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The Implementation of Microstructural and Heat Treatment Models to Development of Forming Technology of Critical Aluminum-Alloy Parts

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Abstract. The demand for high performance and energy efficient transportation systems have boosted interest in lightweight design solutions. To achieve maximum weight reductions, it is not enough just to replace steel parts by their aluminium analogues, but it is necessary to change the entire concept of vehicle design. In this case we must develop methods for manufacturing a variety of critical parts with unusual and difficult to produce shapes. The mechanical properties of the material in these parts must also be optimised and tightly controlled to provide the best distribution within the part volume. The only way to achieve these goals is to implement technology development methods based on simulation of the entire manufacturing chain from preparing a billet through the forming operations and heat treatment of the product. The paper presents an approach to such technology development. The simulation of the technological chain starts with extruding a round billet. Depending on the extrusion process parameters, the billet can have different levels of material workout and variation of grain size throughout the volume. After extrusion, the billet gets formed into the required shape in a forging process. The main requirements at this stage are to get the near net shape of the product without defects and to provide proper configuration of grain flow that strengthens the product in the most critical direction. Then the product undergoes solution treatment, quenching and ageing. The simulation of all these stages are performed by QForm FEM code that provides thermo-mechanical coupled deformation of the material during extrusion and forging. To provide microstructure and heat treatment simulation, special subroutines has been developed by the authors. The proposed approach is illustrated by an industrial case study.

FINITE ELEMENT MODEL

Microstructure Evolution Model

The mechanical properties of hot forged parts are very much dependent on grain flow and microstructure obtained during deformation and further heat treatment. In principle, the properties can be controlled and improved by processing parameters that provide the proper material flow pattern and influence microstructural evolution. Thus, to predict and control grain size distribution in finish forged or extruded products, mathematical models of microstructural evolution are required. Dynamic recrystallization and grain growth are the major phenomena that drive the microstructural evolution during hot deformation of aluminum alloys. Recrystallization is the process of replacing the original deformed structure with grains with less defects.

Dynamic recrystallization occurs during the deformation process when the strain reaches some critical value that can be expressed as follows:

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$$\varepsilon_c = A_c \cdot d_0^{M_c} \cdot \dot{\varepsilon}^{L_c} \cdot \exp\left(\frac{Q_c}{RT}\right) + C_c , \quad (1)$$

where d_0 is the initial grain size, µm; $\dot{\varepsilon}$ is the plastic strain-rate, s^{-1}; T is the temperature; R is the universal gas constant, 8.314 J K^{-1} mol^{-1}; A_c, M_c, L_c, Q_c, C_c are constants.

The kinetics of recrystallization is similar to the kinetics of phase transformations because it includes the nucleation on new grains and grain growth mechanism and can be approximated fairly well by the Johnson-Mehl-Avrami-Kolmogorov equation (JMAK). In QForm the fraction of the volume that has passed through dynamic recrystallization is calculated as follows:

$$X_d = 1 - \exp\left[-\beta_d \cdot \left(\frac{\varepsilon}{A_d \cdot d_0^{M_d} \cdot \dot{\varepsilon}^{L_d} \cdot \exp\left(\frac{Q_d}{RT}\right) + C_d} \right)^{k_d} \right], \quad (2)$$

where $A_d, M_d, L_d, Q_d, C_d, \beta_d, k_d$ are constants.

The average size of the recrystallized grains depends on parameters of the deformation process such as the strain-rate, temperature and initial grain size:

$$d_d = A_{gd} \cdot d_0^{M_{gd}} \cdot \dot{\varepsilon}^{L_{gd}} \cdot \exp\left(\frac{Q_{gd}}{RT}\right) + C_{gd} , \quad (3)$$

where $A_{gd}, M_{gd}, L_{gd}, Q_{gd}, C_{gd}$ the constants.

The change of the average grain size over the time increment in simulation is determined as follows:

$$\delta d = -d_d \cdot dX_d \quad (4)$$

After completing primary recrystallization that is driven by the stored energy of deformation the structure is not stable and further growth of the recrystallized grains may occur. The driving force for this is the reduction in the energy that is stored in the material in the form of defects and grain boundaries. The grain growth is very important when developing the technology because it influences finish product properties that are dependent on grain size. For instance, small grain size is normally required to increase the strength and toughness. The average grain size after normal grain growth can be calculated as follows:

$$d_{gg} = \left[d_0^{M_{gg}} + A_{gg} \cdot t \cdot \exp\left(-\frac{Q_{gg}}{RT}\right) \right]^{\frac{1}{M_{gg}}}, \quad (5)$$

where t is the time; A_{gg}, M_{gg} are constants.

Parameters of the dynamic recrystallization of AA7075 are taken from works [1,2] where it was obtained for an alloy with the chemical composition very close to AA7075. Parameters of grain growth model for alloy AA7075 are taken from work [3]

Heat Treatment Model

After finish of forming operations final mechanical properties of the forged part (hardness, yield strength, tensile strength, toughness, etc.) are provided by heat treatment. For heat treated aluminum alloys like 7075 T6 the sequence of operations includes solution heat treatment at 470 ºC, quenching and 24 hours of artificial aging at 120 ºC [4].

The most important stage of the heat treatment is quenching, since an insufficient cooling rate during quenching of a massive part can lead to lower strength, while non-uniform cooling at high rates can lead to excessive thermal stresses and unacceptable distortion of the part.

The decreasing of mechanical properties during slow cooling of alloy 7075 is caused by the formation of coarse η($MgZn_2$) precipitates that do not have reinforcing effect but lead to the depletion of the supersaturated solid solution and thus reduction of the maximum amount of dispersed hardening particles of metastable η' phase that can be formed during aging. [5].

The Avrami-type equations are often used to describe the kinetics of diffusion-controlled precipitation reactions [6, 7]. In this paper, we assume what the loss of solution can be described by the following equation:

$$\xi_{SL} = 1 - \exp\left(-b \cdot t^{n}\right) \tag{6}$$

where ξ_{SL} is the amount of solution loss, t is the time, b and n are the functions of temperature.

For the purpose of computer simulation Eq. (6) must be rewritten in differential form:

$$d\xi_{SL} = b \cdot n \cdot t^{n-1} \cdot \exp\left(-b \cdot t^{n}\right) \cdot dt \tag{7}$$

Deriving t from Eq. (6) and substituting it in Eq. (7) we obtain the following equation that does not depend explicitly on time:

$$d\xi_{SL} = b \cdot n \cdot \left(1 - \xi_{SL}\right) \cdot \left[\frac{\ln(1 - \xi_{SL})}{-b}\right]^{\frac{n-1}{n}} \cdot dt \tag{8}$$

Based on the assumption that attainable strength depends linearly on solute concentration [8, 9], the following equation can be proposed for differential of tensile strength $d\sigma$:

$$d\sigma = d\xi_{SL} \cdot \left(\sigma_{\min} - \sigma_{\max}\right) \tag{9}$$

where σ_{min} is the ultimate tensile strength (UTS) in fully annealed state (O - temper designation); σ_{max} is the UTS at peak aged state (T6 - temper designation). Both of them can be constant or functions of temperature. In our simulation for alloy 7075 we used the following values [4]: $\sigma_{min} = 230$ MPa and $\sigma_{max} = 570$ MPa.

In QForm FEM code the integration of Eq. (8) and (9) has been performed by using 3-stage Radau IIA method as an implicit variant of Runge-Kutta method [10].

Functions b and n have been determined by TTP curves for the alloy B95 (GOST) (see Fig. 1) that is well investigated and is very similar to alloy 7075 (AISI).

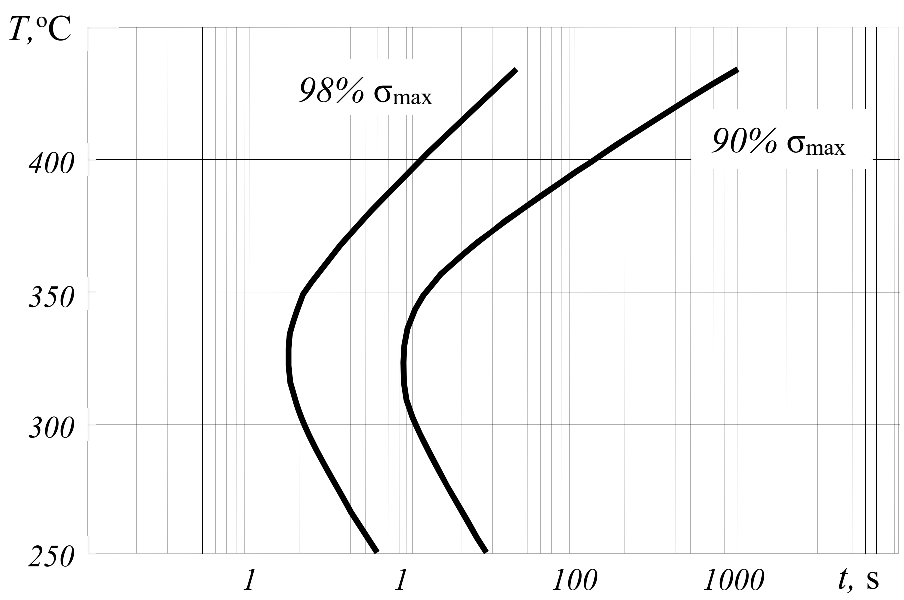


FIGURE 1. TTP-curves for alloy B95 (GOST). Base- Al, 5.28% Zn, 2.80% Mg, 1.52% Cu, 0.21% Mn, 0.14% Cr [11].

SIMULATION RESULTS

The proposed microstructural and heat treatment models have been implemented for production of a structural part “link” manufactured by hot forging using extruded round bar billets made of AA7075 alloy. The technological chain of production of the link consists of a bar extrusion, bending operation and final closed die forging with subsequent heat treatment. Strain distributions obtained by simulation after the bending and final forging operations are shown in Fig. 2.

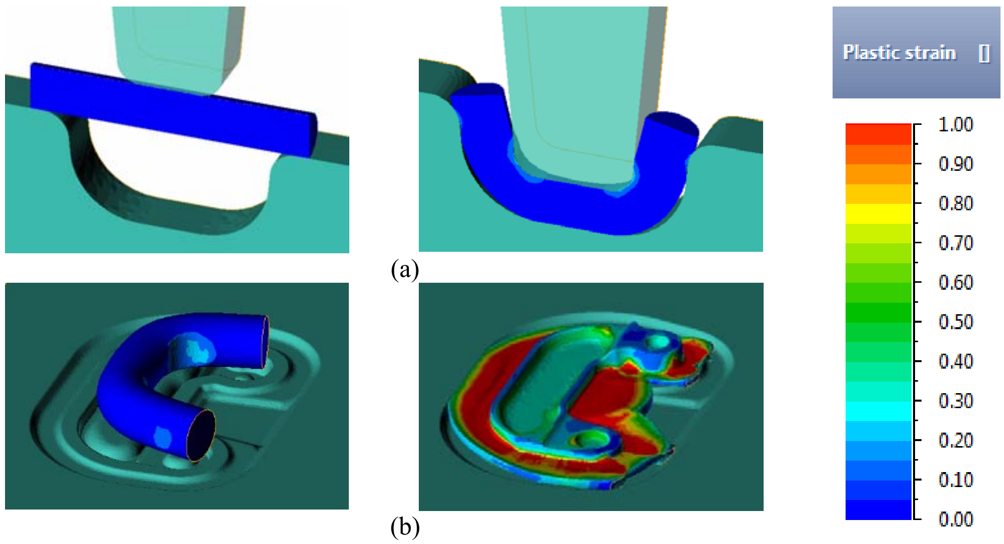


FIGURE 2. Strain distribution before and after bending (a) and final forging (b) of the “link” part.

Microstructure Evolution

To be able to follow the microstructural evolution through the whole technological process the simulation has been implemented starting from the extrusion of the billet. The round bar was obtained by extrusion of an ingot from a 12-inch diameter container. Initial average grain size of the ingot was assumed as 250 μm according to manufacturer specifications. Resulting grain size distribution in the deformation zone and in front end of the extruded bar are shown in Fig. 3.

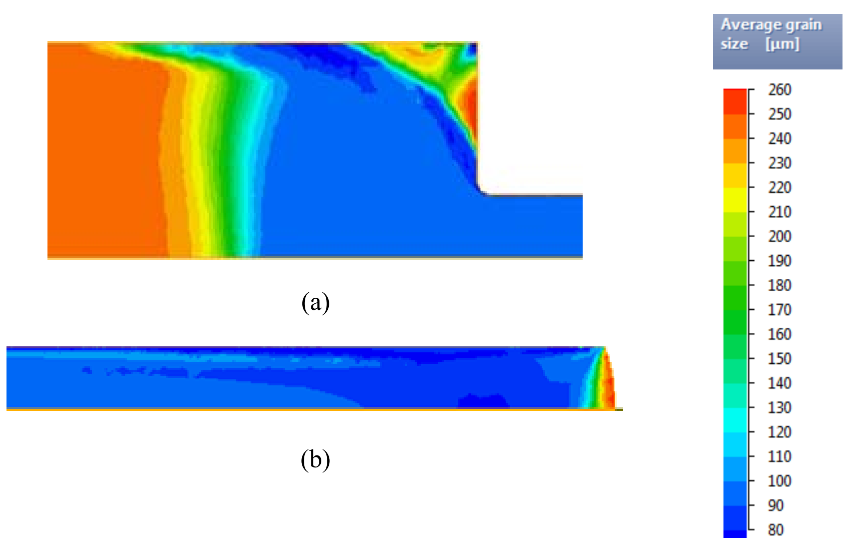
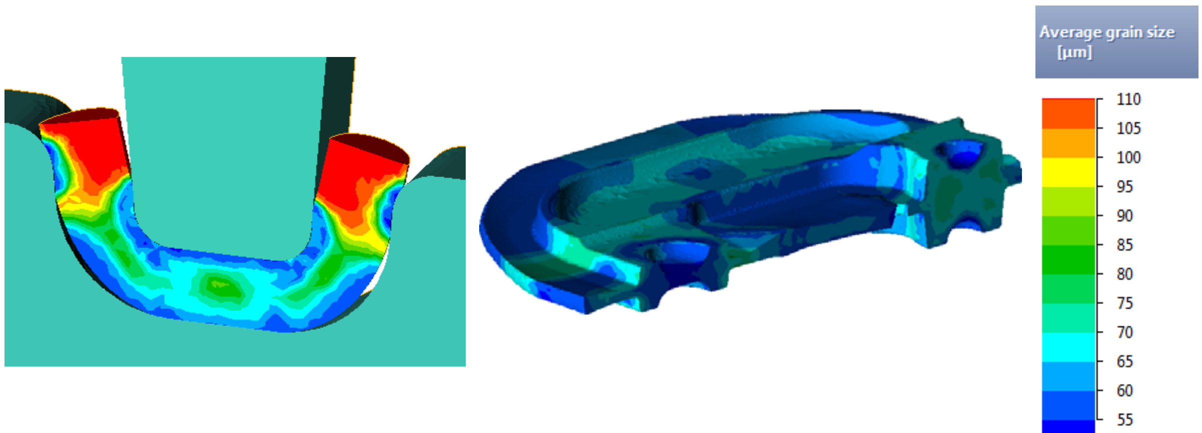


FIGURE 3. Distribution of the average grain size in the extrusion deformation zone (a) and at front end (b) of the extruded bar.

Except for the very front tip of the extruded bar, the average grain size is nearly uniform throughout the bar and the value of the average grain size is about 95 µm. After grain growth during the heating of the bar, the average grain size has grown to about 110 µm and these size grains are to be used to the next operations, i.e. bending and closed die forging**.** The results of calculation of the average grain size after bending of the bar and forging are shown in Fig. 4.



(a) (b)

FIGURE 4. Distribution of average grain size after bending (a) and forging (b)

As seen in Fig. 4a, the ends of the billet after the bending operation keep the initial grain size as it was in the extruded billet because they are not subject to deformation larger than the critical strain. Meanwhile the intensive plastic workout in the closed die forging operation provides significant reduction of the average grain size that is clearly seen in the picture of the link crosscut (Fig. 4b).

Heat Treatment

After hot forging and trimming the flash, heat treatment of the link begins with quenching. The simulation of quenching has been performed for two different cooling conditions, i.e. in still water and in a 20% solution of polyalkylene glycol (PAG) with agitation speed 0.8 m/s. Then solution loss has been calculated using the model briefly explained above. The final mechanical properties of the product after artificial aging are shown in Fig. 5.

According to [4] the minimum acceptable value of UTS for alloy 7075 after T6 treatment is 538 MPa. As it is clearly seen in Fig. 5b when using PAG quenchant in the bulkiest zone of the "link" the solution loss reaches 11%. As shown in Fig. 5d in approximately of 5% of the part volume we are not able to obtain required UTS level. On the other hand, quenching in water with higher cooling rate provide the solution loss not larger than 5% (Fig. 5a). The UTS in this case is larger than the required value throughout the entire volume of the part (Fig. 5c).

CONCLUSIONS

1. The model of microstructural evolution based on JMAK approach has been realized and implemented in commercial FEM code QForm.
2. Another developed model provides calculation of the solution loss and final mechanical properties after heat treatment according to T6 specification.
3. Both models have been implemented to the industrial manufacturing case study of the part "link" made of aluminium alloy AA7075.
4. Grain size distribution and final mechanical properties obtained in simulation proved the prospects of the developed models for their implementation in the industry.
5. The next planned step of the development of the models is to consider the influence of the grain size and other microstructural parameters on the mechanical properties after heat treatment.

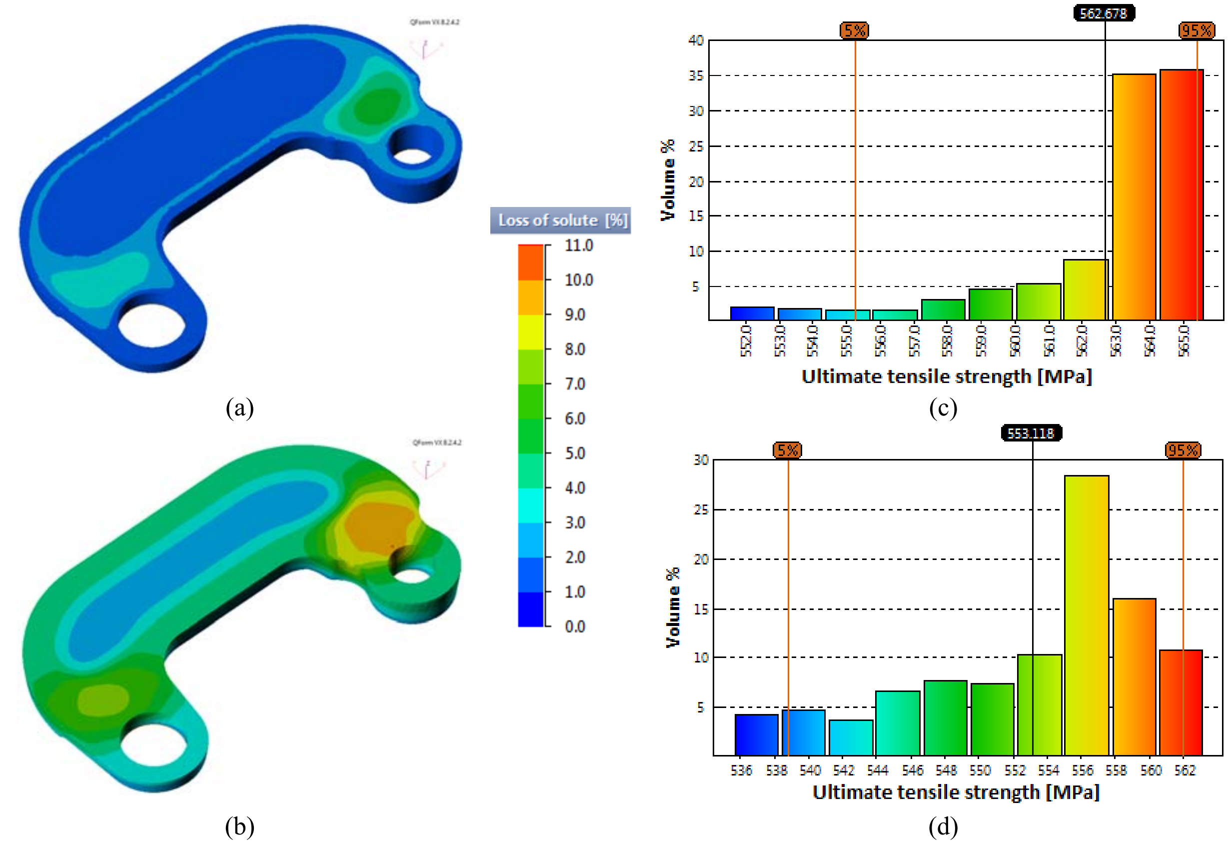


FIGURE 5. Amount of solution loss in the central cross-section of the part after quenching in still water (a) and in 20% PAG solute (b), and the histograms of volume distribution of UTS level for the same cases: water (c) and PAG (d) respectively.

REFERENCES

1. Y. Yi and Y. Shi, AIP Conf. Proc., Vol. 907. pp. 481–486 (2007).
2. Y. Yi and X. Fu, J. Central South University of Tech., Vol. 15. № 1. pp. 1-5 (2008).
3. A. Abdollah-Zadeh and A. Mehri, SCIREA J. Mat., Vol. 1. № 1. pp. 20-30 (2016).
4. Aluminum and aluminum alloys. ASM specialty handbook, ed. by J.R. Davis (ASM International, Materials Park), 1993.
5. M. Conserva and P. Fiorini, Metall. Trans. 4, 857- 862 (1973).
6. J.T. Staley, Mater. Sci. Technol. 3, 923-935 (1987).
7. D.H. Bratland, O. Grøng, H. Shercliff, O.R. Myhr and S. Tjøtta, Acta mater. 45:1, 1-22 (1997).
8. J.T. Staley, R.D. Doherty and A.P. Jaworski, Metall. Trans. A. 24A, 2417-2427 (1993).
9. R.J. Flynn and J.S. Robinson, J. Mater. Process. Technol. 153-154, 674-680 (2004).
10. E. Hairer and G. Wanner, Solving Ordinary Differential Equations II. Stiff and Differential-Algebraic Problems (Springer-Verlag, Berlin Heidelberg, 1991), pp. 129-138.
11. V.G. Davydov, V.V. Zakharov, E.D. Zakharov and I.I. Novikov, Diagrams of Isothermal Decomposition of Solutions in Aluminum Alloys [in Russian] (Metallurgiya, Moscow, 1973), p. 101.