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MATHEMATICAL MODELING OF PHENOMENA OF DYNAMIC RECRYSTALLIZATION DURING HOT PLASTIC DEFORMATION IN HIGH-CARBON BAINITIC STEEL

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Based on the research results, coefficients were determined in constitutive equations, describing the kinetics of dynamic recrystallization in high-carbon bainitic steel during hot deformation. The developed mathematical model takes into account the dependence of changing kinetics in the size evolution of the initial austenite grains, the value of strain, strain rate, temperature and time. Physical simulations were carried out on rectangular specimens measuring 10 × 15 × 20 mm. Compression tests with a plane state of deformation were carried out using a Gleeble 3800.

Key words: plastic deformation, high - carbon bainite steel, physical modeling, mathematical modeling, dynamic recrystallization

INTRODUCTION

Currently, dynamically developing industry has led to the increased demand for new types of materials. At present, steel sheets are produced from a type of alloys, which are improved by heat treatment producing high strength, characterized by a hardness of maximum 600 HV, but with limited ductility that does not guarantee high impact resistance. The Institute for Ferrous Metallurgy in Gliwice has developed a new type of steel, which is a high-carbon bainitic steel. The steel has high development potential as it allows the achievement of very high level of strength (tensile strength up to 2,5 GPa) and at the same time good ductility, with a relatively small addition of alloying elements (cumulative ratio of 5 - 6 % by mass) [1]. Research on a new generation of high-carbon bainitic steel has been conducted globally for several years and the results so far indicate a high probability of practical application of this steel in the defense, mining and machinery production industries [2]. There is no information in the scientific literature on phenomena occurring during strain in high-carbon bainitic steel. This study attempts to mathematically describe the kinetics of dynamic recrystallization, as well as the size of dynamically recrystallized grain.

METHODOLOGY AND RESEARCH MATERIAL

The material used for this study is high-carbon bainitic steel that was developed at the Institute for Ferrous Metallurgy in Gliwice, with chemical composition shown in Table 1.

Table 1 **The chemical composition of high-carbon bainitic steel used in this study / mass % [1]**

C	Mn	Si	Mo	Co	V	Al
0,83	2,20	1,65	0,39	1,58	0,092	0,039

A range of studies was conducted in order to determine the coefficients in the constitutive equations used for modelling mathematical phenomena that occur during hot deformation of the tested steel grade. At the beginning, the initial austenite grain size was defined, on the basis of experimental studies. The specimens were heated to temperatures between 900 - 1 100 °C for 60 s and then cooled with air at a speed that ensured freezing of the structure. Table 2 shows the results of metallographic examinations under which the initial austenite grain size was defined.

Table 2 **The initial austenite grain size of the alloy**

Temperature / °C	Grain size / μm
900	29,1
950	31,7
1 000	32,1
1 050	89,4
1 100	92,8

To determine the parameters, which are necessary to initiate dynamic recrystallization, it is important to know the real course of plastic flow curves for steel. With the proper analysis of plastic flow curve, it can be determined whether there is a dynamic recrystallization of the steel. If there is, then the value of the critical strain that is required for the initiation of the process can also be determined, and subsequently a mathematical description of its kinetics will be made. During the analysis of plastic flow curves, a problem arises from

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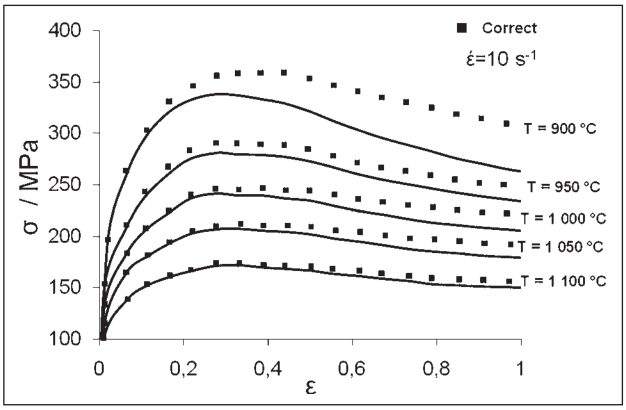

Figure 1 Plastic flow curves of high-carbon bainitic steel with strain rate of 10 s^{-1} at a temperature of 900 - 1 100 °C

the uncontrolled temperature increase of the specimen resulting from strain. To describe the influence of temperature and strain rate on the value of flow stress, the following equation was used (1) [3]:

$$\sigma_p = f\left(\varepsilon, \dot{\varepsilon}\right) \cdot \dot{\varepsilon}^{\frac{c_1}{T}} \cdot \exp\left(\frac{c_2}{T}\right) \qquad (1)$$

where: c_1, c_2 – experimentally determined coefficients dependent on the material.

Coefficients developed (c_1=-322,9; c_2=6 408,9) in equation (1) allowed the introduction of correction for metal flow stress aimed at the value of a given deformation, with the assumption of temperature and strain rate. An example of adjusted plastic flow curves of high-carbon bainitic steel is shown in Figure 1.

The phenomenon of dynamic recrystallization in the microstructure that takes place during hot deformation of steel was analyzed in two stages in the temperature range of 900 - 1 100 °C and a strain rate of 0,1 - 10 s^{-1}. In the first step, on the basis of the developed flow curve that considered temperature correction and strain rate, the strain parameters essential for the phenomenon of dynamic recrystallization were determined. For this purpose, the dependency of reinforcement factor (θ) in the stress function was determined, which describes the behaviour of the material during hot deformation [4-7]:

$$\theta = d\sigma / d\varepsilon \qquad (2)$$

where: σ – value of stress flow, ε – the intensity of strain.

The kinetics of recrystallization dynamics in high-carbon bainitic steel is described by the following equation:

$$X_{DRX} = 1 - \exp\left[-A_{DRX}\left(\frac{\varepsilon - \varepsilon_{kr}}{\varepsilon_p}\right)^{n_{DRX}}\right] \qquad (3)$$

where: ε – strain, ε_{kr} – critical strain determined on the basis of reinforcement, ε_p – peak strain defined on the basis of the flow curve, A_{DRX}, n_{DRX} - material constant for the particular steel grade.

In the second stage of the study, the constitutive equations were expanded, describing peak strain (ε_p), critical strain (ε_{kr}) and strain ($\varepsilon_{0,5}$) corresponding to 50 % of the dynamic recrystallization phase, taking into account the initial austenite grain size and Zener-Hollomon parameters [8, 9]:

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \qquad (4)$$

where: $\dot{\varepsilon}$ - strain rate, Q - activation energy, R - gas constant, T - temperature.

The value of activation energy occurring in equation (4) was determined for a temperature range of 900 - 1 100 °C and a strain rate between 0,1 - 10 s^{-1} in accordance with equation [4, 5]:

$$Q = R \cdot \left[\frac{\partial\left(\ln\left(\sinh\left(\alpha\sigma_p\right)\right)\right)}{\partial\left(1/T\right)}\right]_{\dot{\varepsilon}} \cdot \left[\frac{\partial \ln \dot{\varepsilon}}{\partial\left(\ln\left(\sinh\left(\alpha\sigma_p\right)\right)\right)}\right]_T \qquad (5)$$

where: σ_p - yield stress, α – material constant that is empirically determined for the test grade.

In analysis of the right side of equation (5), it can be stated that the first part of the equation is the slope of the dependency graph of the ln(sinh($\alpha\sigma_p$)) from 1/T, while the second part of the equation presents an inverse slope that reflects the course of dependency of the ln(sinh($\alpha\sigma_p$)) from ln $\dot{\varepsilon}$.

In the second part of equation (5), there is a material constant α, which can be determined from the following equation [4, 5]:

$$\alpha = \frac{\beta}{n'} \qquad (6)$$

The values of material constant n' and β can be determined by an appropriate dependency slope of $\ln \dot{\varepsilon} = f\left(\ln \sigma_p\right)$ and a dependency slope of $\ln \dot{\varepsilon} = f\left(\sigma_p\right)$. From the dependence presented in determined by equation (5), the activation energy of high-carbon bainitic steel was 385,44 kJ/mol. Determined on the basis of Zener- Holloman (eq. 4) parameter and the initial grain size of the austenite, the values of the coefficients were determined in the constitutive equation that describes peak strain at ε_p of high-carbon bainitic steel. To determine the coefficients, the basic dependency was used, which is presented in the Figures 2 and 3.

Finally, the mathematical model of the constitutive equation describing peak strain ε_p for the tested steel is as follows:

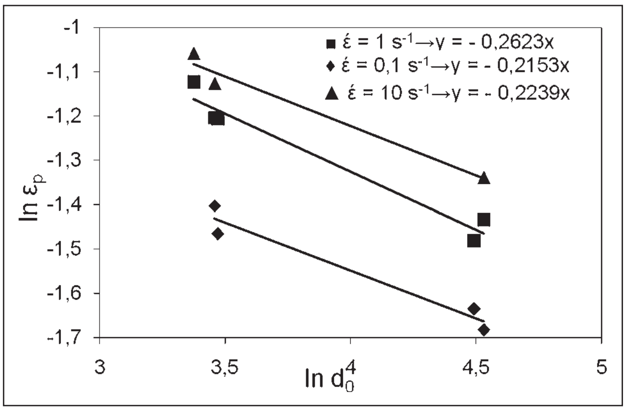

Figure 2 The dependence of peak strain (ln ε_p) from an initial austenite grain size (ln d_0), according to which the average value of the exponent of the initial austenite grain size was determined

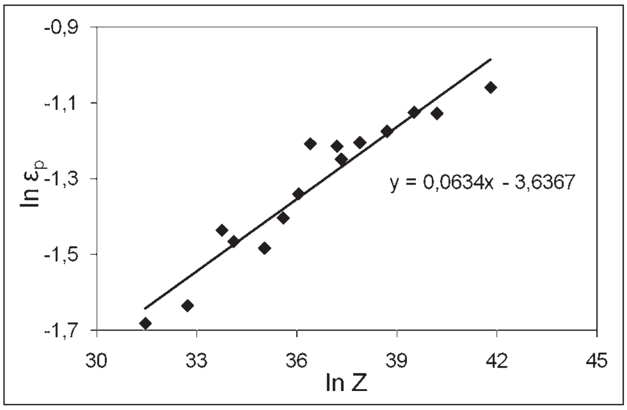

Figure 3 The dependence of peak strain (ln ε_p) from the Zener-Hollomon parameter (ln Z), according to which the value of the exponent Zener-Hollomon parameter was determined

$$\varepsilon_p = 0{,}0656 \times d_0^{-0{,}2338} \times Z^{0{,}0634} \qquad (7)$$

The material constant *'c'* in equation (8) was determined as follows:

$$c = \frac{\varepsilon_{kr}}{\varepsilon_p} = 0{,}6220 \qquad (8)$$

The value of the constant *'c'* in (equation 8) is an average value quotient of ε_{kr} / ε_p, determined for temperature 900 - 1 100 °C and strain rate 0,1 - 10 s^{-1}. The constitutive equation finishing the critical strain ε_{kr} was determined based on equations (7) and (8) and the final for ε_{kr} is as follows:

$$\varepsilon_{kr} = 0{,}0408 \times d_0^{-0{,}2338} \times Z^{0{,}0634} \qquad (9)$$

Another important equation in the mathematical model describing the dynamic recrystallization phenomenon is the equation for defining the strain $\varepsilon_{0,5}$, at which the material is at the 50 % phase of dynamic recrystallization [10-13]. In order to determine the value of the strain, the equation that described function of the initial austenite grain size and Zener-Hollomon parameter was used. The values of the coefficients occurring in the equation were determined from the graphical dependence, shown in Figures 4 and 5.

Finally for the investigated steel, strain $\varepsilon_{0.5}$ was described by the equation:

$$\varepsilon_{0,5} = 0{,}1333 \times d_0^{-0{,}2434} \times Z^{0{,}064} \qquad (10)$$

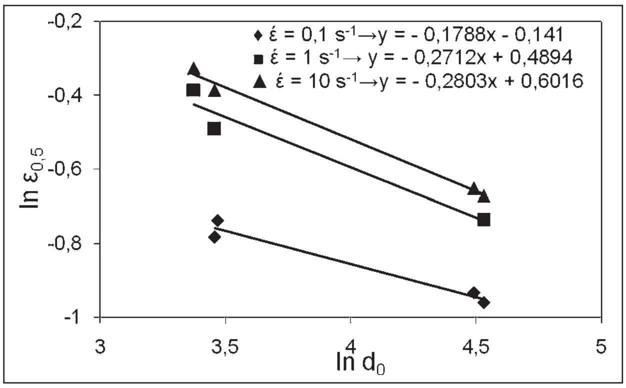

Figure 4 The dependence of half recrystallization strain (ln $\varepsilon_{0,5}$) from an initial austenite grain size (ln d_0)

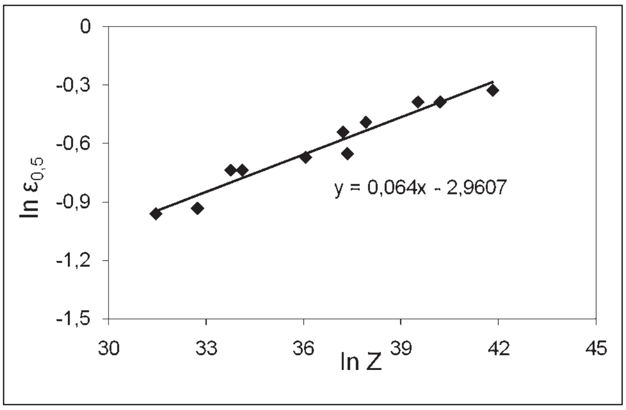

Figure 5 The dependence of half recrystallization strain (ln $\varepsilon_{0,5}$) from the Zener-Hollomon parameter (ln Z)

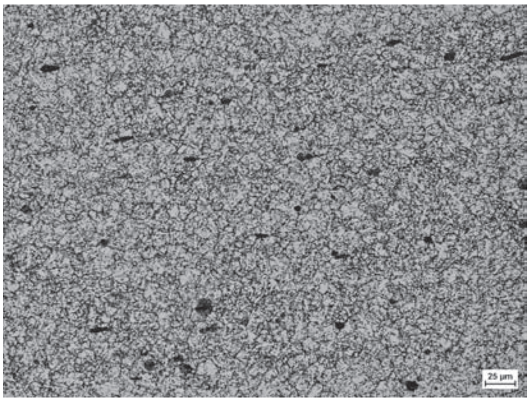

Figure 6 The microstructure of the specimens after experimental testing for T = 900 °C; ε = 0,28; $\dot{\varepsilon}$ = 0,1 s^{-1} $d\gamma$ = 23,7 µm; area 200x; Etching with picric acid ($C_6H_3N_3O_7$)

Using the determined constitutive equations (9 and 10) which are describing the dependence of ε_{kr} and $\varepsilon_{0,5}$ of the initial grain size and the Zener-Hollomon parameter, kinetics of dynamic recrystallization can be described with dependence:

$$X_{DRX}(t) = 1 - \exp\left[-4{,}3802\left(\frac{\varepsilon - \varepsilon_{kr}}{\varepsilon_{0,5} - \varepsilon_{kr}}\right)^{2{,}2394}\right] \qquad (11)$$

Figure 6 shows an example of metallographic imaging conducted during experimental studies.

Linear regression of dependency from lnd_{DRX} function lnZ (fig.7) was performed in order to determine the coefficients.

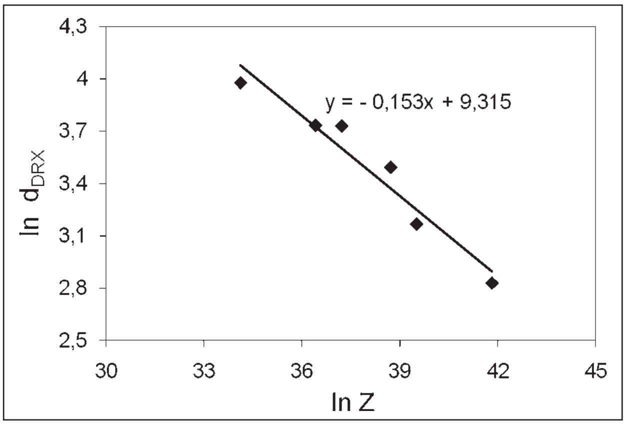

Figure 7 The dependence of dynamically recrystallized grains (ln d_{DRX}) from the Zener-Hollomon parameter (ln Z)

On the basis of the linearization, recrystallized grain size, which results from dynamic recrystallization of high - carbon bainitic steel is described by the following equation:

$$d_{DRX} = 11111{,}1 \times Z^{-0{,}1535} \tag{12}$$

SUMMARY

High-carbon bainitic steel is characterized by excellent mechanical properties and plasticity thanks to the structure of bainite in the form of plates whose thickness is in the range of nanometers. Thanks to this it is starting to play a more and more important role among alloy steels. This steel is of particular relevance to the defense industry, where it can be used for armor plating, with very good results. Based on the results of these experimental studies, coefficients and material constants in the constitutive equations were developed, thereby, describing the phenomena occurring during strain caused by heat. The same mathematical description was made for the kinetics of dynamic recrystallization. Coefficients and material constants in the equations describing the grain size achieved in dynamic recrystallization were also developed. Based on the analysis, it was found that for the tested steel, dynamic recrystallization is more intensive when deformation increases. The value of critical strain (ε_{kr}) at a strain rate of 0,1 s^{-1} is in the range 0,11 - 0,2 at temperatures in the range 900 - 1 100 °C.

REFERENCES

[1] Patent application of the Institute of Ferrous Metallurgy to the The Patent Office of Republic of Poland: No. P.394037 - Stal bainityczno-austenityczna i sposób wytwarzania z tej stali blach, No. Nr P.396431 – Sposób obróbki cieplnej stali bainityczno-austenityczne

[2] Skuza Z., Prusak R., Kolmasiak C.: Restructuring of the metallurgical industry in the aspect of economics system change and integration with the European Union, Metallurgy 46 (2007) 3, 221-224

[3] Knapiński M., Kawałek A., Dyja H., Kwapisz M.: Krzywe umocnienia stali mikrostopowej przeznaczonej do produkcji blach grubych w kategorii wytrzymałościowej X80, Hutnik Wiadomości Hutnicze 9 (2011), 818-821

[4] Shaban M., Eghbali B.: Determination of critical conditions for dynamic recrystallization of a microalloyed steel, Materials Science and Engineering A 527 (2010), 4320-4325

[5] Liu J., Cui Z., Ruan L.: A new kinetics model of dynamic recrystallization for magnesium alloy AZ31B, Materials Science and Engineering A 529 (2011), 300-310

[6] John J.J, Xavier Q, Lan J, Etienne M: The Avrami kinetics of dynamic recrystallization, Acta Materialia 57 (2009), 2748-2756

[7] Mirzadeh H, Najafizadeh A.: Prediction of the critical conditions for initiation of dynamic recrystallization, Materials and Design 31 (2010), 1174-1179

[8] Knapinski M., Dyja H., Kawalek A., Fraczek T., Laber K.: Analysis of the microstructure evolution during thermomechanical treatment of the steel plates in grade X80-X100, Metalurgija 52 (2013) 2, 239-242

[9] Chen F., Cui Z., Chen S.: Recrystallization of 30Cr2Ni4MoV ultra-super-critical rotor steel during hot deformation. Part I: Dynamic recrystallization, Materials Science and Engineering A 528 (2011), 5073–5080

[10] Stradomski, G.; Dyja, H.; Stradomski, Z.: The microstructure change during modeling of conventional and thermomechanical rolling of S355 steel bars, Materials Science Forum 638-642 (2010), 2573-2578

[11] Stradomski G., Rydz D., Dyja, H.: Changes of microstructure after physical modeling of conventional and normalising rolling of bars from carbon-manganese steel, Steel research international (2008), 203-207

[12] Kuziak R., Pidvysots’kyy V., Zalecki W., Molenda R., Łapczyński Z.: Symulacja numeryczna i symulacja fizyczna w skali laboratoryjnej zmian mikrostruktury austenitu w procesie walcowania blach ze stali konstrukcyjnej wielofazowej, Prace Instytutu Metalurgii Żelaza, 64 (2012) 1, 17-23

[13] Beynon J.H., Sellars C.M.: Modelling microstructure and its effects during multipass hot rolling, ISIJ Int. 32 (1992), 359-367

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