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DETERMINATION OF ACTIVATION ENERGY FOR STATIC RECRYSTALLIZATION USING MULTIPASS CONTINUOUS COOLING TORSION TEST

N. Radović, Đ. Drobnjak, K. Raić

Department of Metallurgical Engineering, Faculty of Technology and Metallurgy University of Belgrade, Serbia, nenrad@tmf.bg.ac.rs

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Abstract

Two microalloyed steels (Nb low carbon and V medium carbon) were tested by means of multistage continuous cooling torsion with aim to evaluate the interpass recrystallization data, by means of T_{nr} (temperature of no-recrystallization) temperatures. In the region of short interpass intervals, i.e. region where the static recrystallization is governed by the presence of alloying elements in solid solutions, interpass time was varied between 1.8, 2.7, 5 and 10s. Since the recrystallization fraction on T_{nr} temperature is constant, it was possible to plot lnt-1/T dependence (where t is interpass time and T obtained T_{nr} temperature) and calculate the slopes representing Q_{SRX}, i.e. activation energy for static recrystallization. Q_{SRX} values were determined for both low carbon Nb and medium carbon V microalloyed steels and previously reported steels. Calculated values are very close and show good agreement with previously published data estimated after employment the traditional procedure.

Key words: Activation Energy; Static Recrystallization, T_{nr} temperature

Introduction

The main task of controlled rolling of microalloyed (MA) steels is to obtain the structure consisting of uniform small ferrite grains in order to provide good mechanical and technological properties. These demands have imposed an extensive research, targeting mechanisms and kinetics of all processes occurring during hot rolling (i.e. recrystallization and precipitation of secondary phases ? in either dynamic or static conditions) [1-9].

One direction of the research was focused on static recrystallization (SRX) behavior. The description of SRX kinetics and influences of processing parameters are most usually defined by the Johnson-Mehl-Avrami-Kolmogorov equation [10]:

$$X = 1 - \exp\left[-0.692 \cdot \left(\frac{t}{t_{0.5}}\right)\right]^n \quad (1)$$

where: X-recrystallized fraction, n-Avrami exponent, t-time, and $t_{0.5}$-time for 50% recrystallization, calculated using the following equation:

$$t_{0.5} = A \cdot \varepsilon^{-p} \cdot \dot{\varepsilon}^{-q} \cdot d_0^{-r} \cdot \exp\left(\frac{Q_{SRX}}{R \cdot T}\right) \quad (2)$$

where: ε, έ, d_0 and T are strain, strain rate, initial grain size and temperature, respectively, A, p, q, r, R are constants, and Q_{SRX} is activation energy for static recrystallization. Values of Q_{SRX} for most of microalloyed steels in high temperature range have been reported to be between 240 and 450 kJ/mol, mainly due to differences in chemical composition [1-9].

Medina and Quispe [5] reported an improved model that takes into account the influence of chemical composition on Q_{SRX}, in temperature range above static recrystallization critical temperature (SRCT), i.e. in the temperature range above which static recrystallization is complete. These studies were carried out on laboratory scale at constant temperature (isothermally). On the other hand, recrystallization behavior during continuous cooling (conditions close to industrial practice) was investigated mainly with the aim to determine the no recrystallization temperature, T_{nr}, in the manner introduced by Boratto et al. [1].

The aim of this work was to make an attempt to establish a simple procedure for estimation of activation energy for static recrystallization, based on the data obtained in commonly used test for determination of T_{nr} temperature and activation energy for static recrystallization Q_{SRX}.

Experimental

Two microalloyed steels (Nb low carbon and V medium carbon) were tested in this work. The chemical composition of steels is given in Table 1.

Table 1. Chemical composition of tested steels, wt%

Steel	C	Mn	Si	Nb	V	Ti	N
V-steel	0.31	1.55	0.39	-	0.13	-	0.012
Nb/Ti-steel	0.074	1.15	0.21	0.035	-	0.016	0.009

Prior heat treatment and specimen geometry were discussed elsewhere [8,9]. Specimens were tested using torsion tester in temperature range 1150-780°C. In order to estimate the T_{nr} temperatures, the multipass anisothermal Boratto tests [1] were performed, with modifications of strain per pass (ε=0.35) and strain rate (έ=$1.5s^{-1}$), with temperature step of 25°C, and identical interpass intervals of either 1.8; 2.7; 5 and 10 seconds. To assess the reproducibility, three specimens were tested for each set of conditions.

Results

Set of multipass flow curves at decreasing temperature, shown in Figure 1(a) is representative of a testing with 5 seconds interpass interval. There is an increase in flow stress in two stages (as revealed by the change in slope of an imaginary envelope curve joining the stress maxima of the successive passes) with decreasing temperature, a feature typical not only of the present but also of most microalloyed steels. The T_{nr} is estimated from the mean flow stress (MFS) vs. 1/T plots, exhibiting the two stage behavior. MFS is calculated for each pass by numerical integration. The temperatures at which the two linear segments intersect is identified as the T_{nr} temperature (Figure1b) [1,7-9].

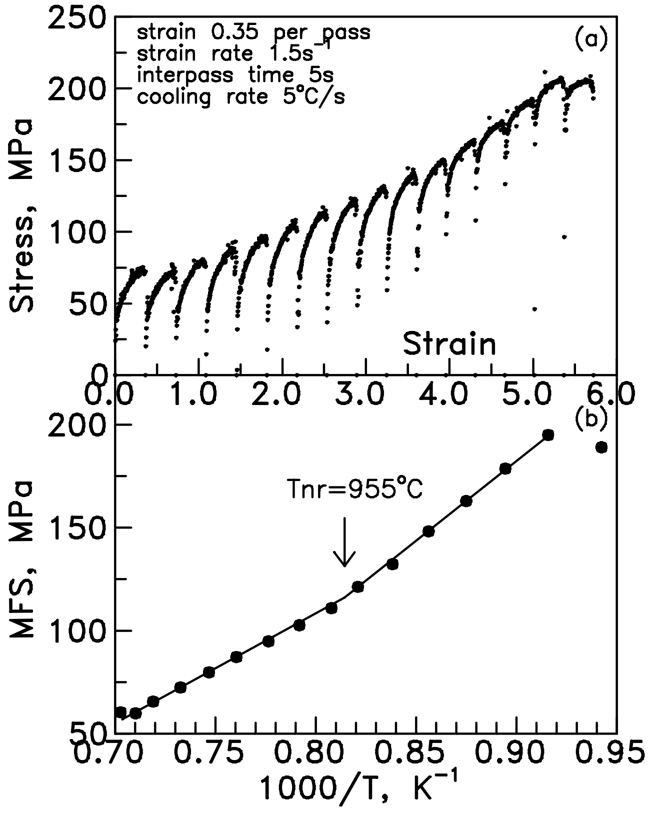

Figure 1. Influence of interpass time on T_{nr} temperature

The T_{nr} obtained in all tests is plotted as a function of interpass time (Figure 2). It is obvious that for both steels the T_{nr} temperature decreases with increasing interpass time.

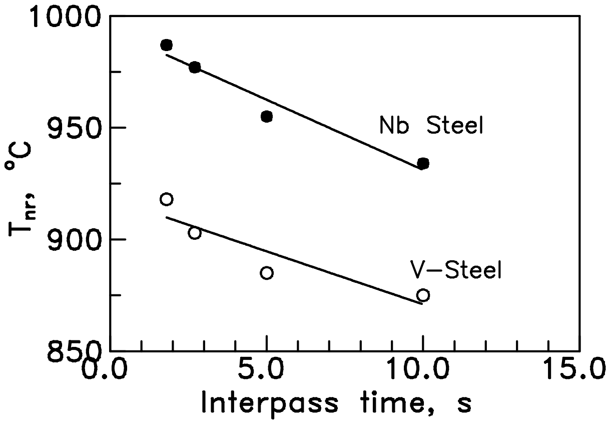

Figure 2. Influence of interpass time on $\boldsymbol{T_{nr}}$ *temperature*

Discussion

Interpass time dependence of T_{nr} temperature is in good agreement with previously published data [2,3,6,8,9]. The decrease of T_{nr} temperature with increase of interpass time is attributed to longer time available for incubation period, also indicating that the onset of the T_{nr} is related to constant recrystallized fraction. Also, in this interpass time region (1.8<t<10s) the only mechanism of recrystallization suppression is influence of alloying elements in solid solution on grain boundary mobility [11]. Therefore, after rearranging, equation (2) becomes equation (3), i.e.:

$$\ln t = \ln A - p \cdot \ln \varepsilon - q \cdot \ln \dot{\varepsilon} - r \cdot \ln d_0 + \frac{Q_{SRX}}{R} \cdot \frac{1}{T} = C + \frac{Q_{SRX}}{R} \cdot \frac{1}{T} \tag{3}$$

Q_{SRX} can be calculated from equation (3), by plotting lnt vs 1/T , where t is interpass time and temperature is T_{nr}, where t is interpass time and T obtained T_{nr} temperature. A slope in this plot is equal to Q_{SRX}/R (R-universal gas constant). Figure 3 shows lnt vs. $1/T_{nr}$ plots for steels tested in this work, together with some previously published data [6].

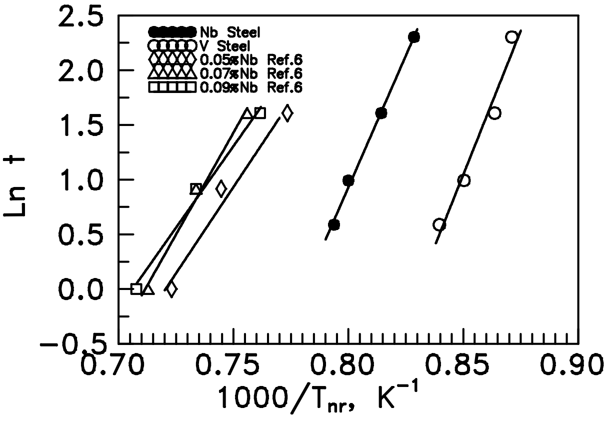

Figure 3. Time-temperature dependences for Nb and V steel

Using the slopes determined from Figure 3 and equation (3), Q_{SRX} values of 274 kJ/mol and 258 kJ/mol for V and Nb steels, respectively, were calculated. These values are in good agreement with previously published data [2-7]. The Q_{SRX} value obtained for Nb steel is also in good agreement with values predicted by Medina and Quispe model, although it should be noted that the chemical composition of V steel was not included in the model. To confirm the proposed procedure for determination of Q_{SRX} from torsion continuous cooling multipass tests, data reported by Bai [6] were also used. Values for Q_{SRX} were calculated both using slopes from Figure 3 and Medina and Quispe model. All results are summarized in Table 2. All calculated values are very close to values for diffusion of Nb in austenite [12] or lattice self diffusion of iron [13].

Table 2. Activation energy for static recrystallization estimated from Figure 2 and calculated using Medina and Quispe (M & Q) model [5]

Steel	Q_{SRX}, kJ/mol	
	This work	M & Q model [5]
V-steel	274	NA
Nb-steel	258	270
0.05 Nb [6]	259	265
0.07 Nb [6]	300	272
0.09 Nb [6]	248	269

NA - Not Applicable - model does not include influence of vanadium.

Determination of Q_{SRX} in this manner requires only few specimens to be tested (for each interpass time), while the usual manner requires a series of isothermal testing, with large number of specimens on each temperature.

Conclusion

Two microalloyed steels (Nb low carbon and V medium carbon) were tested by means of continuous cooling multipass tests on high temperature torsion tester**,** with aim to investigate the recrystallization kinetics. The determination of activation energy for static recrystallization, Q_{SRX}, was limited to temperatures above T_{nr}, i.e temperature range in which microalloying elements are in the solid solution. T_{nr} temperatures are, in all cases, related to equal amount of recrystallized fraction, enabling plotting dependence of interpass time on temperature, i.e. lnt vs.$1/T_{nr}$. Q_{SRX} values of 258kJ/mol for Nb steel and 274 kJ/mol for V-steel are in good agreement with previously reported results.

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