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Mechanical properties of a recrystallized low carbon steel

R. Mendoza [a], A. Molina [b], F. Serrania [c], J.A. Juarez-Islas [d,*]

[a] *Ispat Mexicana S.A. de C.V., Fco. J. Mujica No 1B, Cd. Lazaro Cardenas, Universidad Autonoma del Estado de Morelos, Michoacan, Mexico*
[b] *Fac. Quimica—UNAM, Circuito Exterior S/N, Cd. Universitaria, 04510 Mexico, D.F.*
[c] *Instituto de Ingenieria, Circuito Exterior S/N, Cd. Universitaria, 04510 Mexico, D.F.*
[d] *Instituto de Investigaciones en Materiales—UNAM, Circuito Exterior S/N, Cd. Universitaria, 04510 Mexico, D.F.*

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Abstract

A low carbon steel sheet with 0.035% Cr responded positively to continuous annealing at 800 °C with fully recrystallized grains at ~120 s. Retardation of recrystallization was assumed to be the result of the contribution of precipitation pinning. Fully recrystallized specimens fulfilled target properties demanded by the automotive and household appliance industries.

Keywords: Steel; Rolling; Annealing; Recrystallization; Mechanical properties

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1. Introduction

During the past years in the Mexican steel industry, especial attention has been paid to the development of steels with low carbon and nitrogen contents [1], to the control of elements in part per million and to the elimination of central segregation during the last stages of solidification [2]. These improvements lead for the first time to the production of ultra low carbon steels with C plus N contents ~0.01 wt.%. The resulting steel slabs have responded positively to the applied hot rolling, coiling and cold rolling procedures and in spite of not achieving the typical chemical composition for interstitial free steels, the mechanical properties of annealed sheets equivalent to extra deep drawing applications were reached [3]. In general, during the development of steels with good deep drawing properties, research has been focused to study microstructure evolution during thermomechanical processing [4], precipitation of TiN, TiS, $(Ti,Nb)_4C_2S_2$, TiC and (Ti,Nb)C during thermomechanical processing, coiling and annealing [5], recrystallization [6] and formation of $\{1\,1\,1\}\langle uvw\rangle$ recrystallization textures in steel sheets [7]. This work present results of the effect of recrystallization on the mechanical properties of annealed sheets from an experimental steel which is intended to fulfill some applications in the automotive and household appliance industries.

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[*] Corresponding author. Tel.: +56225489; fax: +56161371.
E-mail address: julioalb@servidor.unam.mx (J.A. Juarez-Islas).

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Table 1
Chemical composition for the low carbon steel under study (in wt.%)

C	N_2	Mn	Al	Si	P	S	Cu	Cr	Nb	Ni	Ti
0.010	0.004	0.20	0.040	0.017	0.017	0.005	0.005	0.035	0.002	0.005	0.002

2. Experimental details

The steel under study was obtained after melting 100% sponge iron into an electric arc furnace, vacuum degassed, ladle treated and continuously casted to get ingots of 200 mm in thickness and 962 mm wide. Slabs were re-heated at 1100 °C and hot rolled to 2.6 mm in thickness (15% reduction per pass, 91% of total reduction) with a finishing temperature of 870 °C and coiled at 600 °C. The hot rolled coils were room temperature cold rolled 73% reduction to get 0.7 mm in thickness. Cold rolled coils were: (i) batch annealed at 670 °C (20 h) under a N_2–H_2 atmosphere (ratio 4/1) and (ii) continuously annealed at 700, 750 and 800 °C. Specimens were metallographically observed and progression of recrystallization followed by a point counting technique (ASTM E112-828). STEM observations and microanalysis were performed on a 1200 Jeol transmission electron microscope. Flat tensile tests (ASTM E-8-98) on fully recrystallized specimens were performed on an Instron 1125 (15 tones) test machine.

3. Results and discussion

The average chemical composition for the experimental low carbon steel under study is shown in Table 1, which was designed to fulfill the automotive and household appliance industries with target properties of 170 MPa of 0.2% yield strength, 345 MPa of tensile strength, 46% of elongation, a strain hardening exponent, $n > 0.21$ and an average plastic anisotropy ratio, $r \geqslant 2$.

During characterization of samples, a ferrite microstructure was observed in the re-heated, hot rolled and coiled specimens with the presence of globular carbides in subgrain boundaries of ferrite matrix (Fig. 1a). These carbides (identified by STEM as $Cr_{23}C_6$) were aligned on the large-angle boundary of the cold rolled ferrite (Fig. 1b). During annealing, the recrystallized grains nucleated and grew from the large-angle boundary of the cold rolled ferrite (Fig. 1c).

Room temperature mechanical properties of batch and continuous annealed steel coils are shown in Table 1 together with target properties.

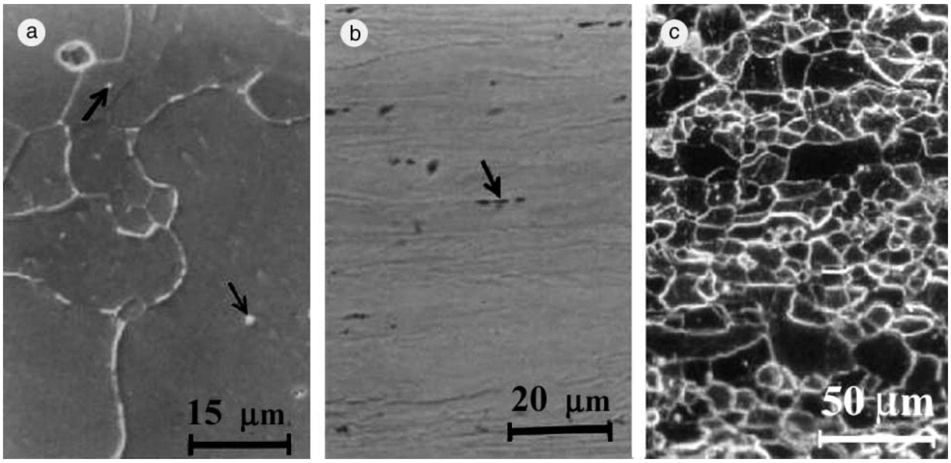

Fig. 1. Ferrite microstructure observed in (a) coils, (b) cold rolled and (c) partially recrystallized specimens with the presence of $Cr_{23}C_6$ carbides (shown by arrows).

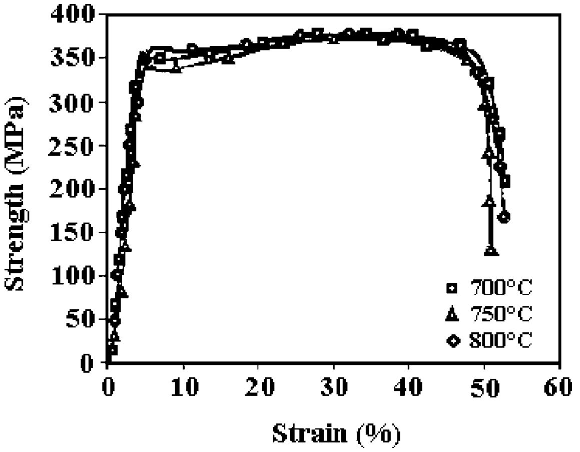

Fig. 2. Strength–strain curves for continuously annealed specimens at 700, 750 and 800 °C.

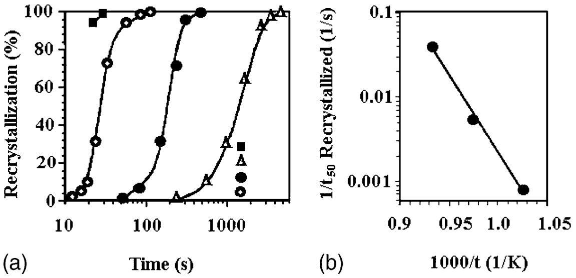

Fig. 3. (a) Recrystallization curves and (b) Arrhenius plot for the apparent activation energy of recrystallization, for the experimental low carbon steel, cold rolled 73%, coiled at 600 °C and annealed at 700, 750 and 800 °C.

As can be seen, after batch annealing, the tensile mechanical properties and *r* values were inferior to target properties, while continuous annealed coils and specially those annealed at a temperature of 800 °C showed tensile mechanical properties (Fig. 2), *r* and *n* values above target properties (Table 2).

Fig. 3 shows the progress of recrystallization for the cold rolled steel at annealing temperatures of 700, 750 and 800 °C and also an Arrhenius plot for the apparent activation energy of recrystallization. Regarding recrystallization, the rate of recrystallization for the three temperatures (i.e. 1.2×10^2 s at 800 °C, Fig. 3a) is reduced as compared with the rate of recrystallization of Al-killed steels (curve AK in Fig. 3a) which reaches 100% of recrystallization at about 20 s at 700 °C [6].

To follow ferrite recrystallization kinetics, an Arrhenius equation of the form $1/t_r = A_O e^{(-Q/RT)}$ was assumed (Fig. 3b), where t_r is the time needed for the steel during annealing to reach 50% of recrystallization, A_O is a preexponential frequency constant, Q is the apparent activation energy for recrystallization, R the gas constant and T the temperature. Table 3 shows values of the apparent activation energy for recrystallization and preexponential factors for the steel under study together with data for aluminium killed and titanium stabilized interstitial free steels. The apparent activation energy of recrystallization for the low carbon steel under study was close to that corresponding to titanium stabilized steel and different to the value corresponding to the aluminiun killed steel, which implies the need for more energy to get a complete recrystallization of the deformed ferrite of the low carbon steel under study as compared with the aluminum killed steel.

During recrystallization of the low carbon steel, ferrite grains nucleate and grow mainly from the large-angle boundaries of the cold rolled microstructure, resembling a semiblocky microstructure. As recrystallization proceed, grain boundary migration was retarded due to the presence of

Table 2
Mechanical properties of annealed steel specimens with a fully recrystallized microstructure

Properties→ Specimen↓	0.2YS (MPa)	TS (MPa)	El (%)	*r* (–)	*n* (–)
Target properties	170	345	46	⩾ 2	>0.21
Batch annealing 670 °C	169 ± 17	318 ± 20	43.8 ± 2.8	1.98 ± 0.03	0.24 ± 0.01
Isothermal annealing 700 °C	327 ± 25	383 ± 18	43.4 ± 3.5	1.35 ± 0.12	0.32 ± 0.05
Isothermal annealing 750 °C	344 ± 11	373 ± 9	50.3 ± 0.7	1.62 ± 0.04	0.31 ± 0.03
Isothermal annealing 800 °C	261 ± 9	361 ± 16	51.2 ± 0.5	2.21 ± 0.07	0.30 ± 0.01

± is the average of 20 measurements.

Table 3
Values of Q and A_O for aluminiun killed, low carbon and interstitial free steels

Steel	$1/tf$ (1/s)	T (K)	Q (cal/mol)	A_O (–)
Aluminun killed steel	2.0×10^{-2}	700	43,000	9.30×10^{8} [6]
Low carbon	5.7×10^{-2}	750	79,424	8.40×10^{14}
Interstitial free + Ti	5.0×10^{-3}	750	88,000	4.60×10^{17} [6]

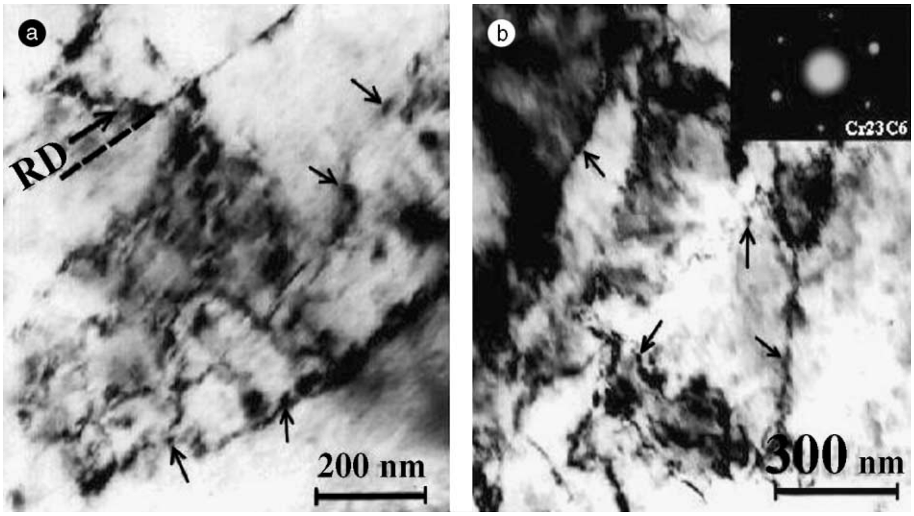

Fig. 4. Microstructure of low carbon steel, coiled at 600 °C and annealed at 800 °C, where it is observed that boundaries of the partially recrystallized grains are decorated with fine precipitates. *RD* = rolling direction.

particles with an average radius of 14.5 ± 5 nm (Fig. 4). In the steel under study, it was observed that chromium carbides particles play an important role to increase the recrystallization stop temperature. To explain this behavior, theories include solute drag [8] and precipitate pinning [9,10]. For precipitate pinning, theories include the rigid boundary model which considers that a grain boundary is only capable of interacting with those precipitates laying within a particle radius of the boundary plane, the flexible boundary method assumes that the boundary is infinitely flexible and moves until pinned by every particle capable of interacting with it, and the subgrain boundary model which considers the effect of precipitates on subgrain boundaries prior to recrystallization.

In order to retard recrystallization, the precipitate pinning force ($F_p = 2\gamma N_v rl$, where γ is the boundary energy, N_v number density of particles, r the particle radius and l the average subgrain diameter) must exceed the driving force of recrystallization ($F_r = \mu b^2 \Delta\rho/2$, where μ is the shear modulus, b the Burgers vector and $\Delta\rho$ the change in dislocation density). From the average particle radius measured in the low carbon steel under study and the data of [10] (i.e. $Fr = 2.1 \times 10^5$ $\mathrm{N\,m^{-2}}$, $1 = 720 \pm 250$ nm and $\gamma = 0.8$ $\mathrm{J\,m^{-2}}$), it was determined a value of $N_v = 3 \times 10^{21}$ ($\mathrm{m^{-3}}$), similar to the value measured by TEM in microalloyed steels and reported in [11], and sufficient to pin the subgrain structure. Therefore, it was assumed that reduction of the recrystallization time of the steel under study as compared with Al-killed steels, is the result of the presence of chromium carbides which impede the necessary migration of the large-angle boundary for stable nucleus formation.

These preliminary results suggest that the low carbon steel under study obtained after using 100% sponge iron as a raw material, responded positively to the applied thermomechanical, coiling and mechanical processes. The addition of microalloying elements such as chromium, as in this case, helped to retard recrystallization by precipitation pinning. Annealed coils at a temperature of 800 °C reaches in 120 s 100% of recrystallization, fulfilling at the same time target properties demanded by the internal automotive and household appliance industries.

4. Conclusions

1. Taking into account the steelmaking practice, thermomechanical, coiling and mechanical processes applied to the steel slab to obtain steel sheets, the addition of 0.035 wt.% Cr to the low carbon steel helped to retard recrystallization kinetics. This can be explained by the presence of fine particles identified as chromium carbides.
2. Steel sheets responded positively to continuous annealing and in particular coils annealed at 800 °C, fulfill the target properties demanded by the internal automotive and household appliance industries. 100% recrystallized specimens showed values of 261 MPa of 0.2% yield strength, 361 MPa of tensile strength, 51.2% of elongation, strain hardening exponent of 0.30 and a average plastic anisotropy ratio of 2.21.
3. The apparent activation energy of recrystallization for the low carbon steel showed a value close to that corresponding to titanium stabilized interstitial free steel, higher than the one corresponding to aluminium killed steels, which implies the need of more energy to achieve 100% of recrystallization.
4. This retardation of recrystallization was assumed to be the result of the contribution of precipitation pinning.

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