Static Recrystallization Modelling of Hot Deformed Steels Containing Several Alloying Elements

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Using torsion tests a model has been constructed to predict the recrystallized fraction of deformed austenite in low alloy and microalloyed steels. The model quantifies the influence of the most common elements (C, Si, Mn, Mo) in low alloy steels and the typical elements (Ti, V, Nb) in microalloyed steels in the recrystallized fraction, when they are in solution. Static recrystallization kinetics follow Avrami's law and expressions for the parameter $t_{0.5}$ and for the exponent n are not given. The values predicted by the model are compared with the experimental values, good concordance being obtained between both.

KEY WORDS: static recrystallization; modelling; Avrami's equation; elements in solution; low alloy and microalloyed steels.

1. Introduction

Most models published^{1–11)} to predict the static recrystallization kinetics of austenite do not take into account the influence of the content of each alloying element and only some take into account the influence of certain elements.¹⁾ In general, authors establish a single model for C–Mn type steels, irrespective of the chemical composition and another for Nb microalloyed steels, irrespective of the content of this element.

However, the content of each element in solution has an effect on the recrystallization kinetics, activation energy being the parameter most sensitive to changes in the chemical composition.^{12,13)} All the elements, except V and C, in the most usual percentages in low alloy and microalloyed steels, tend to increase the activation energy and therefore to delay the recrystallization kinetics.¹³⁾

In this work the static recrystallization kinetics of ten low alloy steels and eight microalloyed steels with Nb, V or Ti are studied using torsion tests. A general expression for Avrami's equation is established, bearing in mind the chemical composition of the steel. In this way the recrystallization kinetics are modelled at temperatures in the austenite phase and where the elements are in solution. Though other authors have studied the influence of several alloying elements on static recrystallization kinetics this study has been merely qualitative.¹⁴⁾ The influence of the grain size, strain and strain rate have also been studied.

In the case of microalloyed steels, the static recrystallization kinetics change when the strain induced precipitation has commenced. At temperatures lower than that at which precipitation commences, known as

the static recrystallization critical temperature (SRCT), activation energy stops being a constant and comes to be a function of the temperature.^{15,16)} Recrystallization at temperatures below SRCT has been studied and modelled, but its complexity calls for a differentiated treatment of the model at temperatures above SRCT, i.e. when all the precipitate forming elements are in solution.¹⁷⁾

2. Materials and Experimental Procedure

The steels used in this study are the same as those used to determine the expression for activation energy¹³⁾ and their composition is showed in the **Table 1**, together with cooling critical temperature (A_{r3}) and austenite grain size (D) at reheating temperature (1 230°C × 10 min). The conditions (temperatures, strains, strain rates) at which the torsion tests were carried out have also been described in the afore mentioned work, as well as the equations for the conversion of the parameters of torsion, torque and number of turns, into equivalent magnitudes of stress and strain, respectively.

The determination of the recrystallized fraction was carried out using the method known as back extrapolation.¹⁸⁾ With this method the softened fraction is approximately equal to the recrystallized fraction.¹⁹⁾

Other tests at different strain rates (0.54, 1.45, 3.63, 5.08 s⁻¹) and different reheating temperatures (1 230, 1 100, 1 000°C) were carried out in order to quantify the influence of strain rate and grain size, respectively.

3. Formulation of the Model

The kinetics of the static recrystallization of austenite can be described by an Avrami equation in the following

Table 1. Chemical composition (wt%), cooling critical temperatures (A_{r3} , at 0.2°C/s) and austenite grain size (D , μm) at 1230°C $\times$ 10 min; being X_i = Mo, Ti, V, Nb.

Steel	C	Si	Mn	X_i	N	A_{r3} , °C	D , μm
C1	0.15	0.21	0.74	-	-	810	187
C2	0.36	0.20	0.82	-	-	740	189
C3	0.53	0.21	0.71	-	-	714	179
S1	0.11	0.26	0.55	-	-	814	143
S2	0.11	1.65	0.47	-	-	896	104
M1	0.11	0.26	0.68	-	-	835	212
M3	0.11	0.25	1.55	-	-	772	192
Mo1	0.44	0.24	0.79	Mo=0.26	-	704	180
Mo2	0.44	0.23	0.79	Mo=0.38	-	714	205
Mo3	0.42	0.27	0.79	Mo=0.18	-	709	193
T5	0.15	0.24	1.12	Ti=0.021	0.0105	791	29
T2	0.15	0.27	1.25	Ti=0.055	0.0100	774	95
T3	0.15	0.26	1.10	Ti=0.075	0.0102	779	90
V1	0.11	0.24	1.10	V=0.043	0.0105	786	172
V2	0.12	0.24	1.10	V=0.060	0.0123	782	167
V3	0.11	0.24	1.00	V=0.093	0.0144	784	165
N1	0.11	0.24	1.23	Nb=0.041	0.0112	786	122
N2	0.11	0.24	1.32	Nb=0.093	0.0119	786	116

way:

$$X_a = 1 - \exp \left[-0.693 \left(\frac{t}{t_{0.5}} \right)^n \right] \quad \text{.....(1)}$$

where X_a is the fraction of the recrystallized volume and $t_{0.5}$ is the time corresponding to half of the recrystallized volume, which depends practically on all the variables which intervene in hot deformation and whose most general expression follows a law of the type:

$$t_{0.5} = A \varepsilon^p \dot{\varepsilon}^q D^s \exp \frac{Q}{RT} \quad \text{.....(2)}$$

where ε is the strain, $\dot{\varepsilon}$ the strain rate, D the grain size, Q the activation energy, T the absolute temperature, $R=8.318 \text{ J mol}^{-1} \text{ K}^{-1}$ and p , q and s are parameters.

On the other hand, for most authors the exponent n in Eq. (3) is a constant and for others¹⁾ it follows a similar law to Eq. (2).

Thus, the construction of the model will be based on the determination of the following magnitudes: A , Q , p , q , s and n . Given that a high number of steels are tested it was necessary to establish some working hypotheses in order to simplify the number of tests to be carried out. These hypotheses have been checked with other models already published, as mentioned above, and are the following:

(1) Temperature and strain are the magnitudes which have the greatest influence on recrystallization. Thus, the recrystallization kinetics of each steel will be studied at different temperatures and at at least two strains.

(2) Grain boundaries are preferential sites for the nucleation of new recrystallized grains and their function is the same in all the steels studied, whatever their composition. Thus, the influence of the grain size will be

Fig. 1. Recrystallized fraction (X_a) plotted against time for different grain sizes. Steel Mo3.

studied in one single steel, generalizing the results to the rest.

(3) Strain rate is the magnitude with the least influence on recrystallization kinetics, to the point that many authors underestimate its influence.^{5,6)} An increase in the strain rate implies an increase in the density of dislocations, but these are not preferential sites for nucleation like the grain boundaries, and therefore are less important than the grain size. Therefore, the influence of strain rate will also be studied in one single steel and the results generalized to the others.

4. Results

Using torsion tests and applying the back extrapolation method, the recrystallized fraction (X_a) was determined against time (t) for all the steels, at the temperatures and strains indicated in Ref. 13). In accordance with Eq. (1), by regression of the experimental points, the values of $t_{0.5}$ and of n were determined in each X_a curve against t for all the steels. In the microalloyed steels, the curves corresponding to temperatures below SRCT present a plateau as a consequence of strain induced precipitation. In these curves the parameter $t_{0.5}$ was measured on the curve itself, it obviously being impossible to measure the value of n , as the curves with a plateau do not obey Avrami's law. All the values of $t_{0.5}$ and n measured are shown in Ref. 13).

Steel Mo3 was used to study the influence of grain size on recrystallization kinetics due to its good quenchability. Three different austenite grain sizes: 193, 137 and 83 μm , were obtained at the reheating temperatures of 1230, 1100 and 1000°C ($\times$ 10 min), respectively. The tests were carried out at 1000°C and Fig. 1 shows the recrystallization fraction curves for the different grain sizes. The values of $t_{0.5}$ and n determined by regression from the experimental points are shown in Table 2.

The influence of strain rate on recrystallization kinetics was studied, selecting a steel C3 at random from the eighteen steels used. The reheating temperature was 1230°C $\times$ 10 min and the tests were carried out at 1000°C with a strain of 0.20 and strain rates of 0.54,

Table 2. Experimental values of $t_{0.5}$ and n for different austenite grain sizes. Steel Mo3. Testing temperature = 1000°C; strain rate = 3.63 s⁻¹.

Initial grain size (μm)	$t_{0.5}$ (s)	n
193	3.92	1.07
137	2.47	0.92
83	1.54	1.08

Fig. 2. Recrystallized fraction (X_a) plotted against time for different strain rates. Steel C3.

Table 3. Experimental values of $t_{0.5}$ and n for different strain rates. Steel C3. Testing temperature = 1000°C.

Strain rate (s ⁻¹)	$t_{0.5}$ (s)	n
0.54	12.27	0.71
1.45	7.82	0.72
3.63	4.47	1.02
5.08	3.86	1.03

1.45, 3.64 and 5.08 s⁻¹, respectively. The recrystallized fraction against time curves indicate that the influence of strain rate on recrystallization kinetics is less than the influence of other variables (Fig. 2). The values of $t_{0.5}$ and n obtained for each strain rate are shown in Table 3.

5. Discussion and Modelling

5.1. Activation Energy

The influence of temperature and the determination of activation energy have been discussed elsewhere, the following expression having been found:¹³⁾

$$Q(\text{J mol}^{-1}) = 124\,714 + 28\,385.68[\text{Mn}] + 64\,716.68[\text{Si}] + 72\,775.40[\text{Mo}] + 76\,830.32[\text{Ti}]^{0.123} + 121\,100.37[\text{Nb}]^{0.100} \dots\dots\dots(3)$$

where each square bracket indicates the percentage by weight of the element indicated. Remember that the values predicted by Eq. (3) against the experimental values showed an index of correlation of 0.98.

Table 4. Values of p in accordance Eq. (4).

Steel	C1	C2	C3	M1	M3	S1	S2	Mo1	Mo2
p	-1.67	-1.56	-1.91	-2.30	-2.15	-1.86	-1.79	-1.87	-1.64
Steel	Mo3	V1	V2	V3	N1	N2	T2	T3	T5
p	-1.34 *	-2.10	-1.94	-1.96	-1.96	-1.87	-2.15	-2.11	-2.25

(*) atypical value

Fig. 3. Parameter p against grain size (D) for the steels used.

5.2. Effect of Grain Size

The nucleation of the new recrystallized grains preferentially takes place on the grain boundaries. For this reason the initial grain size will have an influence on the recrystallization kinetics; the smaller the grain, the faster they become. In accordance with Eq. (2) and the values of $t_{0.5}$ and of D noted in Table 2, the value of 0.996, practically equal to one, was obtained for s .

5.3. Effect of Strain Rate

In accordance with Eq. (2) and the values of Table 3, a value of -0.53 was obtained for q and this confirms that the influence of strain rate on static recrystallization kinetics is less than the influence of other variables (temperature, strain, grain size).

5.4. Effect of Strain

The values of the exponent p of Eq. (2) were similar for all the steels, being between -1.34 and -2.30 (Table 4). Analysis of the variations of p suggested that it was influenced by the initial grain size (D), though most authors have opted for a constant value. However, the high number of readings obtained in this work allow us to make a reasonable valuation of p as a function of the initial grain size. The best relation found between p and D was of the type $p \propto D^\beta$, similar to that found by other authors.²⁰⁾ The expression found for the regression curve of values of p against D for all the steels studied (Fig. 3), except for that indicated with an asterisk in Table 4 which was atypical, was the following:

$$p = -3.7D^{-0.137} \dots\dots\dots(4)$$

The use of Eq. (4), instead of a mean value for p , better predicts the set of values obtained. An expression such

as Eq. (4) is attributed to the fact that when a certain strain is applied, provided that this is less than the critical strain for the start of dynamic recrystallization, a smaller grain size could give rise to an increase in the density of dislocations, especially in the grain boundaries, when the strain is applied in the same conditions of temperature and strain rate.

5.5. Coefficient A

Once the different parameters (Q , p , r , s) have been determined, it only remains to determine coefficient A so that $t_{0.5}$ may be calculated using Eq. (2). The value of A was determined for each steel by inserting into Eq. (2) the experimental values of $t_{0.5}$ and the corresponding temperature, strain and strain rate, as well as the values of the previously determined parameters. The values of A for each steel were very close, thus demonstrating that it is independent of the temperature, strain and strain rate. The mean value for each steel is shown in **Table 5** where a difference may be observed from one steel to another. It may also be seen that there is a certain relation between A and Q predicted by Eq. (3) and that as the latter increases the former diminishes. Possible relations between both magnitudes were studied and it was found that the correlation of the exponential relation was very high, approximately 0.998, clearly demonstrating the dependence of A on the chemical composition. **Figure 4** shows the good relation between both magnitudes, having found the following expression:

$$A = 3.869 \times 10^{-4} \exp(-7.921 \times 10^{-5} Q) \quad \text{.....(5)}$$

It should be noted that Eq. (5) shows a relation between A and Q which is similar to that found for other heat activated physical phenomena and interpreted by means of an Arrhenius-type law.²¹⁾

Table 5. Experimental values of activation energy (Q_e), calculated (Q_c) according to Eq. (3) and coefficient A in Eq. (2).

Steel	Q_e (Jmol ⁻¹)	Q_c (Jmol ⁻¹)	A
C1	159 000	159 310	1.4×10^{-9}
C2	169 000	160 934	1.0×10^{-9}
C3	158 000	158 459	1.0×10^{-9}
S1	160 000	157 153	1.8×10^{-9}
S2	245 000	244 838	1.3×10^{-12}
M1	159 000	160 843	1.2×10^{-9}
M3	190 000	184 891	1.7×10^{-10}
Mo1	180 000	181 593	2.7×10^{-10}
Mo2	193 000	189 678	1.7×10^{-10}
Mo3	173 000	177 712	3.0×10^{-10}
T2	205 000	219 096	9.7×10^{-12}
T3	227 000	217 019	1.2×10^{-11}
T5	210 000	205 784	2.7×10^{-11}
V1	167 000	171 470	5.4×10^{-10}
V2	168 000	171 470	4.5×10^{-10}
V3	163 000	168 632	5.4×10^{-10}
N1	262 000	262 000	4.5×10^{-13}
N2	272 000	272 000	1.6×10^{-13}

5.6. Exponent n

The values obtained for the exponent n of Eq. (1), noted in Ref. 13) showed a slight dependence on the temperature, in accordance with the following expression:

$$n = B \exp\left(-\frac{Q_n}{RT}\right) \quad \text{.....(6)}$$

The values of n were very similar for all the steels, the majority being between 1.50 and 0.62, depending on the temperature. Steel T5 showed the lowest values when the strain was 0.35, though these results are considered statistically atypical. The valuation of this parameter was made by means of the statistical treatment of all the steels. In accordance with Eq. (6) the logarithmical representation of n against $1/T$ allows us to determine the value of Q_n . The values of Q_n were determined for each family of steels, finding values from 6000 Jmol⁻¹ for the V microalloyed steels (V1, V2, V3) and 17000 Jmol⁻¹ for the silicon steels (S1, S2), the rest ranging between these two values, except for the Nb microalloyed steels (N1, N2) which showed a different behaviour, giving values of approximately 43 800 Jmol⁻¹.

Given that all the steels, except the Nb microalloyed steels, presented very similar values of Q_n , the most representative for all of them was taken as the mean value, being approximately 12000 Jmol⁻¹. B was calculated by linear regression, inserting into Eq. (6) the values of n and the corresponding temperature. The mean was taken as the most appropriate estimator, its value being 3.07 with a standard deviation of 0.12. Thus, the expression found for this set of steels was as follows:

$$n = 3.07 \exp\left(-\frac{12000}{RT}\right) \quad \text{.....(7)}$$

Similar calculations were carried out for the Nb microalloyed steels and the following expression was found:

$$n = 38.02 \exp\left(-\frac{43800}{RT}\right) \quad \text{.....(8)}$$

Fig. 4. Coefficient A in Eq. (2) vs. activation energy (Q) in Eq. (3).

Equation (8) differs slightly from Eq. (7) and better predicts the experimental values of n for the Nb steels. Nevertheless, given that the values of n were similar for all the steels,¹³⁾ the generalization of Eq. (7) for all of them, including the Nb steels, would also be acceptable.

Once the expressions for $t_{0.5}$ and n were determined, the static recrystallization kinetics were modelled by simply inserting these expressions into Eq. (1).

5.7. Comparison between Experimental $t_{0.5}$ and Calculated $t_{0.5}$

The model constructed may be verified by comparing the curves of the recrystallized fraction determined experimentally and those predicted by Eq. (1). However, as the former is the most important parameter between $t_{0.5}$ and n , the latter varying only a little from one steel to another and being only slightly dependent on the temperature, the comparison between experimental $t_{0.5}$ ¹³⁾ and $t_{0.5}$ calculated using Eq. (2) for all the steels, will be a good indicator of the power of prediction of the model and offers the material possibility of establishing a comparison for all the experimental values. In this respect, Figs. 5 to 11 show this comparison for each family of steels, respectively, it being possible to observe a high correlation index (r) in all cases.

Finally, though the model constructed does not require resolution and analysis of microstructures, as the recrystallized fraction has been determined by means of the back extrapolation method mentioned above, some microstructures were determined in order to illustrate the work undertaken. A steel with good hardenability was selected, such as steel C3. The microstructures in

Fig. 7. Predicted $t_{0.5}$ in according Eq. (4) vs. experimental $t_{0.5}$ for steels M1 and M3.

Fig. 5. Predicted $t_{0.5}$ in according Eq. (1) vs. experimental $t_{0.5}$ for steels C1, C2 and C3.

Fig. 8. Predicted $t_{0.5}$ in according Eq. (4) vs. experimental $t_{0.5}$ for steels Mo1, Mo2 and Mo3.

Fig. 6. Predicted $t_{0.5}$ in according Eq. (4) vs. experimental $t_{0.5}$ for steels S1 and S2.

Fig. 9. Predicted $t_{0.5}$ in according Eq. (4) vs. experimental $t_{0.5}$ for steels V1, V2 and V3.

Fig. 10. Predicted $t_{0.5}$ in according Eq. (4) vs. experimental $t_{0.5}$ for steels T2, T3 and T5.

Fig. 11. Predicted $t_{0.5}$ in according Eq. (4) vs. experimental $t_{0.5}$ for steels N1 and N2.

Fig. 12. Microstructures of recrystallized fraction in austenite strained at different temperatures and recrystallization times (t_x), for steel C3. ($\epsilon=0.35$; $\dot{\epsilon}=3.63 \text{ s}^{-1}$; X_{am} =measured recrystallized fraction; X_a =calculated recrystallized fraction)

(a): $T=1000^\circ\text{C}$; $t_x=0.4 \text{ s}$; $X_{am}=0.15$; $X_a=0.10$
 (b): $T=1000^\circ\text{C}$; $t_x=1 \text{ s}$; $X_{am}=0.40$; $X_a=0.35$
 (c): $T=1000^\circ\text{C}$; $t_x=4 \text{ s}$; $X_{am}=0.85$; $X_a=0.80$

(d): $T=850^\circ\text{C}$; $t_x=4 \text{ s}$; $X_{am}=0.15$; $X_a=0.17$
 (e): $T=850^\circ\text{C}$; $t_x=15 \text{ s}$; $X_{am}=0.60$; $X_a=0.50$
 (f): $T=850^\circ\text{C}$; $t_x=40 \text{ s}$; $X_{am}=0.90$; $X_a=0.88$

Figs. 12(a) to 12(f) show the deformed austenite in the indicated conditions, held during a certain time at the same temperature and subsequently quenched. The recrystallized fraction was measured by observation with the optical microscope of some 15 fields for each specimen, noting the measured mean value (X_{am}) together with the recrystallized fraction calculated according to the proposed model (X_a).

6. Conclusions

(1) The use of steels with suitable compositions has made it possible to identify the quantitative influence of each alloying element on static recrystallization kinetics.

(2) The influence of strain on recrystallization kinetics is not independent of the microstructure as it depends slightly on the grain size.

(3) Exponent n in Avrami's equation (Eq. (1)) diminishes slightly with the temperature.

(4) Strain rate has less influence than strain and grain size, but its influence is not negligible.

(5) Strain is not an independent variable, its influence on recrystallization kinetics is slightly related with the grain size.

(6) The high correlation index ($r>0.96$) between experimental $t_{0.5}$ and calculated $t_{0.5}$ demonstrates the good prediction of the model.

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