MODELING OF MICROSTRUCTURE EVOLUTION IN MULTI-STAGE HAMMER FORGING AND FAN COOLING OF MICROALLOYED STEEL

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Abstract

The subject of the study is theoretical modeling for analysis of the microstructure development in progressive droughts of the forging sequence aimed at prediction of the parameters of austenite in as-forged condition, prior to and after direct cooling. Based on numerical calculation of temperature, strain and strain-rate, dynamic recrystallization kinetics were analyzed with use of Johnson-Mehl-Avrami-Kolmogorov (JMAK) model, and the transformed ferrite grain size was calculated, with the use of Hodgson-Gibbs and Sellars-Beynon models. After validation of the theoretical models in a simple upsetting, the results have been verified in the industrial forging process, which allowed assessment of applicability of the employed models in microstructure prediction in reference to hammer-forging of microalloyed steel. The obtained results imply the possibility of the microstructure control in multi-stage hammer-forging process and form the basis for comprehensive selection of the forging process parameters oriented at accomplishment of required microstructure and minimization of the within-part non-uniformity.

Keywords: Forging, thermomechanical processing, controlled cooling, microstructure evolution, grain refinement

1. INTRODUCTION

Despite the incessant development of advanced high-strength steels, medium or low carbon microalloy steels still prevail in applications, where excessive strength is redundant, and HSLA grades offer tailored combination of mechanical properties [1]. Although controlled hot-rolling dates back to 60 s and/or 70 s of the former century [2], reproducible implementations of controlled thermomechanical processing (CTMP) into die-forging process can cause technological setbacks. One of the assumptions of cost-effectiveness of the controlled direct cooled process is no reheating. Therefore all differences are inherited by as-forged material by subsequent cooling. Thus, alongside with the deformation history, variation in conditions for the evolution of microstructure, which in controlled thermomechanical processing has a crucial bearing on the final properties, needs to be considered [3]. Contrary to rolling process, satisfactory microstructure/property combinations, by means of controlled processing in die-forging, is harder to achieve. Geometry-related non-uniformities of strain, temperature, strain rate and dynamic phenomenas' aftermath call for nearly individual selection of processing conditions, based on similarity criteria in the modeling methods. Implementation of the controlled thermomechanical processing for new instances of forgings require prediction of expected effect of the processing conditions on microstructure and properties is presented. It is crucial in the light of wide variety of geometries and means of shaping the complex-shape parts with forging techniques, especially in plants where hammers are favored. In most cases, manufacturing technology of die-forged parts involves multi-stage forging, where deformation degree and rate differ between locations. At some stages only a portion of the volume is subject to strain and so the material undergoes dynamic evolution in a selective manner in a bulk. Combination of knowledge of the theoretical background underlying the dynamic phenomena and their effects with numerical modeling enables prediction of the aftermath and design or elimination of some forging operations in processing cycle with regard to anticipated properties of the forged part [4].

The aim of the study is determination of possible scatter in grain size after hammer forging sequence and its development during consecutive intermediate stages, including multi-stroke semi-open die preforming and impression forging, and final controlled cooling with accelerated air. The considered geometry is typical of many parts with head and shank, and the analyzed forging sequence is representative of conventional hammer forging process, which gives the results utilitarian meaning, as the theoretical modeling refers to technological limitations of the forging process. Furthermore, experimental data used for evaluation and verification of the results are derived from semi-industrial sampling, which forms the basis for assessment of applicability of both the models and the material-conditions combinations considered in the study.

2. MATERIALS AND METHODS

2.1. Geometry and material

The composition of the steel used in the study (**Table 1**) was designed as a reduced carbon modification of designated standard grades 29MnSiVS5, 35MnB4VTi or 38MnSiVS5. The industrial process of drop forging of the part shown in **Table 2** consisted of four stages: 1) flattening, 2) preforming of the shank, realized in cogging sequence, 3) blocker and 4) finisher-die forging, realized altogether in 11 - 14 hammer blows [5]. The industrial forging process was the basis for numerical simulation in the code QForm3D, which provided values of essential necessary parameters in consecutive hammer blows. Having validated the temperature calculations, using pyrometer measurement with on-line correction of emissivity [6], temperature, effective strain and effective strain rate, were taken from the simulation.

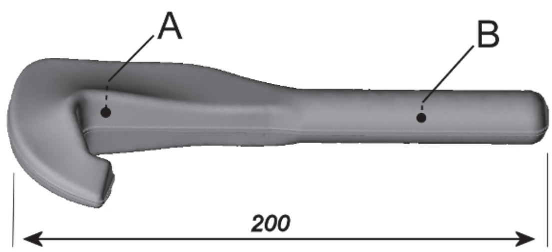

Figure 1 Forged geometry analyzed in the study

Table 1 Chemical composition of the analyzed steel (in wt. %.)

Element	C	Mn	Cr	Si	Mo	Ti	V	Nb	N ppm	Al
Content (wt %)	0.30	1.50	0.42	0.26	0.01	0.011	0.09	0.039	110	0.039

2.2. Assumptions of the mathematical model

In order to analyze the evolution of microstructure during consecutive forging operations, JMAK model based on classic theory of nucleation and grain growth was employed in the study, as the model which was successfully used in modeling dynamic behavior of hot deformed material [7, 8]. Microstructure evolution after thermomechanical processing was based on the thermo-mechanical data derived from numerical modeling in selected points A and B. Calcultation of every increment was started with checking the condition of dynamic recrystallization occurrence, according to the following criterion:

$$\varepsilon_c = C\varepsilon_p \qquad \varepsilon_p = BD_0^m Z^p \tag{1}$$

where: ε_c - threshold strain for dynamic recrystallization to occur, ε_p - peak strain, D_0 - inital austenite grain size, *Z* -Zener-Hollomon parameter, *B, m, p* - material constants.

The threshold strain level, for Nb-containing steel, was calculated as (eq. 2 and 3):

$$\varepsilon_p = \frac{1+20[Nb]}{1{,}78} \cdot 2{,}8 \cdot 10^{-4} D_0^{0{,}5} Z^{0{,}17} \qquad (2)$$

$$\frac{\varepsilon_c}{\varepsilon_p} = 0{,}8 - 11[Nb] + 117[Nb]^2 \qquad (3)$$

Activation energy for recystallization was established on the basis of chemical composition from formula (eq. 4):

$$Q = 267 - 2{,}5\,Mn + 33{,}6\,Si + 35{,}6\,Mo + 70{,}7\,Nb^{0{,}56} + 93{,}7\,Ti^{0{,}59} + 31{,}6\,V \qquad (4)$$

Kinetics of dynamic recrystallization were calculated from JMAK (eq. 5):

$$X = 1 - \exp\left[-0{,}693\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_{0,5}}\right)^2\right] \qquad (5)$$

where: ε - unit deformation, $\varepsilon_{0,5}$ - amount of deformation needed for 50 % recrystallization under considered conditions. Value $\varepsilon_{0,5}$ was determined as (eq.6):

$$\varepsilon_{0,5} = 1{,}144 \cdot 10^{-3} \cdot D_0^{0{,}25} \cdot \dot{\varepsilon}^{0{,}05} \exp\left(\frac{6420}{T}\right) \qquad (6)$$

where: T - forge-end temperature. Dynamic recrystallized austenite grain size was calculated as follows (eq. 7 and 8):

$$D_{dx} = 1{,}6 \cdot 10^4 Z^{-0{,}23} \qquad (7)$$

and after grain growth:

$$D^m = D_0^m + k_s t \exp\left(\frac{Q_g}{RT}\right) \qquad (8)$$

where: t - time after completion of recrystallization, Q_g - grain growth activation energy. For calculation of ferrite grain size after cooling to room temperature Hodgson - Gibb's formula was used (eq. 9-11):

$$d_\alpha = \left(29 - 5CR^{0{,}5} + 20\left[1 - \exp\left(-1{,}5 \cdot 10^{-2} D_\gamma\right)\right]\right) \cdot \left(1 - 0{,}8\varepsilon_a^{0{,}15}\right) \qquad (9)$$

and Sellars-Beynon equation:

$$d_0 = 2{,}5 + 3CR^{-0{,}5} + 20\left[1 - \exp\left(-0{,}015 D_\gamma\right)\right] \qquad (10)$$

$$d_\alpha = d_0\left(1 - 0{,}45\sqrt{\varepsilon_a}\right) \qquad (11)$$

where: ε_a - retained strain, CR - cooling rate.

4. RESULTS

Theoretical prediction of the microstructure development during multiple-stroke forging process depended on reliable estimation of thermo-mechanical parameters in the points of interest. The values of temperature at the beginnings and ends of forging operations, indicated in **Figure 2**, are plotted in **Figure 3a).** As it can be seen, the balance of deformation heat and heat transfer work metal-tool can generate up to 100 °C difference within the volume, which tends to equalize during trimming operation. Analogical plots were constructed for equivalent strain, and the maximum strain rate in the center of cross-sections A and B (**Figure 3b**).

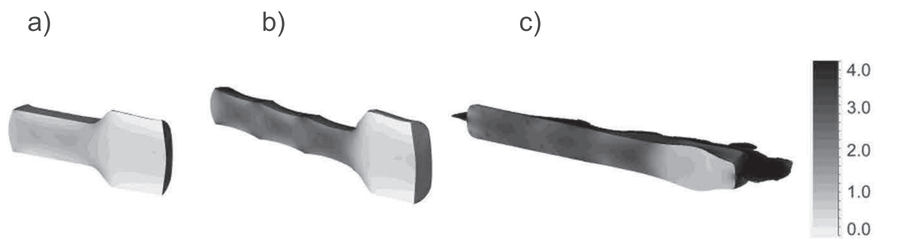

Figure 2 Numerically estimated progression of effective strain in major forging stages (a-c)

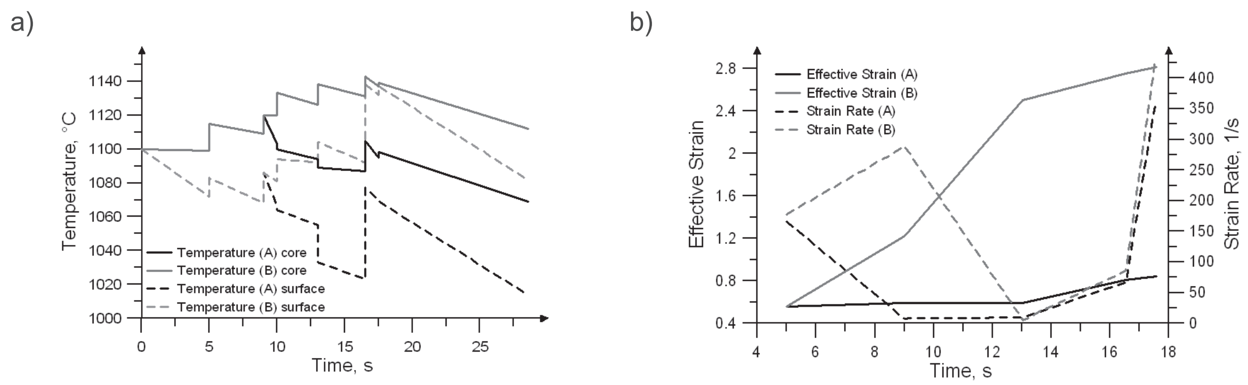

Figure 3 Numerically established history of: a) temperature, b) effective strain and effective strain rate

Due to a different deformation path, the observed state-of-strain related differences are more pronounced, as the shank exhibits nearly four times higher total strain level then the head. These variations formed the basis for further analysis, which results in graphs shown in **Figure 4.** The obtained plots fit to the temperature diagrams, reflecting dynamic behavior in the analyzed points. After initial mild-stroke deformation, the recrystallized grain grew, to be further refined correspondingly to strain-induced driving force and initial austenite grain [9]. What is of the greatest importance in the standpoint of direct heat treatment is the extent of the differences within the volume. Contrary to the typical press-forging process, where in a single stroke of the ram all volume is subject to deformation, in hammer forging multiple blow sequence is encountered, which results in discontinuous realization of the plastic work. As a consequence, dynamic response of the material i.e. microstructure development, not only differ from point to point, but runs independently in time. Thus, while one portion is being deformed, the other one is fully recrystallized or undergoes grain growth before or after deformation. However, comparing the diagrams it can be concluded that the material behavior in the final stages the whole forging sequence eventually is similar between locations on the length and on the cross-sections. The condition of the austenite is reflected by the predicted grain size of the transformation product (**Table 2**). The divergence between locations reaches several microns, which is in agreement with results of the metallographic work (**Figure 5**). The microstructure is composed of acicular ferrite with isolated islands of pearlite, which show up in the shank, that is, where the cooling rate was higher. In both sections (A and B), large non-recrystallized grains are present, which is the aftermath of inhibiting action of precipitates. The fact that they form greater fraction in the section B is due to smaller strain increment in the last stages of forging. Sellars-Beynon model fits better to the results, but non-equiaxed acicular structure justifies the discrepancy

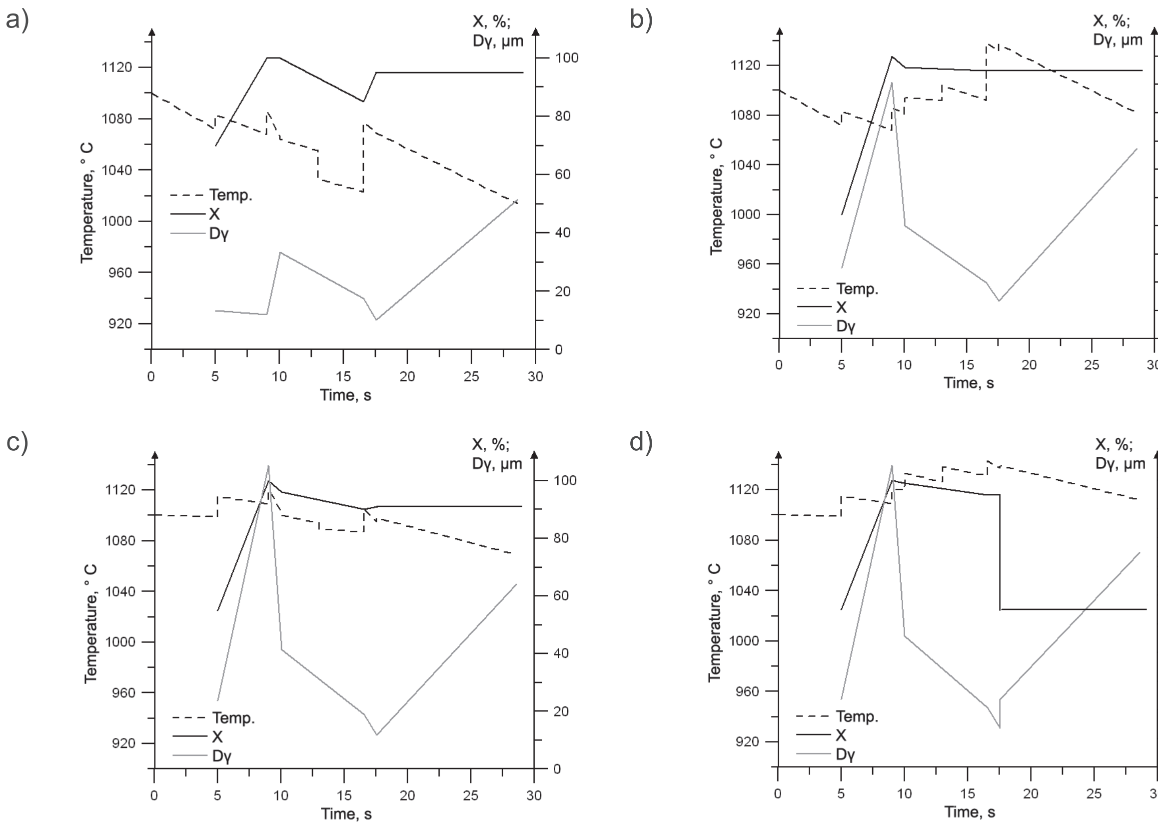

Figure 4 Results of calculation of dynamic recrystallized austenite grain size and recrystallized fraction for various locations: a), b) surface, c), d) core of the head (point A) and the shank (point B), respectively

Table 2 Calculated average ferrite grain size after direct cooling

location		Ferrite grain, D_α, μm	
		Hodgson-Gibbs model	Sellars-Beynon model
section A (head)	surface	62.20	15.14
	core	63.95	15.76
section B (shank)	surface	64.35	16.56
	core	65.24	17.34

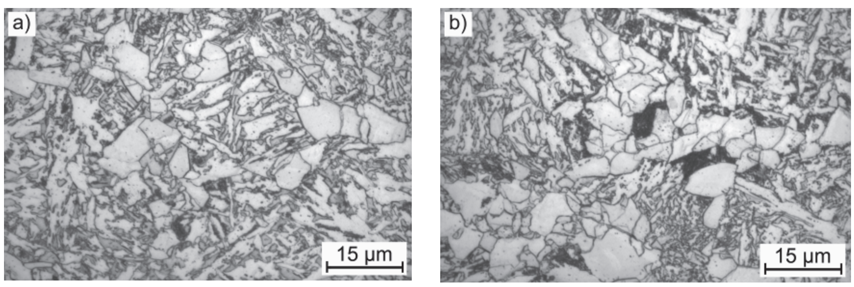

Figure 5 Reference microstructure of the analyzed forged part in section A: a) surface, b) core

4. CONCLUSIONS

The results of application of basic models JMAK presented in the study, indicate applicability of microstructure development analysis in design of forging microalloyed steel on hammers under conditions of controlled thermomechnaical processing. Thereby, they lead to several major conclusions:

Increase in the microalloying elements, mainly Nb, inhibits dynamic recrystallization, necessitating higher level of threshold strain required for that process to occur, which obstruct the kinetics of the process.The microalloying elements inhibits austenite transformation by effective fixing the transformation fronts.

One of the problems featuring processes of forging microalloyed steels is big nonuformity and homogeneity of microstructure diring the forging cycle, which enhances the mechanical nonuniformity related to local changes of flow stress, which leads to excessive stess gradients in the volume subjected to deformation.

Deacrese of the forging temperature influences the kinetics of dynamic recrystallization slowing down the process rate, increasing the amount of the energy accumulated in the material, supplying thus the driving force for possible static recrystallization and eventual austenite grain refinement.

All these effects call for more careful than for traditional grades, selection of forging process parameters. Proper practice here is aid of computer simulation with assumption of microstructure evolution models for microalloyed steels.`

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