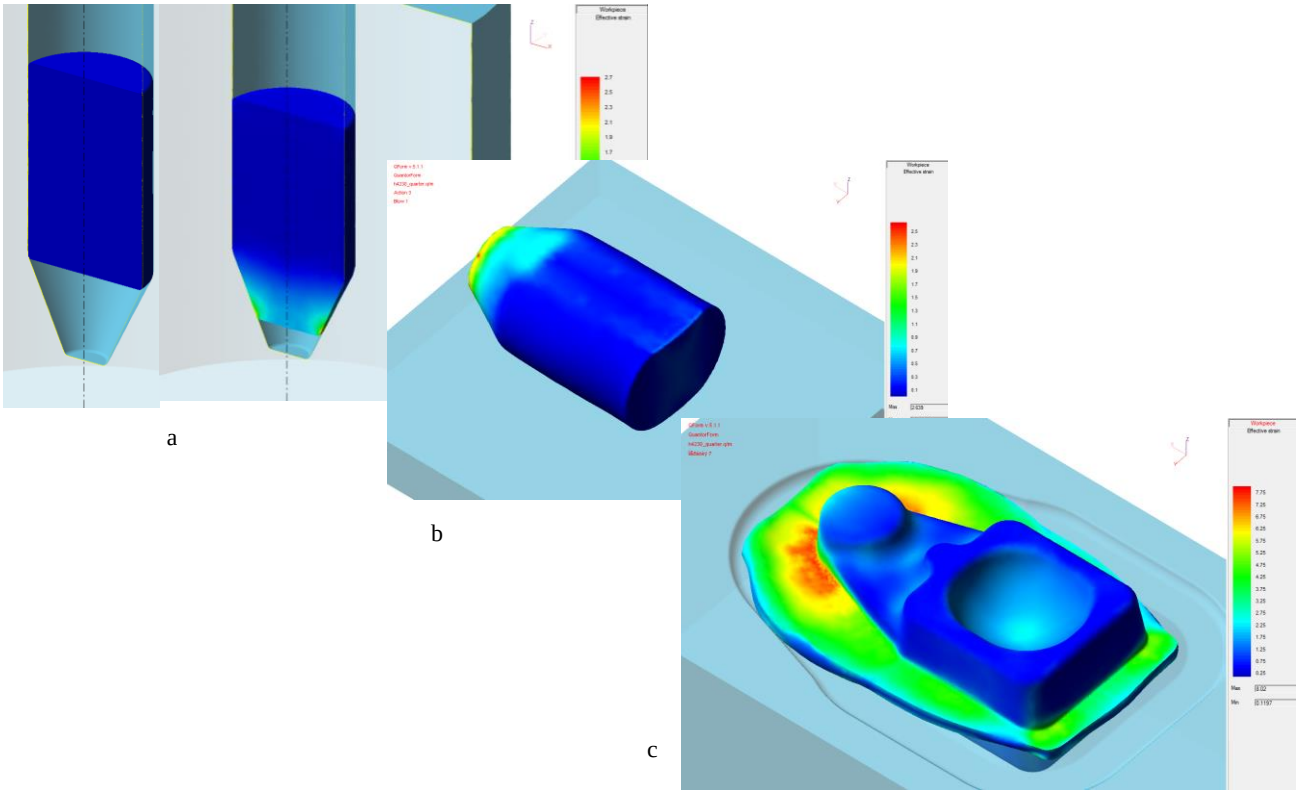


FIGURE 2. Microstructure of Inconel 718 after deformation at 1080 °C and strain–rate 5 s^{-1} and two different values of the strain 0.3 (a) and 0.5 (b).

PRACTICAL IMPLEMENTATION OF THE MODEL

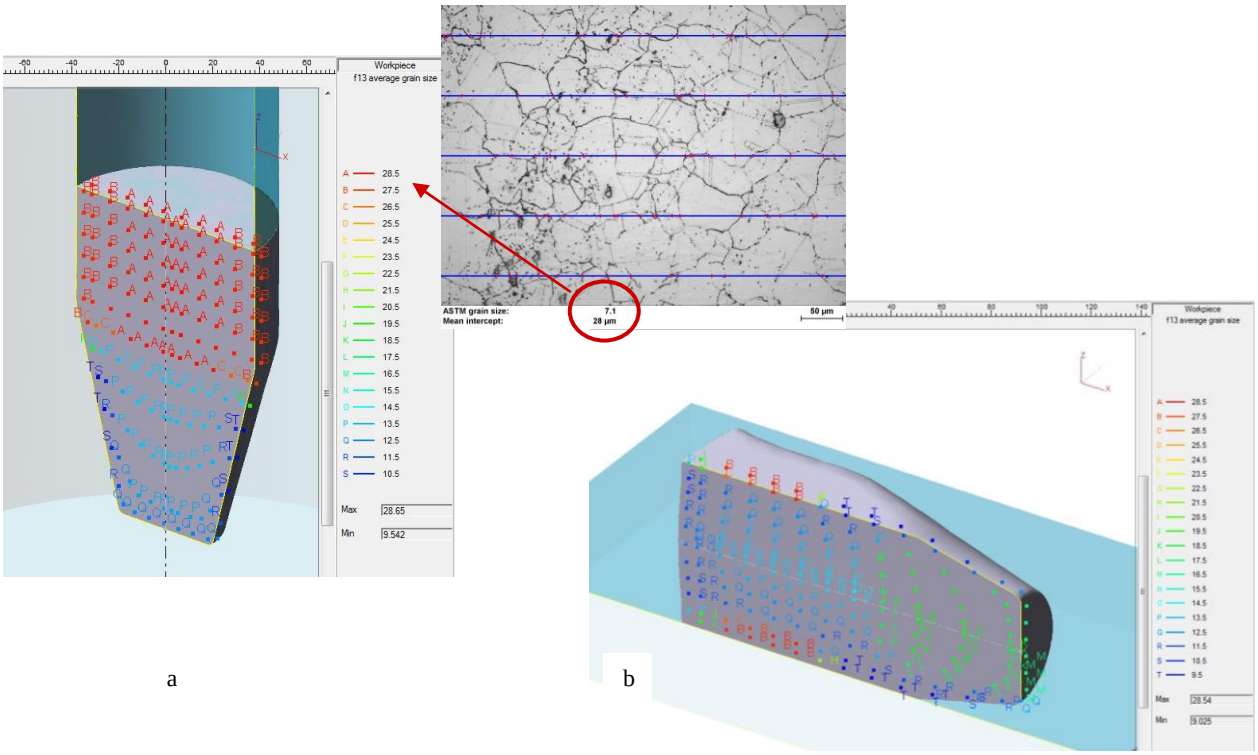
The model has been included into metal forming simulation program QForm3D developed by QuantorForm Ltd. It allows simulation of any metal forming processes performed in any number of stages with heating/cooling operations in between. The test technological process is the forging of a structural component produced in three operations. Fig. 3 shows the shape of the workpiece before the process and after each operation with the distribution of strain on its surface. The initial temperature before the process of 1080 °C has been reached by heating it in a furnace for 30 min.

The initial average grain size in the billet was 28 microns. After the first operation (nosing) it remains unchanged in the half of the billet where there was no deformation (see Fig 4a).



a b c

FIGURE 3. The sequence of the operations used for production of the structural component: nosing (a), flattening (b), closed die forging (c). Material Inconel 718.



a b

FIGURE 4. The grain size after nosing (a) and flattening (b) operations in tracked points of the meridian crosscut section of the workpiece. Initial grain size of 28 microns is shown on the micrograph and corresponds to the level represented by letter "A".

After the flattening operation nearly the whole volume of the workpiece has gotten some deformation and the grains size has been reduced. The only exceptions are the dead zones near the contact with the dies where the deformation is less than the critical value ε_c that is required to start the recrystallisation.

The simulation of the final stage of the technological process (closed die forging) is presented in Fig. 5. The tracked points that are shown here are placed at a depth of 1-2 mm from the forged part surface where the metallographic sections have been done. As we can see on these pictures the simulation very accurately predicts the average grain size in control points M1 and M2. The grain size in the thinnest area of the forged part (control point M1) according to the micrograph is 13 microns while the simulation shows it is within the range of 13.5-14.5 microns (letters "H" and "I"). In the control point M2 that is in the thickest area of the forged part the grain size is 18 microns as seen on the micrograph while the simulation shows that is about 19.5 microns (letter "C").

The presented case study as well as several other test jobs have proven the model accuracy and applicability for predicting the grain size in hot forged parts. Besides of Inconel 718 the models for some other steels and alloys are available from the authors.

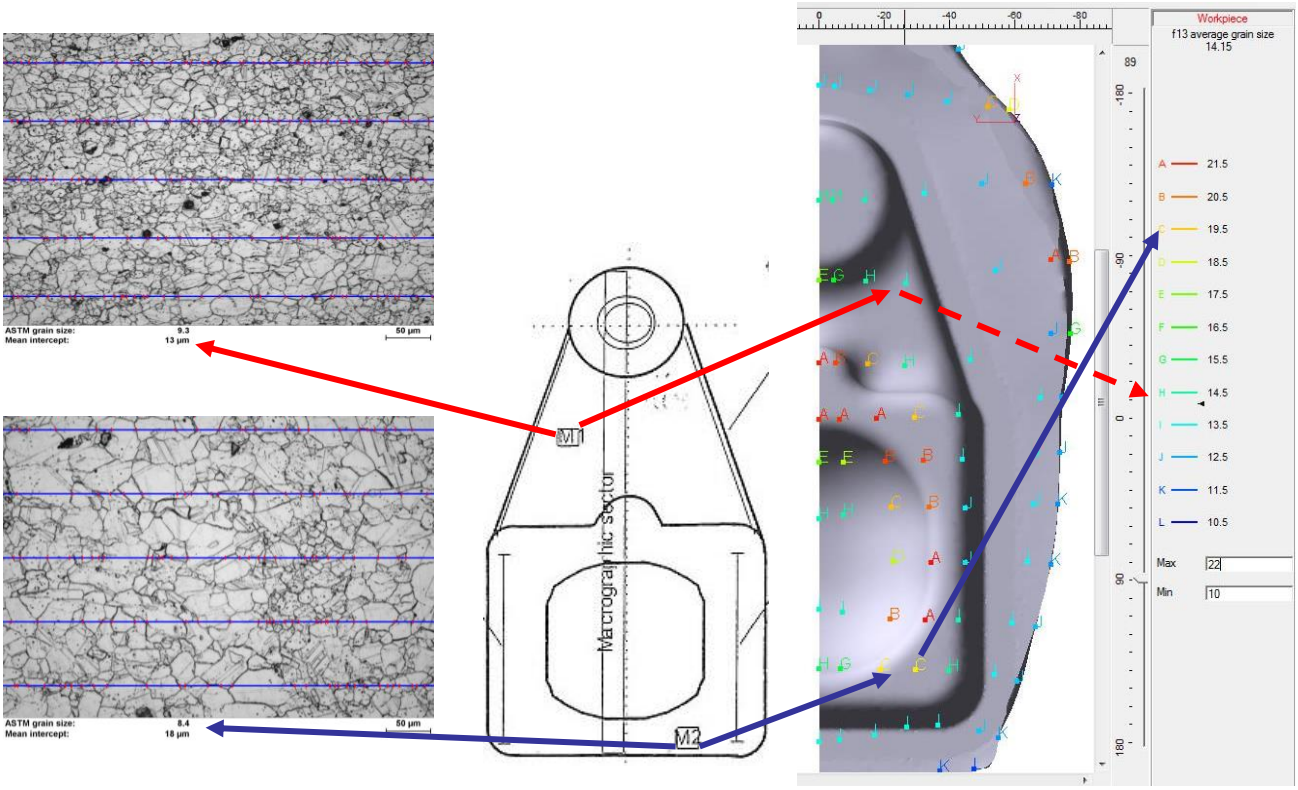


FIGURE 5. The average grain size in two control points M1 and M2 observed experimentally on the micrographs (left) and predicted by means of the simulation (right). Arrows show the correspondence of the points on the cut plan and the legend scale.

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