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Influence of Reheating Conditions on Austenite Grain Growth

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Abstract. The processes of reheating in the temperature range (T_{reheat}) from 950 to 1250°C with the holding time (t_{hold}) from 600 to 3600 s on the material known as high-strength low-alloy (HSLA) steel were investigated. The abnormal grain growth caused by the dissolution of Nb(C_x,N_y) particles was observed after T_{reheat} reached 1150°C. The influence of T_{reheat} on average austenite grain size (AGS) was stronger than that of t_{hold}. Two different models were applied for the description of average AGS on T_{reheat} and t_{hold}.

Keywords. Grain boundaries, grain growth, reheating conditions, steel, precipitation.

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1 Introduction

The reheating conditions (T_{reheat} and t_{hold}) are important parameters influencing the grain size of primary austenite in high-strength low-alloy (HSLA) steels. The values of the reheating conditions are determinated by technological parameters as well as the conception of alloying or microalloying of the steels. The conception of the steels based on C-Mn-Nb-V is characterized by the formation of precipitates such as VC, VN, NbC, NbN and/or Nb(C_x,N_y). The lost of drag effect of the precipitations results in the developed motion of austenite grain boundaries was discussed in [1–9]. The dissolution of VN and VC precipitates occurs at low reheating temperature in the range of 860–1000°C. According to the report [10], the dissolution of niobium precipitates occurs in the temperature range 1050–1200°C, whereby the general equation describing the dissolution on the thermo-dynamical base is in the form:

$$\log(\text{Me}_x(\text{C,N})_y) = A + B/T \quad (1)$$

or

$$T = B/[\log(\text{Me}_x(\text{C,N})_y) - A] \quad [°\text{C}] \quad (2)$$

where: Me [wt. %] is a precipitate component (e.g. Nb, V, Ti and/or Al), C [wt. %] is carbon, N [wt. %] is nitrogen, A and B [dimensionless] are thermodynamic constants, T [°C] is the dissolution temperature.

The two different approaches are used for describing average austenite grain size (average AGS) growth on reheating conditions:

a) a statistical model based on the numerical data processing of measured values using non-linear regression analysis [11] in form:

$$d_\gamma = a_1 \cdot T_{\text{reheat}}^{a_2} \cdot t_{\text{hold}}^{a_3} \quad [\mu\text{m}], \quad (3)$$

where: a_1, a_2, a_3 [dimensionless] are regression coefficients dependent on the reheating conditions, T_{reheat} [°C] is reheating temperature, t_{hold} [s] is holding time at the reheating temperature and

b) a general model based on the physically – metallurgical approach [9]:

$$d_\gamma^n - d_{\gamma,0}^n = (A \cdot \exp(-Q/R \cdot T_{\text{reheat}})) \cdot t_{\text{hold}} \quad [\mu\text{m}], \quad (4)$$

where d_{fl}, $d_{\text{fl},0}$ [μm] are the output and input diameter of AGS, n = 2–10 [dimensionless] and $A = 1.44 \cdot 10^{12}$–$5.02 \cdot 10^{53}$ [dimensionless] are coefficients dependent on the chemical composition and processing conditions, Q [kJ/mol] is the activation energy of grain growth, $R = 8.314 \cdot 10^{-3}$ [kJ/(mol K)] is the universal gas constant, T_{reheat} [°C] is reheating temperature, t_{hold} [s] is holding time at the reheating temperature.

The objective of this investigation is to find out the influence of reheating conditions on the average AGS growth by experiments with possibility of its mathematical description.

2 Experimental Material and Methods

The chemical composition of a microalloyed steel investigated in this study is following (all in wt. %): 0.12 C, 1.54

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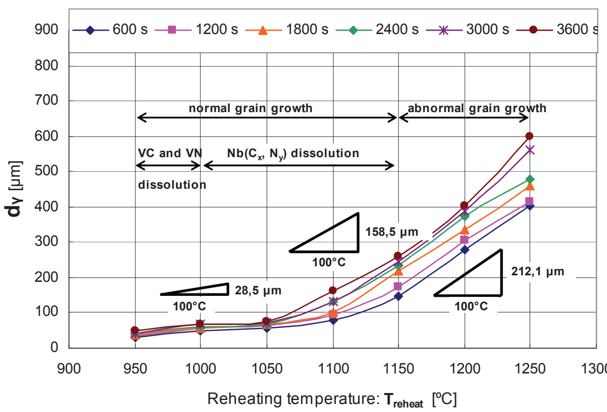

Figure 1. Dependence of the average AGS growth on the reheating temperature and holding time.

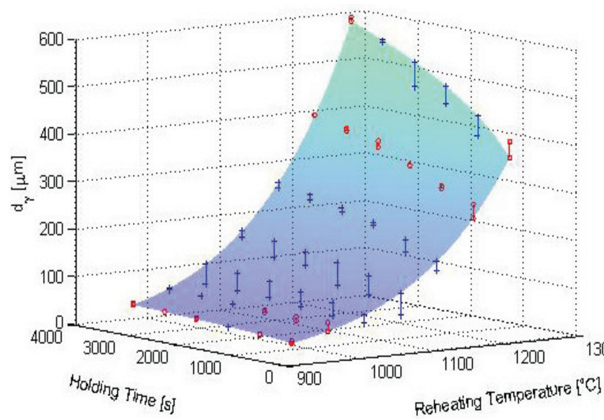

Figure 2. Geometrical interpretation of equation (5) and comparison with measured data.

Mn, 0.12 Si, 0.004 P, 0.001 S, 0.18 V, 0.048 Nb, 0.01 Ti, 0.015 Al, 0.0005 B, 0.0042 N_2 and 0.0015 O_2. The samples were reheated in a furnace at different conditions: reheating temperature is in the range of 950–1250°C with step $\Delta T = 50$°C and holding time in 600–3600 s with step $\Delta t = 600$ s. After reheating, the samples were water quenched. For the visualization of original austenite grain boundaries, the samples were etched in a supersaturated water solution of picric acid. Optical microscopy (Olympus Vanox-T) was used for microstructural analysis. For comparison of measured data with models, the software MATLAB was used.

3 Results and Discussion

The average AGS increased in dependence on reheating temperature and time as shown in Figure 1. Below 1000°C the very slow growth of average AGS was observed, which is caused by the pinning effect of vanadium and niobium carbonitrides to grain boundaries. Vanadium carbides and nitrides were dissolved below 1000°C as shown in Table 1. If the reheating temperature was from interval $T_{\text{reheat}} \in (1000; 1150)$°C small increasing of grain growth was observed resulting from dissolution of $\text{Nb}(\text{C}_x,\text{N}_y)$ precipitates. If the $T_{\text{reheat}} > 1150$°C abnormal grain growth was obtained because dissolved second phase particles are ineffective in retarding grain growth. Reheating temperature has a bigger influence on average AGS growth than holding time at the reheating temperature. There is a good coincidence with the results obtained in a previous research work [12], where the carbides and/or carbonitrides were expected to be formed in the processing of the steel. From the general form of equation (3), the regression coefficients were derived for observed chemical composition as in form:

$$d_\gamma = 6.589 \cdot 10^{-28} \cdot T_{\text{reheat}}^{9.51} \cdot t_{\text{hold}}^{0.2437} \quad [\mu\text{m}]. \tag{5}$$

The geometrical interpretation of equation (5) and comparison with measured values is shown in Figure 2. The vertical bars indicate the deviation of measured and calculated values and their good agreement. The general model described by equation (4) with new values of coefficients derived by non – linear statistical methods obtained form:

$$d_\gamma^3 - d_{\gamma,0}^3 = (3.28725 \cdot 10^{22} \cdot \exp(-460/R \cdot T_{\text{reheat}})) \cdot t_{\text{hold}} \quad [\mu\text{m}]. \tag{6}$$

When $d_{\text{fl},0} = 40$ μm was used as start up diameter of average AGS, then the form of equation (6) for calculation on AGS growth is described by following formula:

$$d_\gamma = \sqrt[3]{\begin{array}{l} 40^3 + 3.28725 \cdot 10^{22} \\ \cdot \exp(-460/8.314 \cdot 10^{-3} \cdot T_{\text{reheat}}) \cdot t_{\text{hold}} \end{array}} \quad [\mu\text{m}]. \tag{6a}$$

The geometrical interpretation of equation (6a) and comparison with measured data is given in Figure 3. The short bars indicate the deviation of measured and calculated values, showing their good agreement. This figure shows that the deviations of calculated values by equation (6a) are lower than those calculated by equation (5).

The role of microalloying elements [13, 14] is pinning effect on grain boundary mobility. The correct reheating conditions have to cause the partial dissolution of precipitates and only normal grain growth. $\text{Nb}(\text{C}_x\text{N}_y)$ particles are stable second-phase and its coarsening rate is very low [9]. $\text{Nb}(\text{C}_x,\text{N}_y)$ precipitates should be dissolved at the reheating temperature, which is sufficiently high. As mentioned above, these particles are dissolved into solid solution above 1150°C and no longer delay the austenite grain growth. Individual temperatures of particles dissolution are shown in Table 1. The onset temperature of the abnormal grain growth of austenite grains is in good agreement with

	Type of precipitate	Equations of particle dissolution	T_{diss} [°C]
1.	$\mathbf{VC_{min}}$	$\log(\%V \cdot \%C) = 6.72 - 9500/T$	860
2.	$\mathbf{VC_{max}}$	$\log(\%V^{4/3} \cdot \%C) = 7.06 - 10800/T$	923
3.	$\mathbf{VN_{min}}$	$\log(\%V \cdot \%N) = 3.4 - 8330/T + 0.12 \cdot (\%Mn)$	969
4.	$\mathbf{VN_{max}}$	$\log(\%V \cdot \%N) = 3.02 - 7840/T$	1000
5.	$\mathbf{NbC_{min}}$	$\log(\%Nb \cdot \%C) = 2.96 - 7510/T$	1171
6.	$\mathbf{NbC_{max}}$	$\log(\%Nb \cdot \%C) = 3.28 - 8266/T + (983/T - 0.598) \cdot (\%Mn)$	1195
7.	$\mathbf{NbC_{0,87min}}$	$\log(\%Nb \cdot \%C^{0.87}) = 3.4 - 7550/T$	1095
8.	$\mathbf{NbC_{0,87max}}$	$\log(\%Nb \cdot \%C^{0.87}) = 3.11 - 7520/T$	1165
9.	$\mathbf{NbC_{0,83}N_{0,14max}}$	$\log(\%Nb \cdot \%C^{0,83} \cdot \%N^{0,14}) = 4,46 - 9800/T$	1152
10.	$\mathbf{NbC_{0,83}N_{0,14min}}$	$\log(\%Nb \cdot \%C^{0,27} \cdot \%N^{0,73}) = 2,9 - 8700/T$	1130

Table 1. Equations for calculation of particles dissolution and their intervals.

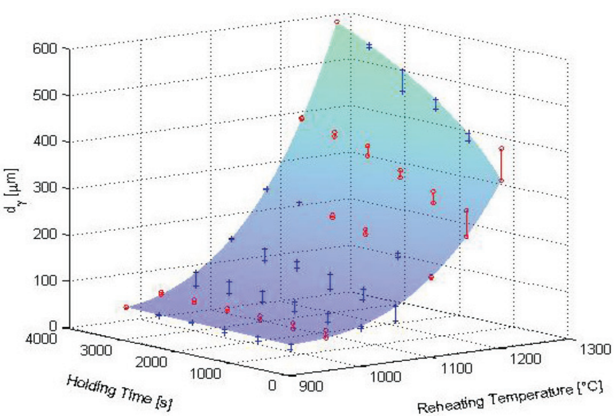

Figure 3. Geometrical interpretation of equation (6a) and comparison with measured data.

the ranges of the particle dissolution temperatures calculated in the literature shown in Table 1.

4 Conclusions

In the present study following conclusions are obtained:

- the calculated and measured data showed applicable correlation,
- the dominant effect on austenite grain growth was shown by reheating temperature and influence of holding was observed as weaker,
- the abnormal AGS growth occurred above 1150 °C reheating temperature of the dissolution of complex $Nb(C_x,N_y)$ precipitates,
- the vanadium carbides and nitrides have dissolution temperatures in the range from 860 to 1000°C and its effect on austenite grain growth is weaker compared to $Nb(C_x,N_y)$,
- the essential measurement data derived new constants in models based on:
  a) the numerical data processing using non-linear regression analysis with equation (5),
  b) the physically – metallurgical approach with equation (6),
- better coincidence of measurement data with models was in case of equation (6a), but equation (5) is acceptable too for quick calculation.

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