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ISSN 0543-5846
METABK 49(1) 67-71 (2010)
UDC-UDK 669.14:548.53 = 111

HOT FORMING RECRYSTALLIZATION KINETICS IN STEEL

Received – Prispjelo: 2008-09-09
Accepted – Prihvaćeno: 2009-01-25
Review Paper – Pregladni rad

The theory of kinetics of static recrystallization of steel during hot forming links the phenomenon to certain critical strain, grain size, strain rate, activation energy and temperature. The basic description is provided by the Avrami equation. An overview of equations used was compiled and comments on selected parameters prepared.

Key words: recrystallization kinetics, steel, hot forming

Kinetika rekristalizacije tijekom vrućeg oblikovanja čelika. Teorija kinetike statičke rekristalizacije čelika tijekom vrućeg oblikovanja ovu pojavu povezuje s kritičnom deformacijom, veličinom zrna, brzinom deformacije, aktivacijskom energijom te s temperaturom. Osnovni opis pruža Avrami jednadžba. Rad pruža pregled korištenih jednadžbi i raspravu pojedinih parametara.

Ključne riječi: kinetika rekristalizacje, čelik, vruće oblikovanje

INTRODUCTION

The main purpose of forming processes (in steels) is to produce fine-grained uniform microstructure resulting from phase transformation.

Rolling of steel sheets above the T_{nr} temperature (the highest temperature, at which recrystallization can take place) without carbonitride precipitation is typical with long interpass delays, which provide time for complete static recrystallization (SRX). Rolling of sheets below T_{nr} flattens austenite grains, as the strain-induced precipitation inhibits the SRX. Neither SRX nor precipitation take place during bar and wire rolling due to short interpass delays. Conversely, dynamic recrystallization (DRX) followed by metadynamic recrystallization (MDRX) takes place during sheet rolling due to strain accumulation. With regard to its interpass delays, strip rolling may be categorized somewhere between the above mentioned processes. In initial passes, where interpass delays are fairly long, the metallurgical response of the material resembles the sheet rolling process.

Hot forming leads to both work hardening and restauration. The entire scope of this problem is too complex to be covered in a single paper.

Therefore, this study focuses on a narrow area comprising the actual restauration kinetics or, more precisely recrystallization. An effort was made to summarize long-year research activity and offer an overview of equations describing the static recrystallization kinetics in terms of time required for restauration of a proportion of the microstructure [1-7].

KINETICS OF STATIC RECRYSTALLIZATION

This process applies to materials characterized with , where $T \geq 0{,}5\, T_m$ is the melting temperature. From the viewpoint of physics, it follows the static recovery, which involves disclocation climb and cross-slip [6]. The process is assumed to take place in two stages: nucleation of new grains and their growth.

Static restauration of microstructure can be divided into recovery and recrystallization. Basic models of static recrystallization kinetics are based on the Johnson-Mehl-Avrami-Kolmogorov equations describing the proportion of recrystallized structure X; and, using the mathematic probability theory, they result in the equation [1-7]

$$X = 1 - \exp\left[A\left(\frac{t}{t_x}\right)^n\right] \qquad (1)$$

As the curve described by this equation has no mathematical expression for 0 and 100 % , the time is normally specified as $t_{0,05}^{SRX}$ or $t_{0,95}^{SRX}$ or sometimes generally as t_x . The general form of the equation is then written as follows [4,7]:

$$t_{0,5}^{SRX} = B \cdot \varepsilon^p \cdot D^q \cdot Z^r \cdot \dot{\varepsilon}^s \cdot \exp\left(\frac{Q_{rs}}{R \cdot T}\right) \qquad (2)$$

where ε represents strain, D is the grain size prior to deformation, Z is the Zener-Hollomon parameter, $\dot{\varepsilon}$ is strain rate listed in s^{-1} , Q_{rs} is the activation energy, R is the gas constant and T is the absolute temperature [8-11].

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Table 1. **Overview of equations describing the kinetics of static recrystallization**

1	in general	$t_{0,5}^{\mathrm{SRX}} = A \cdot Z^{r} \cdot {d_0}^{p} \cdot \varepsilon^{q} \cdot \exp\left(\frac{Q_{\mathrm{rs}}}{R \cdot T}\right)$	[7]
2	C-Mn	$t_{0,5}^{\mathrm{SRX}} = \left(4,323\right)^{\frac{1}{k}} \cdot t_{0,5}^{\mathrm{SRX}}$ $t_{0,5}^{\mathrm{SRX}} = 5 \cdot 10^{-21} \cdot \varepsilon^{-4} \cdot {d_0}^{2} \cdot \exp\left(\frac{Q_{\mathrm{rs}}}{R \cdot T}\right)$	[7]
3	C-Mn-Nb	$t_{0,5}^{\mathrm{SRX}} = 1,9 \cdot 10^{-18} \cdot \dot{\varepsilon}^{-0,41} \cdot \varepsilon^{-2,8} \cdot {d_0}^{2} \cdot \exp\left(\frac{324000}{R \cdot T}\right)$	[8]
4	C-Mn	$t_{0,5}^{\mathrm{SRX}} = 2,05 \cdot 10^{-10} \cdot Z^{-0,375} \cdot {d_0}^{2} \cdot \varepsilon^{-1,7} \cdot \exp\left(\frac{385000}{R \cdot T}\right)$	[12]
5	C-Mn	$t_{0,5}^{\mathrm{SRX}} = 4,22 \cdot 10^{-12} \cdot Z^{-0,375} \cdot {d_0}^{2} \cdot \varepsilon^{-1,7} \cdot \exp\left(\frac{355000}{R \cdot T}\right)$	[12]
6	C-Mn	$t_{0,5}^{\mathrm{SRX}} = 4,35 \cdot 10^{-13} \cdot d_0 \cdot \varepsilon^{0,68} \cdot \dot{\varepsilon}^{-\frac{1}{3}} \cdot \exp\left(\frac{248000}{R \cdot T}\right)$	[13]
7	C-Mn-Nb	$t_{0,5}^{\mathrm{SRX}} = \left(-5,24 + 550\mathrm{Nb}\right) \cdot 10^{-18} \cdot \varepsilon^{(-4+77\mathrm{Nb})} \cdot {d_0}^{2} \cdot \exp\left(\frac{330000}{R \cdot T}\right)$	[14]
8	C-Mn-Nb	$t_{0,5}^{\mathrm{SRX}} = 2,3 \cdot 10^{-15} \cdot \varepsilon^{-2,5} \cdot {d_0}^{2} \cdot \exp\left(\frac{230000}{R \cdot T}\right)$	[14]
9	0,04 % Nb, 0,6 – 1,5 % Mn	$T > 1004\,^{\circ}\mathrm{C}:\quad t_{0,5}^{\mathrm{SRX}} = 2,52 \cdot 10^{-19} \cdot {d_0}^{2} \cdot \varepsilon^{-4} \cdot \exp\left(\frac{325000}{R \cdot T}\right)$ $1004\,^{\circ}\mathrm{C} > T > 891\,^{\circ}\mathrm{C}:\quad t_{0,5}^{\mathrm{SRX}} = 5,94 \cdot 10^{-38} \cdot {d_0}^{2} \cdot \varepsilon^{-4} \cdot \exp\left(\frac{780000}{R \cdot T}\right)$ $T < 1004\,^{\circ}\mathrm{C}:\quad t_{0,5}^{\mathrm{SRX}} = 9,24 \cdot 10^{-9} \cdot {d_0}^{2} \cdot \varepsilon^{-4} \cdot \exp\left(\frac{130000}{R \cdot T}\right)$	[15]
10	C-Mn-V	$t_{0,5}^{\mathrm{SRX}} = 4,29 \cdot 10^{-15} \cdot d_0 \cdot \varepsilon^{2,0} \cdot \dot{\varepsilon}^{-\frac{1}{3}} \cdot \exp\left(\frac{262000}{R \cdot T}\right)$	[13]
11	C-Mn-Nb	$t_{0,5}^{\mathrm{SRX}} = 4,10 \cdot 10^{-15} \cdot d_0 \cdot \varepsilon^{2,0} \cdot \dot{\varepsilon}^{-\frac{1}{3}} \cdot \exp\left(\frac{338000}{R \cdot T}\right)$	[13]
12	C-Mn-Nb-Ti	$t_{0,5}^{\mathrm{SRX}} = 7,25 \cdot 10^{-18} \cdot d_0 \cdot \varepsilon^{2,8} \cdot \dot{\varepsilon}^{-\frac{1}{3}} \cdot \exp\left(\frac{349000}{R \cdot T}\right)$	[13]
13	C-Mn-Nb	$t_{0,5}^{\mathrm{SRX}} = 2,29 \cdot 10^{-15} \cdot \varepsilon^{-2} \cdot Z^{-0,32} \cdot \exp\left(\frac{400000}{R \cdot T}\right)$	[16]
14	C-Mn-Nb-Ti	$t_{0,5}^{\mathrm{SRX}} = 2,1 \cdot 10^{-16} \cdot \dot{\varepsilon}^{-0,43} \cdot \varepsilon^{-3,1} \cdot {d_0}^{2} \cdot \exp\left(\frac{264000}{R \cdot T}\right)$	[17]
15	C-Mn-Nb-Ti-Mo	$t_{0,5}^{\mathrm{SRX}} = 6,0 \cdot 10^{-17} \cdot \dot{\varepsilon}^{-0,43} \cdot \varepsilon^{-3,1} \cdot {d_0}^{2} \cdot \exp\left(\frac{280000}{R \cdot T}\right)$	[17]
16	C-Mn-Nb-Ti-0,2Ni	$t_{0,5}^{\mathrm{SRX}} = 3,3 \cdot 10^{-16} \cdot \dot{\varepsilon}^{-0,43} \cdot \varepsilon^{-3,1} \cdot {d_0}^{2} \cdot \exp\left(\frac{261000}{R \cdot T}\right)$	[17]
17	C-Mn-Nb-Ti-0,5 Ni	$t_{0,5}^{\mathrm{SRX}} = 7,4 \cdot 10^{-16} \cdot \dot{\varepsilon}^{-0,43} \cdot \varepsilon^{-3,1} \cdot {d_0}^{2} \cdot \exp\left(\frac{253000}{R \cdot T}\right)$	[17]
18	C-Mn-Nb-Ti-0,36Cr	$t_{0,5}^{\mathrm{SRX}} = 7,6 \cdot 10^{-15} \cdot \dot{\varepsilon}^{-0,43} \cdot \varepsilon^{-3,1} \cdot {d_0}^{2} \cdot \exp\left(\frac{230000}{R \cdot T}\right)$	[17]
19	C-Mn-Nb-Ti-0,6Cr	$t_{0,5}^{\mathrm{SRX}} = 5,8 \cdot 10^{-14} \cdot \dot{\varepsilon}^{-0,43} \cdot \varepsilon^{-3,1} \cdot {d_0}^{2} \cdot \exp\left(\frac{207000}{R \cdot T}\right)$	[17]
20	C-Mn-Nb	$t_{0,05r} = 6,75 \cdot 10^{-20} \cdot D^{2} \cdot \varepsilon^{-4} \cdot \exp\left(\frac{300000}{R \cdot T}\right) \cdot \exp\left\{\left[\left(\frac{2,75 \cdot 10^{5}}{T} - 185\right)\right] \cdot [\mathrm{Nb}]\right\}$	[18]
21	C-Mn-Nb	$t_{0,05r} = 6,75 \cdot 10^{-8} \cdot D^{2} \cdot \varepsilon^{-4} \cdot \exp\left(\frac{300000}{R \cdot T}\right) \cdot \exp\left[\left(\frac{275000}{R \cdot T} - 185\right) \cdot [\mathrm{Nb}]\right] \cdot$ $\cdot \exp\left[\left(\frac{1,534 \cdot 10^{7}}{R \cdot T} - \frac{206300}{r}\right) \frac{[\mathrm{Nb}] \cdot [\mathrm{C}]}{r}\right]$	[19]

22	C-Mn-Nb	$t_{0,5}^{\mathrm{SRX}} = 1{,}27 \cdot 10^{-20} \cdot \varepsilon^{-3{,}81} \cdot \dot{\varepsilon}^{-0{,}36} \cdot \exp\left(\frac{404000}{R \cdot T}\right)$ 0,05 % Nb $t_{0,5}^{\mathrm{SRX}} = 2{,}86 \cdot 10^{-21} \cdot \varepsilon^{-3{,}8} \cdot \dot{\varepsilon}^{-0{,}42} \cdot \exp\left(\frac{436000}{R \cdot T}\right)$ 0,055 % Nb, 0,003 % B $t_{0,5}^{\mathrm{SRX}} = 1{,}06 \cdot 10^{-27} \cdot \varepsilon^{-3{,}55} \cdot \dot{\varepsilon}^{-0{,}33} \cdot \exp\left(\frac{559000}{R \cdot T}\right)$ 0,058 % Nb, 0,003 % B	[20]
23	C-Mn-Nb-Ti-Al	$t_{0,5}^{\mathrm{SRX}} = \left(-5{,}24 + 550 \cdot \left[\mathrm{Nb}_{\mathrm{eq}}\right]\right) \cdot 10^{-18} \cdot d_0{}^2 \cdot \varepsilon^{-4+77 \cdot \left[\mathrm{Nb}_{\mathrm{eq}}\right]} \cdot \exp\left(\frac{330000}{R \cdot T}\right)$ $\left[\mathrm{Nb}_{\mathrm{eq}}\right] = [\mathrm{Nb}] + 0{,}31 \cdot [\mathrm{Ti}] + 0{,}15 \cdot [\mathrm{Al}]$	[21] [22]
24	0,7C-Mn	$t_{0,5}^{\mathrm{SRX}} = 2{,}4 \cdot 10^{-8} \cdot \varepsilon^{p} \cdot \dot{\varepsilon}^{-0{,}29} \cdot D^{-0{,}2} \cdot \exp\left(\frac{160420}{R \cdot T}\right)$	[23]
25	C-Mn-Ti-V	$t_{0,5}^{\mathrm{SRX}} = 5 \cdot 10^{-18} \cdot (\varepsilon - 0{,}085)^{-3{,}5} \cdot D^2 \cdot \exp\left(\frac{280000}{R \cdot T}\right)$	[24]
26	C-Mn	$t_{0,5}^{\mathrm{SRX}} = 5 \cdot 10^{-21} \cdot \varepsilon^{-4} \cdot D_0{}^{-2} \cdot \exp\left(\frac{320000}{R \cdot T}\right)$ $t_{0,95r} = (4{,}323)^{\frac{1}{1{,}7}} \cdot t_{0,5}^{\mathrm{SRX}}$	[25]
27	C-Mn-Nb-Ti	$t_{0,5}^{\mathrm{SRX}} = A \cdot 10^{-20} \cdot d^2 \cdot \varepsilon^{-4} \cdot \exp\left(\frac{350000}{R \cdot T}\right)$	[27]
28	C-Mn	$t_x = A_x \cdot \varepsilon^{-1{,}5} \cdot \exp\left(\frac{319400}{R \cdot T}\right)$ X 10 % 50 % 95 % A_x $3{,}85 \cdot 10^{-11}$ $3{,}33 \cdot 10^{-13}$ $1{,}85 \cdot 10^{-14}$	[2]

Substantial part of this study consisted in gathering the equations listed in Table 1. [12-54]. Due to the scope of the paper, some references are listed only to indicate that they contain other particular equations. Where possible, the summary also states in general terms the type of steel, to which the equation applies.

CONCLUSION

Statistics is a tricky science, which is the reason why any calculation of average values based on the equations shown would be rather misleading. Besides, it is apparent that it was not possible to gather results of all experiments that had been conducted in the field. Another fundamental drawback of the comparison is the lack of detailed data on the particular material, different testing conditions including the type of strain itself (twisting, upsetting, field testing,...), pre-heating method and thus the initial grain size, etc. In such cases, one has to refer to individual references for detailed specification. Despite, certain relationships can be established by estimate.

The normal strain rate exponent is –0,3, which forms the expression $\dot{\varepsilon}^{-0{,}3}$ and approaches the long-known expression $Z^{-0{,}375}$ first published by Sellars. This suggests that the dependence is not very strong. Apparently, an increase in strain rate by an order of magnitude reduces the time by half. The role of strain magnitude is difficult to predict. From the range of the theoretical value of -4 in the exponent in ε^{-4} up to $\varepsilon^{-1{,}5}$ one can assume that the effect of dynamic recrystallization comes into play as the exponent value becomes lower and, once the critical strain is achieved, it is practically unusable.

There is no general conclusion to be made: the lower the number, the shorter the incubation time (or even none). One can only recommend that the equations be used only for small amounts of strain – roughly up to $\varepsilon \approx 0{,}3$ through 0,4 in common steels above 1 000 °C, where the formation of a peak on the stress-strain curve can be expected.

The effect of temperature is definite and based on the exponential relationship: the higher the temperature, the shorter the time.

Activation energy is mentioned as well. The general rule is that increasing concentration of alloying elements (including micro-alloying additions) leads to an increase in the value. However, all the mathematical experiments, though based on statistics, were flawed in terms of comparing disparate initial states. Moreover, as proven above, it is difficult to confirm whether Q is a constant. The overview of otherwise similar chemical compositions and numerical values of Q_{rs} clearly shows its significant scatter, which makes its use as a typical quantity for a given chemical composition virtually impossible.

A great number of equations was gathered for HSLA C-Mn-Nb steels (from Table 1. No. 11,7,..) which have similar chemical compositions. In this case, an actual calculation was performed. The resulting values of $t_{0,5}^{\mathrm{SRX}}$ were plotted in a chart in Figure 1, which shows data for different literature sources and four different temperatures used ranging from 850 to 1 000 °C (1 123 to 1 273

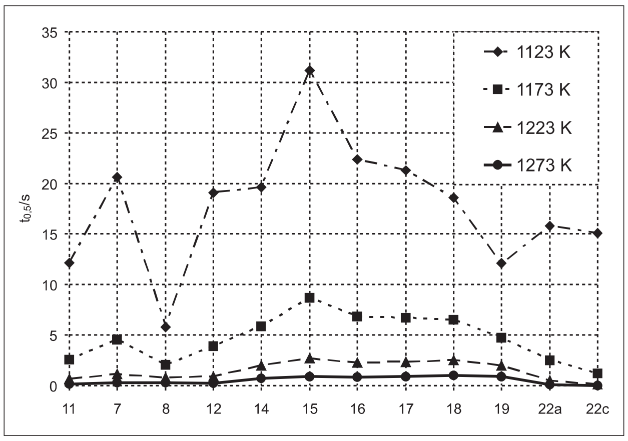

Figure 1. Values of $t_{0,5}$ (SRX) for C-Mn-Nb

K). The value of 850 °C was used intentionally, although one can assume that such temperature may not be in line with the requirement for the temperature of non-recrystallization T_{nr} . A single set of input parameters was used for all calculations : 0,06Nb; strain $\varepsilon = 0{,}2$; strain rate $\dot{\varepsilon} = 10$ 1/s; d_0 = 30 μm; R = 8,314 J/(mol·K). Not all parameters were used in all equations in all cases. Some equations incorporate the influence of chemical elements, in particular for HSLA steels. However, the range of results is limited. To certain extent, the effects of microalloying elements can be expressed by increasing the activation energy value.

It becomes apparent that despite the differences in mathematical structures of equations, their results are comparable. One can conclude that at 900 °C the average value is $t_{0,5}^{\mathrm{SRX}} = 4{,}5$ s and at 1 000 °C it is $t_{0,5}^{\mathrm{SRX}} = 0{,}45$ s.

The purpose of this study was to gather data on available equations describing the progress of static recrystallization and to discuss these relationships.

The study was co-funded by the Czech Science Foundation under the projects no. GAČR 106/07/0631, GAČR 106/06/P321 and by the Ministry of Education, Youth and Sports of the Czech Republic MSMT 6198910015. The authors would like to express theirs thanks to these institutions.

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Note: The responsible translator for Engish language is J. Drnek, Czech Republic.

ACKNOWLEDGEMENT TO REVIEWERS
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