THE MODEL OF AUSTENITE MICROSTRUCTURE OF HIGH-CARBON STEEL

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Abstract

The paper present the concept of a mathematical model for predicting changes in the austenite microstructure of high-carbon steel. Based of physical modeling changes of microstructure the mathematical model for predicting changes in the austenite microstructure was built. Model is based on the classic Sellars equations developed by taking into account the parameters of plastic forming processes and their impact on the processes occurring in the deformed steel. The coefficients of mathematical equations describing the evolution of deformed austenite microstructure were calculated based on the results of experimental studies carried out in the Institute of Plastic Working and Safety Engineering Czestochowa University of Technology. For the verification of the accuracy developed model laboratory studies were conducted using a metallurgical processes simulator Gleeble 3800. Comparison of the results obtained in the theoretical and experimental studies have confirmed good agreement developed model of the microstructure evolution for high-carbon steel.

Keywords: Microstructure prediction, mathematical model of austenite evolution, hot rolling, high-carbon steel

1. INTRODUCTION

The high-carbon steel rods are used for wire ropes and steel cords. They are produced in a continuous rolling mills with accelerated cooling device. High carbon wire rods should have a uniform pearlite structure with uniformly distributed cementite plates having a thickness of 0.02÷ 0.04 μm and the distances between the plates at 0.1÷0.2 μm [1]. The pearlitic morphology depends on size of austenite grains. The main aim of rolling process is reduction of cross section and grain of austenite. Properly designed technology of rolling enables size reduction of austenite, which by the way accelerated, controlled cooling it possible to obtain a finished product pearlite structure of the intended morphology. For prediction of softening phenomena and reduction of austenite grain size a model of evolution austenite microstructure are required. A lot of works describing a modeling of the microstructure and mechanical properties of steel formed by plastic working have been published; nevertheless, the problem of predicting of them for products after hot rolling and cooling has not been satisfactorily solved yet. A lot of models are proposed in literature [2 ÷ 4], which can be used for predicting the development of microstructure for particular groups of steel. However, the application of a general model for a specific steel grade causes the simulation results to deviate from the actual results. Hence, there is a need for adapting the general model for a selected steel grade. The present study adopts the Sellars solution for high-carbon steel to the prediction of phenomena occurring in the steel and the grain size of austenite formed by means of multi-stage deformation.

2. PHYSICAL MODELING OF MICROSTRUCTURE EVOLUTION

For determine the influence of deformation on microstructure of high-carbon steel physical simulations using a simulator metallurgical Gleeble 3800 were done. The samples were heated to temperature of 1100 °C at a rate of 5 °C / s, holding for 10 minutes, and then cooled down at 10 °C / s to the deformation temperature (800÷1100 °C). Physical simulation of deformation were carried out for wide range of deformation with a total deformation ε = 1.2 in a range of strain rate 1÷200 s^{-1}. For the evaluation of the size of the former austenite grain uses the fact that during the cooling speed guarantee structure obtained pearlitic ferrite secretion occurs

in the form of a grid because the former austenite grain boundaries. Recorded flow corves in **Figure 1** and **Figure 2** are presented.

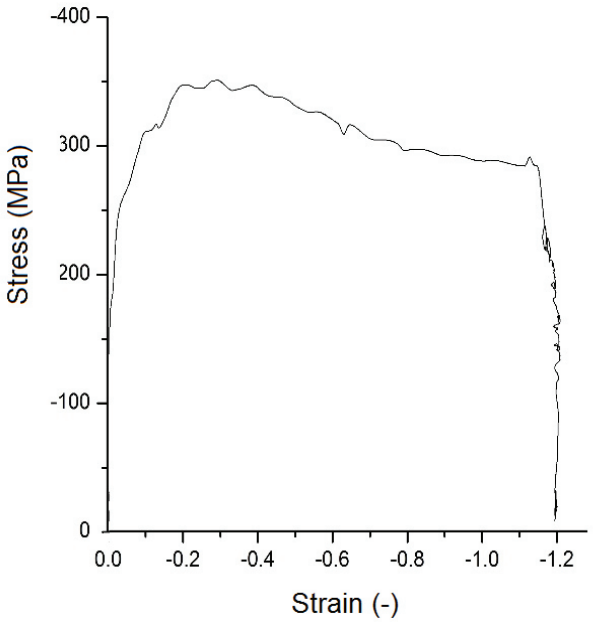

Figure 1 The flow curve of C70D steel for temperature 900 °C and deformation rate $\dot{\varepsilon} = 50 s^{-1}$

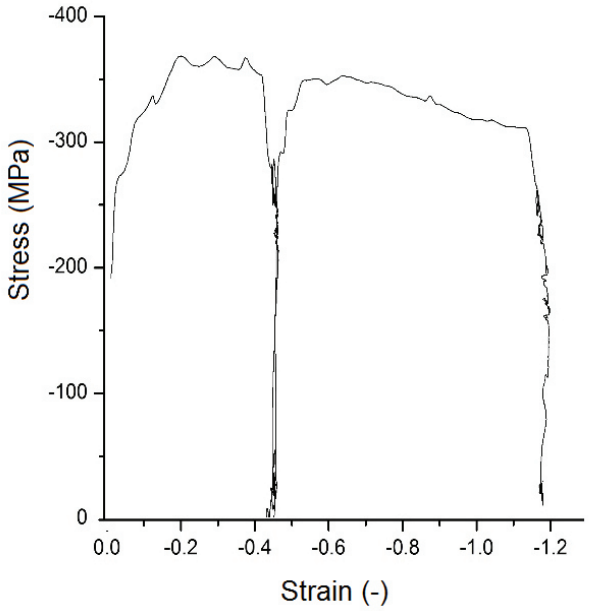

Figure 2 The flow curve of C70D steel for temperature 900 °C and deformation rate $\dot{\varepsilon} = 50 s^{-1}$

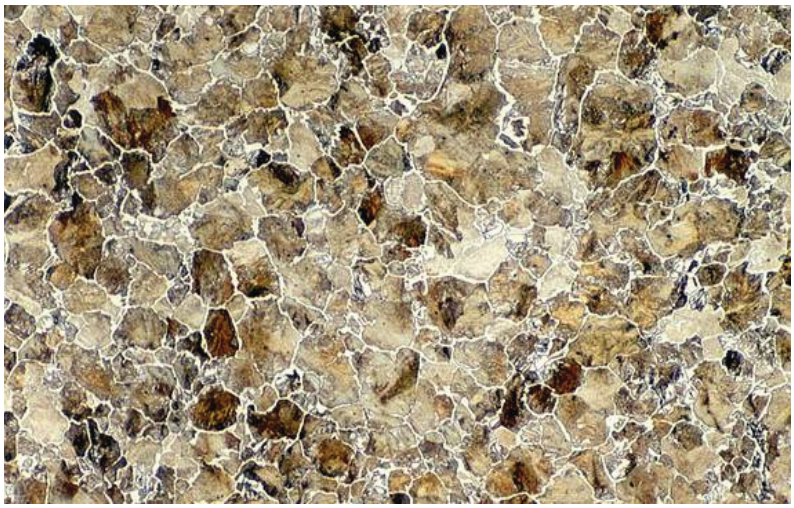

Figure 3 Pearlitic microstructure with ferrite network of C70D steel after physical simulation, mag 200X

Based on data posted on **Figure 1** and **Figure 2** can be concluded that the main process of removing deformation strengthening is a dynamic recrystallization. However, its start is needed large deformation. The peak deformation (ε_p), which deformation corresponding to the maximum stress on the flow curve and which is a parameter in determining the start of dynamic recrystallization, assumes a value equal to ε_p = 0.35÷0.40 and with increasing strain rate moves towards large deformations. Lower values cause deformation start in the analyzed species steel static recrystallization. In range of temperature 800÷1000 °C and deformation range ε = 0.20÷0.60 static recrystallization were observed. In **Table 1** result of metallographic investigation samples deformed in controlled conditions (temperature range 1000÷1100 °C) are presented.

Table 1 Result of metallographic investigation samples of C70D steel after microstructure austenite modeling

No	Temperature T (ºC)	Strain ε (-)	Strain rate (s^{-1})	Softening phenomena	d_1 / d_2 (-)	Austenitic grain size Dy_{rec}, (μm)
1	1000	0.4	1	R. Dynamic $\varepsilon_p = 0.38$	0.10	17
				R. Metadynamic	0.90	26
2	1000	0.4	10	R. Static	0.95	22
3	1000	0.4	100	R. Static	1.00	22
4	1000	0.5	1	R. Dynamic $\varepsilon_p = 0.38$	0.15	17
				R. Metadynamic	0.85	25
5	1000	0.5	10	R. Static	1.00	25
6	1000	0.5	100	R. Static	1.00	25
7	1100	0.05	1	Growth	-	107
8	1100	0.05	10	Growth	-	85
9	1100	0.1	1	Growth	-	69
10	1100	0.1	10	Growth	-	65
11	1100	0.2	1	R. Static	0.98	41
12	1100	0.2	10	R. Static	1.00	41
13	1100	0.3	1	R. Static	1.00	37
14	1100	0.3	10	R. Static	1.00	37
15	1100	0.4	1	R. Dynamic $\varepsilon_p = 0.32$	0.20	17
				R. Metadynamic	0.80	26
16	1100	0.4	10	R. Static	1.00	21

On the basis of the test results presented in **Table 1** it is possible to determine the parameters equations describing changes of austenite grain size as a function of deformation. In order to facilitate the calculation of approximation the experimental data have been arranged to a database with basic data of analyzed patterns deformation.

3. PREDICTION OF AUSTENITE MICROSTRUCTURE EVOLUTION

The plastic working processes in a manner that allows the determination of phenomena occurring in the material enables the accurate prediction of the grain size of austenite prior to the pearitic transformation and the value of transferred deformation. This is of particular importance when designing a technology for the manufacture of sections that are characterized by mechanical properties [5, 6]. For predicting the parameters of microstructure of austenite after rolling processes, a computer program based on the Sellars model was built according to the algorithm shown in [4]. Based on the rolling process parameters (the number of passes, the times of breaks between the passes, the magnitudes of deformations and deformation speeds in passes), it is possible to establish the phenomena occurring in the steel after deformation and to determine the austenite grain size and the non- recrystallized strain. To determine the coefficients of the mathematical model equations developed based on the results of experimental research (**Table 1**). Based on previous results of the work

made at The Institute of Plastic Working and Safety Engineering on the mathematical modeling the method of least squares for systems of nonlinear equations combined with the method of approximation of nonlinear equations of Newton were used. For prediction of austenite microstructure evolution below are implemented:

peak deformation: $$\varepsilon_p = 0{,}0047 \; d\gamma_0^{0{,}001} \; Z^{0{,}1475} \quad (1)$$

deformation for dynamic recrystallization: $$\varepsilon_c = 0{,}9 \cdot \varepsilon_p \quad (2)$$

volume of dynamic recrystallization: $$X_{RD} = 1 - \exp\left[-0{,}693\left(\frac{\varepsilon - \varepsilon_c}{\varepsilon_p}\right)^{1{,}4}\right] \quad (3)$$

volume of meta-dynamic recrystallization: $$X_{RMD} = 1 - \exp\left[\left(-0{,}693\frac{t_p}{t_{05\,MD}}\right)^{13}\right] \quad (4)$$

time for 50% meta-dynamic recrystallization: $$t_{05\,MD} = 0{,}0000106 \cdot Z^{-0{,}6} \exp\frac{Q}{\mathrm{RT}} \quad (5)$$

austenite grain size after dynamic recrystallization: $$D_{RD} = 1400 \cdot Z^{-0{,}15} \quad (6)$$

time for 50% static recrystallization: $$t_{05} = 11{,}4 \cdot 10^{-14} d\gamma_0^0 \varepsilon^{-3{,}8} \dot{\varepsilon}^{-0{,}41} \exp\left(\frac{252000}{RT}\right) \quad (7)$$

time for full static recrystallization: $$t_{095} = 4{,}323^{\frac{1}{1{,}2}} t_{05}\,, \quad (8)$$

time for 5% static recrystallization: $$t_{005} = t_{05}\frac{\ln(0{,}95)}{-0{,}694} \quad (9)$$

volume of static recrystallization: $$X = 1 - \exp\left(-0.693 \cdot \left(\frac{t_p}{t_{05}}\right)^{1{,}08}\right) \quad (10)$$

growing austenite grain size after small deformation: $$D_{growth_{\dot{\varepsilon}}} = 420\varepsilon^{-0{,}08} d_{\gamma 0}^{0{,}25} Z^{-0{,}1} \quad (11)$$

where: ε_c - critical deformation for dynamic recrystalization; ε_p - peak deformation; $d_{\gamma 0}$ - initial austenite grain size; Z - Zener - Hollomon parameter; t_p - time between deformation steps, T - temperature, K; Q - energy.

4. MODEL VERIFICATIONS

In order to verify the model applied, the results obtained from the developed model was compared with the results obtained from the most commonly used models of the evolution of the microstructure of austenite low carbon steel Choquet, Roberts and Yada. Exemplary results are presented in **Figure 4** and **Figure 5**.

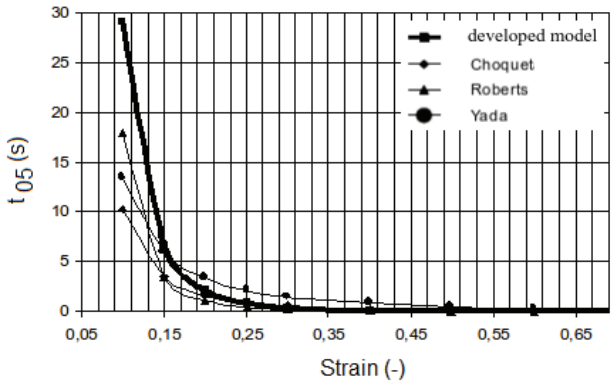

Figure 4 The change of time for 50 % static recrystalization $t_{0.5}$ as a function of deformation (T = 1000 °C; d_γ = 100 μm)

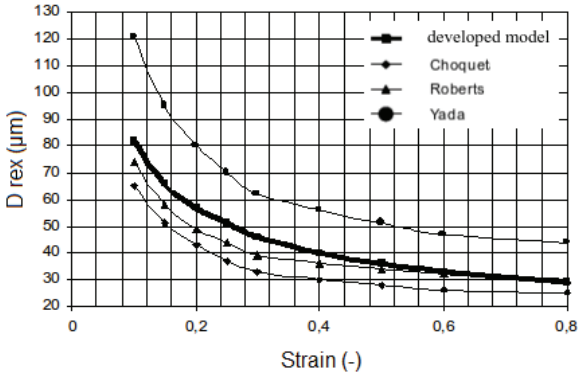

Figure 5 The change of austenite grain size D_{rex} after static recrystalization as a function of deformation (T = 900 °C; d_γ = 100 μm)

Table 2 Parameters of physical modeling and obtained result during model verification

No	Temperature (°C)	Deformation (-)	Deformation rate (s^{-1})	Austenite grain size (physical modeling) (μm)	Austenite grain size (numerical simulation) (μm)	Ä grain size (%)
I	1000 980 960	0.6 0.3 0.3	1 1 1	17	15	7.1
II	1000 980 960 940 920 900	0.2 0.2 0.2 0.2 0.2 0.2	5 5 5 5 5 5	31	27	11.3
III	1000 980 960 940 920 900	0.1 0.1 0.1 0.1 0.1 0.1	10 10 10 10 10 10	42	35	9.8
IV	1000 980 960 940 920 900	0.25 0.22 0.2 0.18 0.16 0.15	10 10 10 10 10 10	31	28	9.0

The physical simulation for model verification by Gleeble 3800 were done too. Parameters of experiments and obtained result are presented in **Table 2**. In studies It was assumed that a safe margin of error obtained between the experimental results and theoretical should not exceed 10 %. As it can be noticed for the testing variants only for the variant II the difference between the austenite former grain size estimated in laboratory test and from theoretical model is more than 10 %. Estimated results confirmed high accuracy of presented model for predictiom of austenite grain size in hot rolled high carbon steels.

5. CONCLUSION

The concept of a mathematical model for predicting changes of austenite microstructure in high- carbon steel is presented. In this work for microstructure evolution model of Sellars has been adopted to investigated steel grade. The coefficients of mathematical equations describing the change of deformed austenite microstructure were calculated based on the results of experimental studies carried out in the Institute of Plastic Working and Safety Engineering Czestochowa University of Technology. For the verification of the accuracy developed model laboratory studies were conducted using a metallurgical processes simulator Gleeble 3800. On the basis of the performed verification it can be found that the developed model for the evolution of the austenite microstructure in high carbon steels allows the correct determination of the austenite grain size formed by multi-stage hot deformation. Comparison of the results obtained in the theoretical and experimental studies have confirmed good agreement.

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