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MODELING THE DYNAMICALLY RECRYSTALLIZED GRAIN SIZE EVOLUTION OF A SUPERALLOY

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Abstract. The evolution of the UNS 6617 alloy microstructure during the hot deformation and the effect of hot deformation parameters on the grain structure and on the dynamic recrystallization were studied. A mathematical model which is capable to calculate the dynamically recrystallized austenite grain size of the alloy was built.

1. Introduction

Development of the energy industry and turbine technology is characterized by a continuous increase of operating temperatures, which became possible owing to intensive development of heat resistant steels and superalloys capable of operating at high temperatures concurrently with aggressive environments [1]. It is known that austenite grain size is one of the most important technological features which also influence the end-product properties. For the development of optimal regimes of hot deformation which could provide necessary grain size, first it is appropriate to realize the physical modeling of metal forming in a laboratory by means of the plastometer.

The purpose of this paper is to study the evolution of the UNS 6617 alloy microstructure during the hot deformation and estimation of the effect of the hot deformation parameters on the grain structure and on the dynamic recrystallization, as well as to build a mathematical model which will be capable to calculate the dynamically recrystallized austenite grain size of the alloy. Calculations of the hot deformation activation energy of the alloy were made, and a mathematical model of dynamic recrystallization using a Zener–Hollomon parameter was developed.

2. Experimental

Specimens for torsion tests were cut from forgings. In the experiments all the samples were heated to 1150 °C, soaked to obtain equal temperature over the cross section, then some of the specimens were deformed at 1150 °C and all the others were deformed after cooling to 1050 °C or 900 °C. Strain rates (έ) were 0.5 s^{-1} and 5 s^{-1}, strains (ε) were 0.2 – 0.9. Immediately after the deformation all the specimens were water quenched.

The microstructure of the deformed specimens was studied on polish sections made close to the cylindrical surface of the specimen and then compared with the initial structure.

Stresses and strains were calculated in accordance with Von Mises criterion [2]:

$$\varepsilon = \frac{2\pi RN}{\sqrt{3L}}, \qquad (1)$$

$$\sigma = \frac{\sqrt{3}}{2\pi R^3}\left(3C + N\frac{dC}{dN}\right), \tag{2}$$

where N – number of turns, C – torque.

3. Discussion

In Fig. 1 the stress-strain curves obtained by the torsion tests are shown. The initial microstructure of the alloy after heating to 1150 ºC, and some of the microstructures after deformation are shown in Fig. 2.

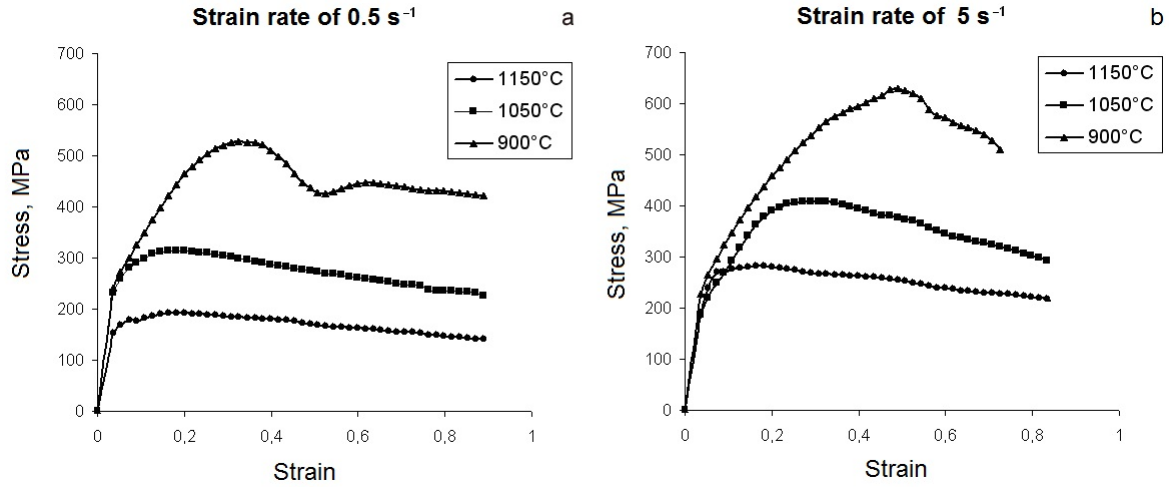


Fig. 1. Stress-strain curves at different strain rates: a – 0.5 s^{-1}, b – 5 s^{-1}.

As can be seen from the curves shown in Fig. 1, the peak stress and peak strain values increase with the increasing of strain rate. There is a significant stress growth with the decreasing of deformation temperature, and this tendency augments to a greater extent with increasing of strain rate.

Microstructure analysis shows a decrease in average grain size of the deformed samples compared to the initial grain size (Fig. 2a), meanwhile elongation of grains and appearance of the recrystallized grains take place (Figs. 2b, 2c, 2d). Lowering the deformation temperature is accompanied by increased elongation and decreased volume fraction of recrystallization (Fig. 2d). With the growth of deformation temperature, strain and strain rate, the volume fraction of recrystallization increases.

The volume fraction of recrystallized grains, with sizes of up to 50 microns, enlarges with increasing of deformation temperature, stress, and strain rate.

Deformation induced decrease of the average grain size (compared to the initial state) can be associated with beginning of the dynamic recrystallization and, therefore, appearance of recrystallized grains and with the formation of the substructure with high angle misorientation of subgrains as it was noted in [3].

During the early stages of plastic deformation the main role is played by individual dislocations; their monotonically increasing density does not exceed 10^8 - 10^9 cm^{-2} [3]. With the increasing of strain the dislocation ensembles with different types of structures are formed (from cellular to fragmented structure) with different sizes of cells and misorientation angles. The latter may reach the values corresponding to high angle misorientation, and with a certain

combination of deformation temperature, strain and strain rate the recrystallized grains are formed; this fact is especially evident in the microstructure of the specimens subjected to deformation at 1050 °C and 1150 °C (see Figs. 2b, 2c, 2d).

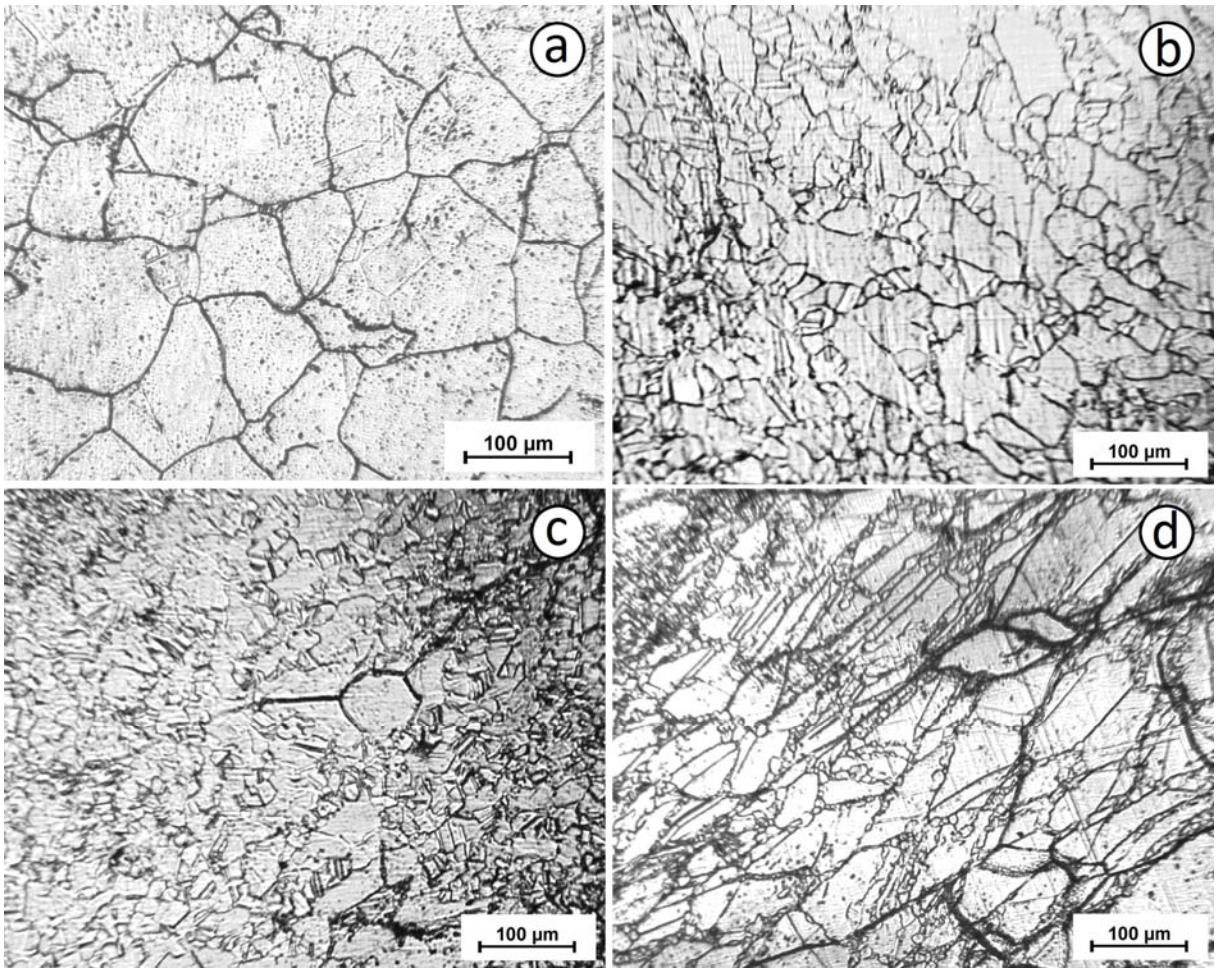


Fig. 2. Microstrustructure of the investigated alloy: a)– initial structure (T_{heat} = 1150 ºC);
b)– structure at ε = 0.4, T_{def} = 1150 °C, έ = 0.5 s^{-1};
c)– structure at ε = 0.4, T_{def} = 1150 °C, έ = 5 s^{-1};
d)– structure at ε = 0.9, T_{def} = 1050 °C, έ = 5 s^{-1}.

Using the results of physical modeling for the calculation of the deformation regimes which can provide a desirable grain size, first it is advisable to calculate the hot deformation activation energy [4]. Constitutive equations are commonly used to calculate the activation energy [5]. Equation (3) shown below is the base equation.

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = f(\sigma), \tag{3}$$

where Z – the Zener–Hollomon parameter, $\dot{\varepsilon}$ – strain rate, Q – hot deformation activation energy, R – universal gas constant (8.31 $J \cdot mol^{-1} \cdot K^{-1}$), T – deformation temperature

In the constitutive equations, Z parameter may be considered as a function of stress. In [6, 7] the power–law function was proposed for calculation the Zener–Hollomon parameter:

$$Z = f(\sigma) = B\sigma_p^k, \tag{4}$$

where σ_p – peak stress; k and B – approximation parameters

In [7] in addition to power–law function the exponential function was used:

$$Z = f(\sigma) = C\exp(\beta\sigma_p), \tag{5}$$

where σ_p – peak stress; C and β – approximation parameters

According to Sellars and Tegart [8] the using of the hyperbolic sine gives more adequate approximation of the Z–σ–relation for all values of stress and all types of hot deformation:

$$Z = f(\sigma) = A[\sin(\alpha\sigma_p)]^n, \tag{6}$$

where σ_p – peak stress; A, α and n– approximation parameters. However, for the approximation by formula (6) the parameters of equations (4) and (5) must be calculated. After substituting expressions (4), (5), (6) into equation (3) and after taking the logarithm the following is obtained:

$$\ln\dot{\varepsilon} + \frac{Q}{R}\left(\frac{1}{T}\right) = \ln B + k\ln\sigma_p, \tag{7}$$

$$\ln\dot{\varepsilon} + \frac{Q}{R}\left(\frac{1}{T}\right) = \ln C + \beta\sigma_p, \tag{8}$$

$$\ln\dot{\varepsilon} + \frac{Q}{R}\left(\frac{1}{T}\right) = \ln A + n\ln[\sinh(\alpha\sigma_p)]. \tag{9}$$

Parameter α is an approximation parameter which is independent of temperature [2], which make $\ln\dot{\varepsilon} - \ln[\sinh(\alpha\sigma_p)]$ plots linear and parallel [5]:

$$\alpha \approx \frac{\beta}{k}. \tag{10}$$

Equations (7), (8), (9) are appeared to be linear at a constant temperature [9], thus the coefficients k, β and n are the slopes of the plots of the above mentioned equations:

$$k = \left[\frac{\partial\ln\dot{\varepsilon}}{\partial\ln[\sigma_p]}\right]_{T=const}, \tag{11}$$

$$\beta = \left[\frac{\partial\ln\dot{\varepsilon}}{\partial\ln\sigma_p}\right]_{T=const}, \tag{12}$$

$$n = \left[\frac{\partial\ln\dot{\varepsilon}}{\partial\ln[\sinh(\alpha\sigma_p)]}\right]_{T=const}. \tag{13}$$

Using the data obtained by torsion–tests, that is, knowing T, $\dot{\varepsilon}$ and σ_p for each of the stress–strain curve (Fig. 1), the slopes of all the lines (Fig. 3) were found.

The average values of k and β are 9.2543 and 0.02424, respectively.

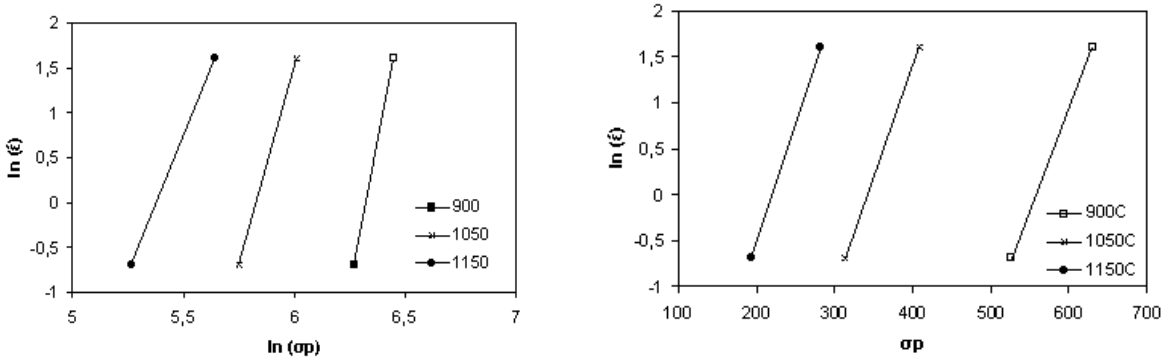
Using these average values of k and β and equation (10) the value of α was calculated: α=0.00262.

The obtained value of the parameter α was used in (13) to find the parameters n (the slopes of the ln$\dot{\varepsilon}$–ln[sinh($\alpha\sigma_p$)] plots). The obtained average value of n is 6.2628.

Equation (9) is linear at a constant strain rate – this equation was used to determine the activation energy, which appears to be a slope of the line nln[sinh(ασp)]–1/T:

$$Q = Rn\left[\frac{\partial \ln \sinh\left(\alpha\sigma_p\right)}{\partial\left(\frac{1}{\mathrm{T}}\right)}\right]_{\dot{\varepsilon}=const}. \qquad (14)$$

Thus to find the activation energy according to approximation (6), the slopes of the lines (Fig. 4) need to be found (similar to previous calculations of the parameters k, b and n) plotted using three points with the aid of the least squares method, and then calculate the average slope for the two strain rates, which will be the value of the hot deformation activation energy for the investigated alloy.



a *b*

Fig. 3. Plots used to calculate the slopes:
a)– dependence ln $\dot{\varepsilon}$ of ln σ_p used for calculating parameter k;
b)– dependence ln $\dot{\varepsilon}$ of σ_p for calculating parameter β.

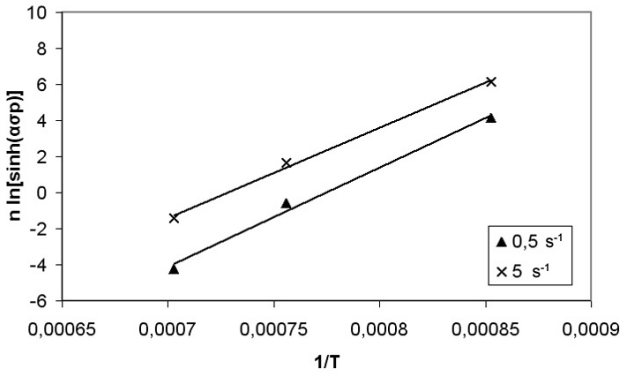


Fig. 4. Plots $n$ln[sinh($\alpha\sigma_p$)] – 1/T used for calculation of activation energy, obtained by the least squares method.

The obtained mean value of the activation energy is 437 kJ/mol, which exceeds the value of the activation energy of pure nickel, 297 kJ/mol, reported in [8]. Next, using formula (3) the values of Z for each deformation regime were calculated (Table 1).

Table 1. Values of the Zener–Holllomon parameter calculated for hot deformation.

T, ºC	$\dot{\varepsilon} = 0.5\ s^{-1}$	$\dot{\varepsilon} = 5\ s^{-1}$
900	$1.512 \cdot 10^{19}$	$1.512 \cdot 10^{20}$
1050	$9.353 \cdot 10^{16}$	$9.353 \cdot 10^{17}$
1150	$5.717 \cdot 10^{15}$	$5.717 \cdot 10^{16}$

The following equation [4, 10] was used to build a mathematical model allowing the calculation of recrystallized grain size:

$$d_{dyn} = A_{dyn} Z^{n_{dyn}}, \tag{15}$$

where d_{dyn} – the dynamically recrystallized grain size, A_{dyn}, n_{dyn} – material constants.

Histograms of the dynamically recrystallized grain size distribution were plotted. The distribution's medians were considered to be the values of the recrystallized grain size corresponding to each deformation regime. As a result of approximation of the d_{dyn}–Z dependence the following coefficients of equation (15) were obtained: $A_{dyn} = 9.851$, $n_{dyn} = 0.014$. Thus for the alloy in question the following model was obtained:

$$d_{dyn} = 9{,}851 \cdot Z^{0{,}014}. \tag{16}$$

Using the obtained model, the sizes of dynamically recrystallized grains for each deformation regime were calculated. The calculation results and the actual data are presented in Fig. 5. As can be seen the best agreement is provided at low degrees of deformation ($\varepsilon = 0.2$), where the difference between the actual values in relation to the calculated ones does not exceed 6.5 %, and at the deformation at high temperatures (1150 °C), where difference is not more than 14.6 %. Less agreement (more than 14.6 %) of the calculated and experimental data in the other cases can be attributed to the fact that the activation energy and coefficients n and b are temperature dependent parameters, the modeling of which, or taking into account the temperature factor, is the subject of further research.

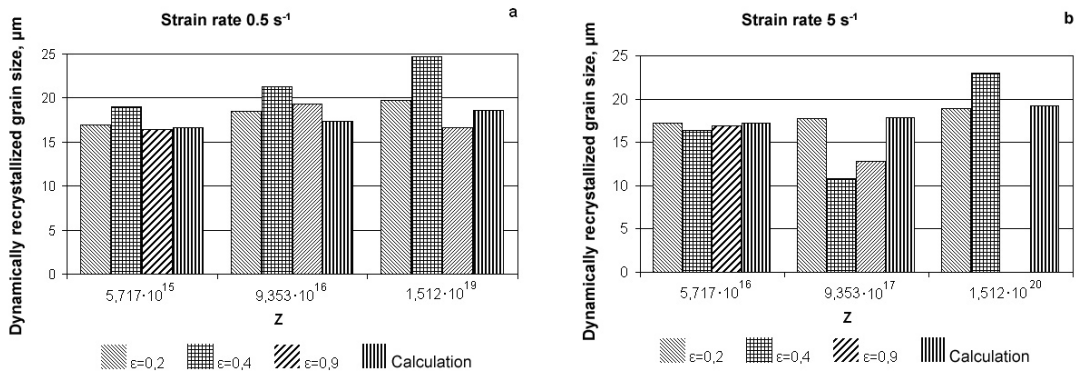


Fig. 5. Dependence of dynamically recrystallized grain size on the parameter Z for different strain rates: a – 0.5 s^{-1}, b – 5 s^{-1}

4. Conclusions

1) It is found that the size of dynamically recrystallized grains varies from 3 to 50 microns depending on the deformation temperature, strain and strain rate.

2) A mathematical model of dynamic recrystallization was built, which provides calculating the dynamically recrystallized grain size of the alloy with error of 6.5% at $\varepsilon = 0.2$ for all the investigated temperatures and strain rates. At a temperature of 1150°C and strain rate of 5 s^{-1}, the error of calculation is less than 4.6%; at strain rate 0.5 s^{-1} – the error is no more than 14.6%. At a temperature of 1050°C and strain rate of 5 s^{-1}, the calculation error does not exceed 39.7%; at strain rate 0.5 s^{-1} – it is no more than 22.9%.

3) The results of this study may be used to develop the regimes of hot deformation, allowing obtain a necessary dynamically recrystallized grain size.

References

[1] S.B. Maslenkov, *Heat Resistant Steels and Alloys* (Metallurgiya, Moscow, 1983), in Russian.

[2] S.F. Medina, C.A. Hernández // *Acta Mater*. **44** (1996) 137.

[3] G.E. Kodzhaspirov, A.I. Rudskoi, V.V. Rybin, *Physical Basis of Energy Saving Technologies and Manufacturing of Products Using Plastic Deformation* (Nauka, St. Petersburg, 2006), in Russian.

[4] T. Matsui, H. Takizawa, H. Kikuchi, S. Wakita // *Superalloys* (2000) 127.

[5] H. Mirzadeh, A. Najafizadeh, M. Moazeny // *Metallurgical and Materials Transactions A*, **40** (2009) 12.

[6] H. Mirzadeh, A. Najafizadeh, M. Moazeny // *Materials Science and Technology* **26** (2010) 501.

[7] A. Momeni, K. Dehghani // *Metallurgical and Materials Transactions A*, Online First™, 8 December 2010.

[8] C. M. Sellars, W. J. Tegart, // *M. Mem. Sci. Rev. Metallurgie* **63** (1966).

[9] J.L. Uvira, J.J. Jonas // *Trans. Metall. Soc. AIME* **242** (1968) 1619.

[10] P.A. Manohar, K. Lim, A.D. Rollett, Y. Lee // *Materials Science Forum* **426–432** (2003) 3789.