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Influence of titanium on the static recrystallization of a medium carbon microalloyed steel

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Static recrystallization kinetics of three medium carbon steels, microalloyed with vanadium and titanium (titanium varied from 0.003 to 0.039% in weight), were studied by hot torsion test simulation. A higher recrystallization time was observed in the steel with 0.019 wt% Ti. This difference in recrystallization time was checked by metallographic observations and mechanical softening. This time shift implies different activation energies, which were calculated by the time needed to obtain a 50% recrystallized structure and also by solving the Zener–Hollomon equation. Evolution of the kinetics of recrystallization as a function of temperature was also studied. In addition, the critical allowable temperature for a fully recrystallized structure was investigated.

1. Introduction

Microalloyed steels studied usually have a low carbon content, $C \leqslant 0.2$ wt% and are microalloyed with vanadium or niobium. The present work is part of a wider research programme [1] carried out to study the influence of titanium percentage on the mechanical properties of medium carbon vanadium–titanium microalloyed steel, as well as optimization of the hot and warm forging processes facing the manufacturing of critical automotive forged parts. The use of titanium to control grain growth improves the toughness of vanadium microalloyed steels. Vanadium is responsible for precipitation strengthening [1, 2). Studies dedicated to mechanical behaviour optimization of forging processes, particle distribution and its effect have already been published [2–5]. In this paper the influence of titanium content on recrystallization kinetics is shown, and coherence between the different aspects observed.

2. Experimental procedure

The compositions of the steels used are shown in Table I, and details of the manufacturing process have been described elsewhere [1, 4]; the hot torsion machine has been described also [3, 4]. The test samples were austenitized for 10^3 s at 1523 K and then deformed to $\varepsilon = 0.7$ (true deformation) at a deformation rate of $\dot{\varepsilon} = 18.9\ s^{-1}$. The samples were quenched after deformation, at increasing times. The austenitic grain size obtained after deformation was studied by means of a computerized image analyser, which gave the statistical medium diameter intercept when the structure was recrystallized fully. When the structure was partially recrystallized, the percentages of elongated and equiaxial grains were determined.

Particle distribution and size have been studied previously in forging simulations [1–3]. Mechanical softening was studied following the double deformation method [6–8], using the same deformation parameters, ε and $\dot{\varepsilon}$, and different temperatures. Finally, torsion tests at various deformation conditions were carried out in order to obtain the apparent activation energy for deformation and to compare it with that derived from recrystallization kinetics.

3. Results and discussion

Austenitic grain size versus strain is shown in Fig. 1. A small stabilized grain size can be observed in steel No. 2. The static recrystallization kinetics of the three steels after deformation at 1398 K can be observed in Fig. 2. The time for recrystallization at this temperature is extremely short. In steel No. 1, the time needed to obtain a 0.5 recrystallized fractions [8] $t_{0.5}$, is $t \sim 0.007$ s; in steel No. 3 $t_{0.5} = 0.01$ s, and 0.08 s for steel No. 2.

Fig. 3 clearly shows similar behaviour at 1173 K for steels No. 1 and 3, and also shows the longer recrystallization time needed for steel No. 2 ($t_{0.5} = 0.3$, 0.4 and 5 s, respectively).

Fig. 4 shows the recrystallized fraction plotted versus time, following metallographic observation and mechanical softening between the results obtained by the two methods can be seen in Fig. 4 at 1398 and 1173 K. At 1143 K it is possible to obtain a 95% recrystallized structure at 2×10^4 s (not shown in the figure); but at 1123 K the percentage of the recrystallized structure remains lower than 50% until 10^6 s. A temperature between 1123 and 1143 K is needed to obtain a fully recrystallized structure, in agreement

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TABLE I Chemical composition (wt %) of steels used

	C	Mn	Si	S	P	Cr	Ni	Mo	V	Ti	Cu	Sn	Al	N_2 (p.p.m.)	O_2 (p.p.m.)
Steel 1	0.29	1.34	0.41	0.026	0.021	0.09	0.10	0.02	0.10	0.003	0.244	0.02	0.029	167	30
Steel 2	0.29	1.28	0.34	0.028	0.017	0.13	0.08	0.01	0.09	0.019	0.134	0.015	0.036	106	45
Steel 3	0.32	1.39	0.33	0.021	0.015	0.13	0.14	0.03	0.129	0.039	0.129	0.017	0.049	148	57

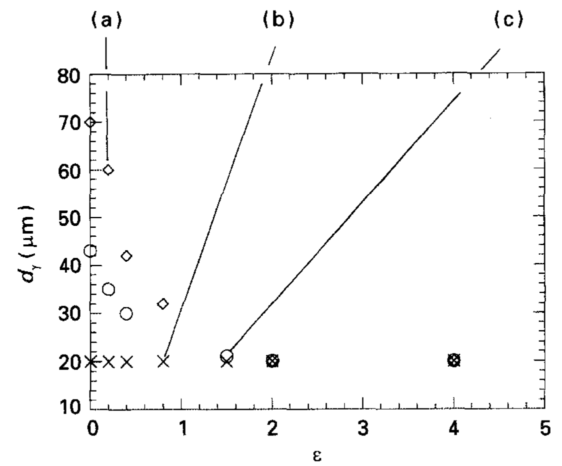

Figure 1 Grain size, d_γ, versus strain, ε, at strain rate, $\dot{\varepsilon} = 7\ s^{-1}$, austenization temperature, T_γ = 1523 K and deformation temperature, T_{def} = 1398 K: (◇) steel 1, (×) steel 2, (○) steel 3.

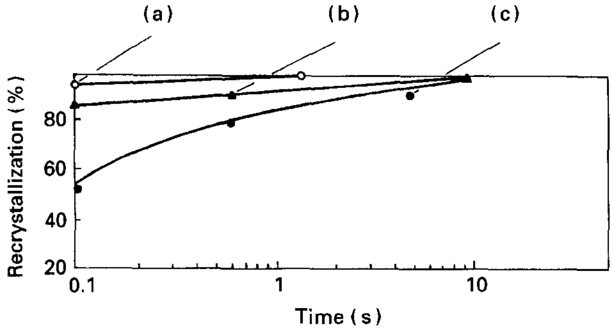

Figure 2 Static recrystallization time of three steels after ε = 0.7, $\dot{\varepsilon} = 18.9\ s^{-1}$, T_{def} = 1398 K and T_γ = 1523 K: (○) steel 1, (●) steel 2, (▲) steel 3.

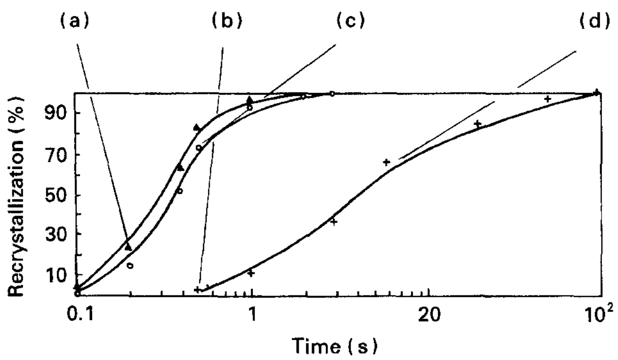

Figure 3 Static recrystallization time of three steels after ε = 0.7, $\dot{\varepsilon} = 18.9\ s^{-1}$, T_{def} = 1173 K and T_γ = 1523 K: (▲) steel 1, (+) steel 2, (○) steel 3.

with other works [8, 9]. An apparent activation energy, Q, of 326 kJ mol^{-1} is derived for the $t_{0.5}$ values [7] at 1398, 1173, 1163 and 1143 K, which is higher than previous values obtained [1, 5] in steel No. 1

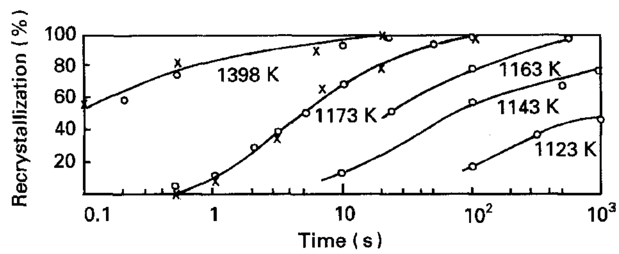

Figure 4 Static recrystallization time of steel No. 2 at different deformation temperatures: ε = 0.7, $\dot{\varepsilon} = 18.9\ s^{-1}$, T_γ = 1523 K. (×) metallographic observation, (○) mechanical softening.

TABLE II Torsion tests: deformation parameters and results

$\dot{\varepsilon}$ (s^{-1})	T (K)	σ (MPa)
1	1473	60
7	1473	75
14	1473	81
1	1373	79
3	1373	88
7	1373	100
14	1373	108
7	1423	86
7	1323	113

(252 kJ mol^{-1}). Furthermore, $t_{0.5}$ at 1398 and 1173 K for steels No. 1 and 3 provides similar values (250 kJ mol^{-1}).

In order to check the different apparent activation energy of steel No. 2, various tests were carried out to obtain the Zener–Hollomon equation. The deformation conditions and stress results are shown in Table II.

The Zener–Hollomon equation, obtained by an iterative method [5], is

$$\dot{\varepsilon}eRT \;=\; 7.41 \times 10^{11} (\mathrm{Sh} = 0.016\sigma)^{4.76}$$

where I is the temperature; Sh, the hyperbolic sinus; R, the gas constant, equals 8.314 J mol^{-1}; and $Q = 339 \times 10^3$ J mol^{-1}.

This high value is in agreement with that obtained from recrystallization kinetics, and shows that titanium acts as an inhibitor of grain boundary migration [9–11]. Table III shows the results of distribution and size of precipitates obtained by transmission electron microscopy (TEM) in the three studied steels after forging simulations [2]. In agreement with Gladman [12], distribution and size are better in steel No. 2 than in steels No. 1 and 3. Steel No. 1 does not contain titanium in appreciable percentage, but has particles composed of vanadium nitrides and carbonitrides [2]. Titanium does not hinder austenitic grain growth, but

TABLE III Parameters of the precipitates

Steel temperature sequences (K)	Number of precipitates	Mean distance between particles (nm)			Precipitate size distribution (%)[c]				Mean size, *d* (nm)	Volume of particles fraction
		Max.	Min.	Mean	< 20	20–40	40–60	> 60		
Steel 1										
$T_\gamma = 1523$ $T_2 = 1398$	50	1011	13	322	88 (44)	10 (5)	2 (1)	0	8.8	0.007
$T_\gamma = 1373$ $T_2 = 1323$	62	656	5	207	90 (58)	8 (5)	2 (1)	0	9.2	0.005
Steel 2										
$T_\gamma = 1523$ $T_2 = 1398$	45	1054	4	333	91 (42)	9 (3)	0	0	14.3	0.008
$T_\gamma = 1373$ $T_2 = 1323$	70	750	7	310	97 (68)	3 (2)	0	0	9.2	0.002
Steel 3										
$T_\gamma = 1523$	2[a]	270	200	240	0	0	50 (1)	50 (2)	65.0	0.009
$T_2 = 1398$	40[b]	830	10	320	85 (34)	15 (6)	0	0	10.5	0.006
$T_\gamma = 1373$	4[a]	320	320	320	0	0	50 (2)	50 (2)	45.0	0.011
$T_2 = 1323$	56[b]	630	14	380	84 (47)	16 (9)	0	0	9.3	0.004

[a] Segregated zones.
[b] Unsegregated zones.
[c] Number in parentheses refers to the amount of precipitates present.

TABLE IV Experimental results for the three steels

Heating sequences (K)	σ_T (MPa)	$\sigma_{0.2}$(MPa)	H_{v10}	ITT (°C)
Steel 1, 0.003 wt % Ti				
$T_\gamma = 1523$	860	626	269	15
$T_2 = 1398$				
$T_\gamma = 1373$	870	633	271	−7
$T_2 = 1323$				
Steel 2, 0.019 wt % Ti				
$T_\gamma = 1523$	748	491	243	−5
$T_2 = 1398$				
$T_\gamma = 1373$	760	510	233	−20
$T_2 = 1323$				
Steel 3, 0.039 wt % Ti				
$T_\gamma = 1523$	870	598	290	69
$T_2 = 1398$				
$T_\gamma = 1373$	850	569	270	36
$T_2 = 1323$				

has an important role in increasing precipitation strengthening. Steel No. 3 exhibits zones where the precipitates have been segregated, exceeding the critical size; the precipitates do not inhibit boundary grain migration. Finally, Table IV shows the actual results obtained from connecting rods carried out following the forging sequences, previously optimized by torsion tests [1–3]. In agreement with the previous paragraph, steel No. 2 has better toughness results and a lower impact transition temperature due to the smaller grain size.

4. Conclusions

1. Titanium content of 0.020 wt % has maximum efficiency as a retarder of static recrystallization in medium carbon microalloyed steels.

2. The apparent activation energy of the recrystallization process also reaches a maximum when the titanium concentration is near 0.020 wt %. When the titanium concentration is lower or higher than 0.020 wt %, the behaviour of medium carbon microalloyed steels approximates that of C–Mn steels.

3. The temperature limit for obtaining a fully recrystallized structure is also similar to that for C–Mn steels.

4. In the case of the steel with 0.019 wt % Ti this temperature raises to 1123 K, indicating that titanium is less effective than Nb and more effective than V as a single microalloying element.

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