Simulation of microstructure development and formation of mechanical properties in metal forming technology.

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Abstract. The paper presents an approach that combines the simulation of the technological processes on two levels. One of them is finite element model that predicts the 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 during the pauses. 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 microstructural model is Sellars formulation. The model parameters are derived by parameterization of the experiments done with the material specimens for wide range of the strain, strain-rate, temperature variation and different 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 simulations results and practice that opened the way for its implementation in industry.

Keywords: Hot Forging, Finite Elements, Microstructure.

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 present work is based on Sellars formulation that includes semi-empirical models of dynamic and static recrystallisation and grain growth [1]. It is also based on further development of this approach that can be found in works [2-5]. The implementation of the developed method has been accomplished for the needs of aerospace industry where the requirements to guarantee product properties are the most critical.

Model formulation

Formation of the microstructure takes place during the whole manufacturing process of the metal. Starting with the solidification the microstructure is changing during hot and cold forming until final heat treatment. Main mechanisms of microstructure formation in hot forming processes can be classified as follows:

- Microstructure formation during heating
- Grain growth during and after heating
- Dissolution of precipitates
- Recreation and/or recrystallisation during deformation
- Recreation and/or recrystallisation in pauses between deformation stages.

The hardening and softening of metals during forming processes is determined by the number, arrangement and movement of existing dislocations in the crystal lattice. The dislocation density in metals changes with the beginning of transformation. The effective stress during the deformation generates dislocation from existing sources. The dislocations may be blocked by different obstructions and merge together. They also can be thermally activated that may reduce the dislocation density and cause softening of the material. Depending on the nature and timing of softening reaction it is called dynamic or static recovery and static or dynamic recrystallisation. The processes that take place during microstructural evolution can be described in analytical form but the parameters of the models still require experimental determination. Thus the microstructure evolution models to large extend are still empirical.

The model used in present work 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

$$\varepsilon_c = a_1 \cdot D_0^{a_2} \cdot Z^{a_3} \qquad (1)$$

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

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

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

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

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

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:

$$D_{dyn} = d_1 Z^{d_2} \qquad (4)$$

where $d_1 \ldots d_2$ are the material dependent parameters. Thus all parameters mentioned above ($a_1 \ldots a_3$, $c_1 \ldots c_4$, 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:

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

where

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

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:

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

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:

$$D_{KW}{}^{n} - D_0{}^{n} = \lambda * t * e^{\frac{-Q_{KW}}{RT}} \qquad (8)$$

where t is the time, D_{KW} is the grain size after grain growth, D_0 is the initial grain size, Q_{KW} is the activation energy for the grain growth, λ and n are material dependent parameters.

The model specified above requires experimental determination of the material dependent parameters. It has been done by series of 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 [6].

Practical Implementation of the Model

The model has been included into metal forming simulation program QForm3D developed by QuantorForm Ltd. [7]. It allows simulation of any metal forming processes performed in any number of stages with heating/cooling operations in between. In present work the material is considered as incompressible rigid-viscoplastic continua and elastic deformations are neglected. The nodal values of velocity components and mean stress are considered as independent variables. Velocity and mean stress are approximated within tetrahedral elements. Another independent nodal value is the temperature. Iterative updating of heat generation and flow stress provides thermo-mechanical coupling of the problem. The dies are treated as rigid bodies with specified friction and heat transfer conditions on their surfaces.

The accurate transfer of the die geometry from CAD to QForm3D is provided by the use of finite elements of second order of approximation. For this purpose quadratic isoparametric elements with curved faces are implemented. This approach allows frequent re-meshing without “undercut” of the workpiece surface and provides very good volume constancy.

The program generates the mesh fully automatically without any user’s intervention. The adaptive self-controlled algorithm provides optimal mesh density distribution at any stage of deformation process. Smaller elements are automatically generated in critical areas to allow the investigation of specific effects such as material flow defects (laps), die filling, etc.

The flow stress data for Inconel 718 have been derived experimentally by GMT Berlin GmbH using compression tests and for the needs of simulation they have been presented as a function of strain, strain-rate and temperature using interpolation for the whole range of the parameters.

The analised technological process is the forging of a structural aerospace component produced in three operations. Fig. 1 shows the shape of the workpiece before the process and after each operation with the distribution of strain on its surface and in a crosscut. The initial temperature 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 no deformation appear at this stage (see Fig 2a).

After the flattening operation nearly the whole volume of the workpiece has got some deformation and the grain 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 (Fig. 2b).

The simulation of the final stage of the technological process (closed die forging) is presented in Fig. 3. 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 that 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 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 also available.

Further development of the model includes coupling of the results of microstructure prediction with the flow stress because depending on the grain size evolution and the progress of dynamic and static recrystallisation the flow stress may change. This work will require additional experiments to find out the actual flow stress at different stages of recrystallisation and recovery.

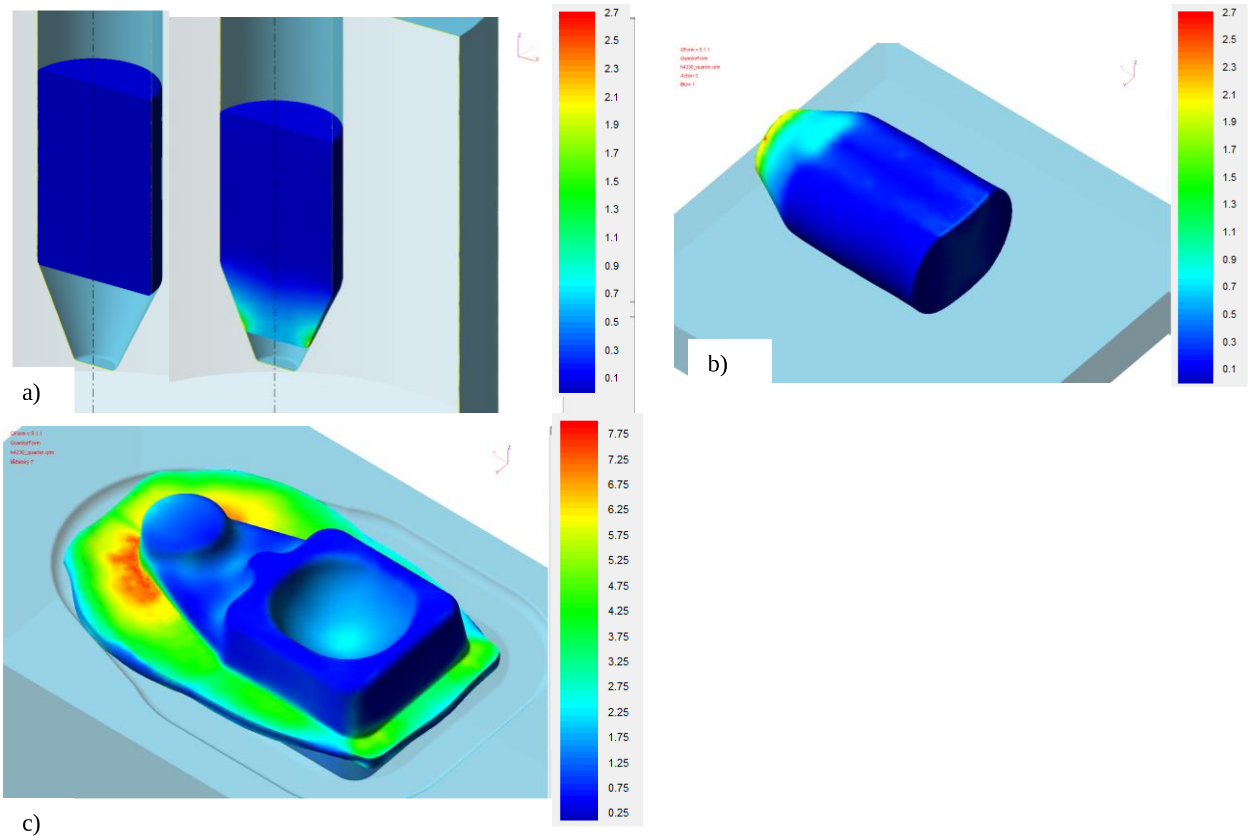
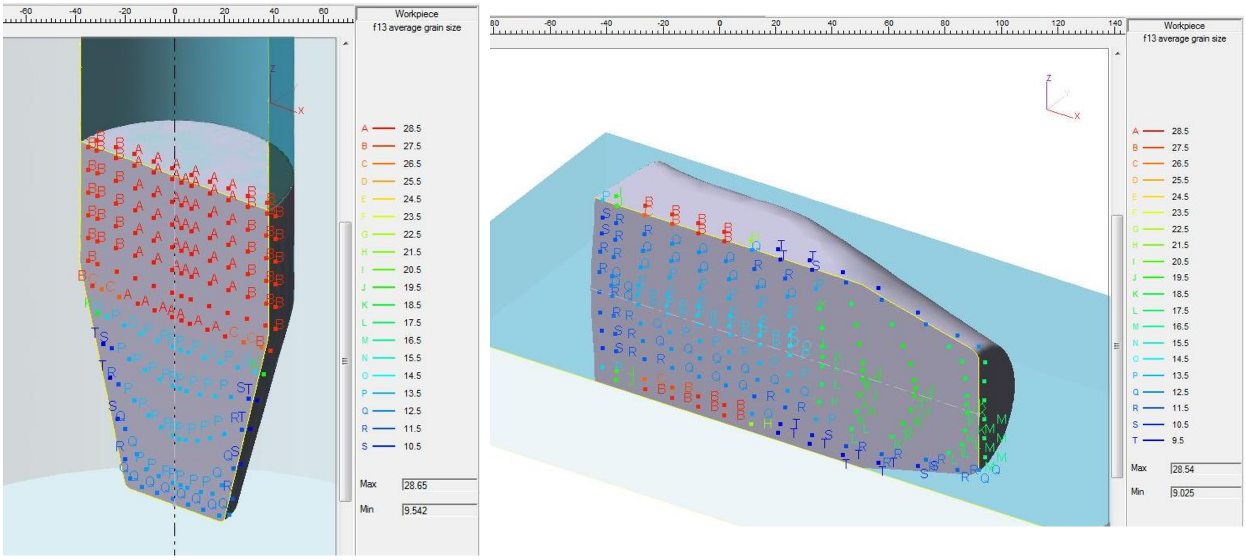


Fig. 1. The sequence of the operations used for production of the structural component: nosing (a), flattening (b), closed die forging (c). Material Inconel 718, effective strain distribution is shown.



a) b)

Fig. 2. 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 corresponds to the level represented by letter “A”.

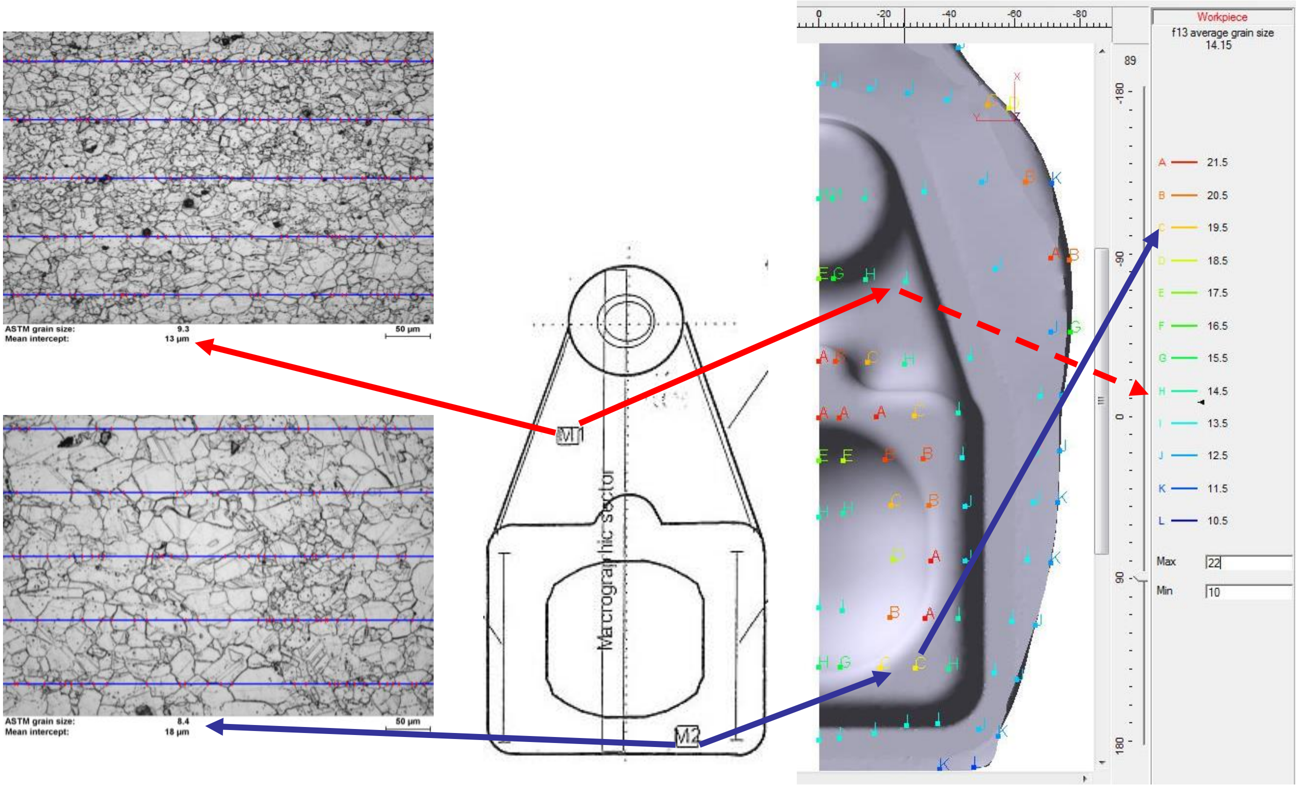


Fig. 3. The average grain size in two control points M1 and M2 observed experimentally on the micrographs (left) and predicted by means of the simulation (right). Arrows show the correspondence of the points on the cut plan and the legend scale.

Additional information about mechanical properties of the forged part can be obtained from the grain flow pattern in its critical cross sections. The grain flow configuration appears as a result of distortion of the initial fibre structure of the billet during the whole forging process. The best mechanical properties are observed along the grain flow lines. Thus to provide the best performance of the part the grain flow lines orientation should be preferably aligned along the direction of the biggest principal stress in the product when it is in operation. As seen on Fig. 4 the patterns of the grain flow predicted in the simulation and observed in experiments are very similar. The fibres of the material have no loops or other irregularities and they are predominantly aligned in direction of the tensile stress in the part.

a) b)

Fig. 4. The grain flow in the meridian cross section of the finish part obtained in the simulation (a) and observed in the real part after its polishing and etching (b).

Conclusions

1. The program module that realizes semi-empirical model of dynamic and static recrystallisation and grain growth has been included to Finite-Element metal forming simulation code QForm3D.
2. The model has been applied to industrial case of manufacturing of an aerospace part in three forming operations.
3. The average grain size has been checked after the final operation and this test has shown good correspondence of the predicted and measured values that has proved the accuracy of the model.

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