Materials Science and Engineering A368 (2004) 249–254

MATERIALS SCIENCE & ENGINEERING A

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Evaluation of low carbon Al-killed/Cr-stabilized steel to be used in the automobile industry

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Received 16 June 2003; received in revised form 31 October 2003

Abstract

An Al-killed/Cr-stabilized low carbon steel was produced in the steel industry using electric arc furnace, vacuum degassing, ladle treatment and continuous casting route. The resulting slabs were then hot rolled at 1100 °C, coiled at 600 °C, cold rolled and annealed at 700 °C. After evaluation of the microstructure, texture and mechanical properties, the fully recrystallized coils fulfilled the target properties established by the automobile industry.

Keywords: Low carbon steel; Microstructure; Annealing; Texture; Mechanical properties

1. Introduction

Ultra low carbon Ti-stabilized interstitial free steel sheets (IF) have been developed for use in the automotive industry because they meet the requirements for good drawability in order to produce panels with complex shapes [1]. This high formability has been achieved as a result of lowering the interstitial carbon and nitrogen contents during the steelmaking practice and by the addition of stabilizing elements such as titanium and niobium [2]. As a result, the ferrite matrix of heavily cold rolled IF sheet steels, recrystallized during annealing to a polycrystalline structure with a strong γ-fiber (⟨1 1 1⟩//ND) recrystallization texture [3]. Formation of recrystallization texture in metals has been discussed exploring two mechanisms: (a) oriented nucleation [3] and (b) selective growth [4,5]; which for high drawability steels, implies that the first mechanism will be dominant [6,7]; it has been shown [8,9] that γ-fiber texture is nucleated at the grain boundaries and proceeds to grow consuming the deformed neighboring grains. In addition, attention has been paid to the improvement of the final product by controlling hot rolling parameters [10]. For instance, hot rolling in the ferrite region followed by annealing recrystallization resulted in stronger γ-fiber [11], and increasing the strain rate during ferrite rolling enhances the development of this texture [12]. Furthermore, lowering the rolling temperature from 850 to 600 °C also resulted in higher γ-fiber intensities [10] which have an impact on the drawability of annealed sheets. This work shows results of an industrial trial of a low carbon Al-killed/Cr-stabilized steel which intended as an annealed sheet for deep drawing applications in the automotive industry.

2. Experimental procedure

An Al-killed/Cr-stabilized low carbon steel was produced at Ispat Mexicana by an electric arc furnace, vacuum degassing, ladle treatment and continuous casting route. The resulting chemical composition of slabs is given in Table 1. The steel slab (250 mm in thickness) was reheated and hot rolled at an average temperature of 1100 °C achieving in 16 steps 81% of accumulative hot-reduction, finishing the hot rolling operation at 840 °C. The resulting plate (5 mm in thickness) was air cooled in the runout table and coiled at 600 °C. After cold rolling, the sheet showed an accumulated thickness reduction of 85%, ending with a thick-

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doi:10.1016/j.msea.2003.11.012

Table 1
Chemical composition of the Al-killed/Cr-stabilized low carbon steel (in wt.%)

C	N_2	Mn	Al	Si	P	S	Ti	Cr	Nb
0.020	0.004	0.20	0.040	0.025	0.011	0.005	0.002	0.035	0.002

ness of 0.3 mm. The sheets were isothermally annealed under an argon atmosphere at 700 °C from 1 to 300 s. The heating and cooling rate of annealed sheet specimens were ∼10 and ∼80 °C/s, respectively. The specimens were metallographically observed under a 440 Stereoscan scanning electron microscope and a 2100 Jeol scanning transmission electron microscope, and the progression of recrystallization was followed by a point counting technique [13]. Flat tensile (ASTM E-8) tests on fully annealed specimens were conducted on an Instron 1125 (10 t) test machine at a strain rate of $5 \times 10^{-3}\,s^{-1}$. From the tensile test experiments in the annealed condition, it was calculated the normal plastic anisotropy ratio value at 0°, 45° and 90° with respect to the rolling direction; from these values, the average plastic anisotropy ratio value was obtained, ($\bar{r}$). Texture measurements on samples were carried out on a Siemens D5000 texture goniometer using cobalt radiation; the pole figures were measured up to a tilt angle $\chi = 80°$; the steps were $\Delta\chi = 2.5°$ in the tilt direction and $\Delta\phi = 4°$ in the azimuth direction.

3. Results and discussion

The microstructure obtained in hot rolled plates is shown in Fig. 1a, obtained after hot rolling of the slab from 1100 to 840 °C in 16 steps and an accumulative hot reduction of 81%, air cooled and coiled at 600 °C. The grain size obtained under these conditions was about 20 ± 0.9 μm. Figs. 1b and c show SEM-micrographs of the as-cold rolled specimen. As may be observed, the ferrite grains are flattened, and inside the grains, some shear bands can be observed. These in-grain shear bands corresponded to the narrow regions of intense shear that carry large strains during deformation and appear to become the major deformation mode [14]. In some interstitial free-steels, it was observed that in-grain shear bands were inclined principally at angles of 30°–35° to the rolling plane [15]. In the steel sheet under study, the shear bands were inclined ∼32° with respect to the rolling plane and were relatively planar and parallel to each other within the individual grains.

The grain boundary, after the cold rolling operation, remaining closely parallel to the sheet plane and when the steel sheet was annealed, recrystallization initiated preferentially in the region of the original grain boundary; spreading from there into the adjacent grains (Fig. 2a). It appears that the coiling temperature of 600 °C in combination with the 85% per cent of accumulative deformation was sufficient to induce recrystallization at 700 °C in 180 s (Fig. 3). This re-

(a)
(b)
(c)

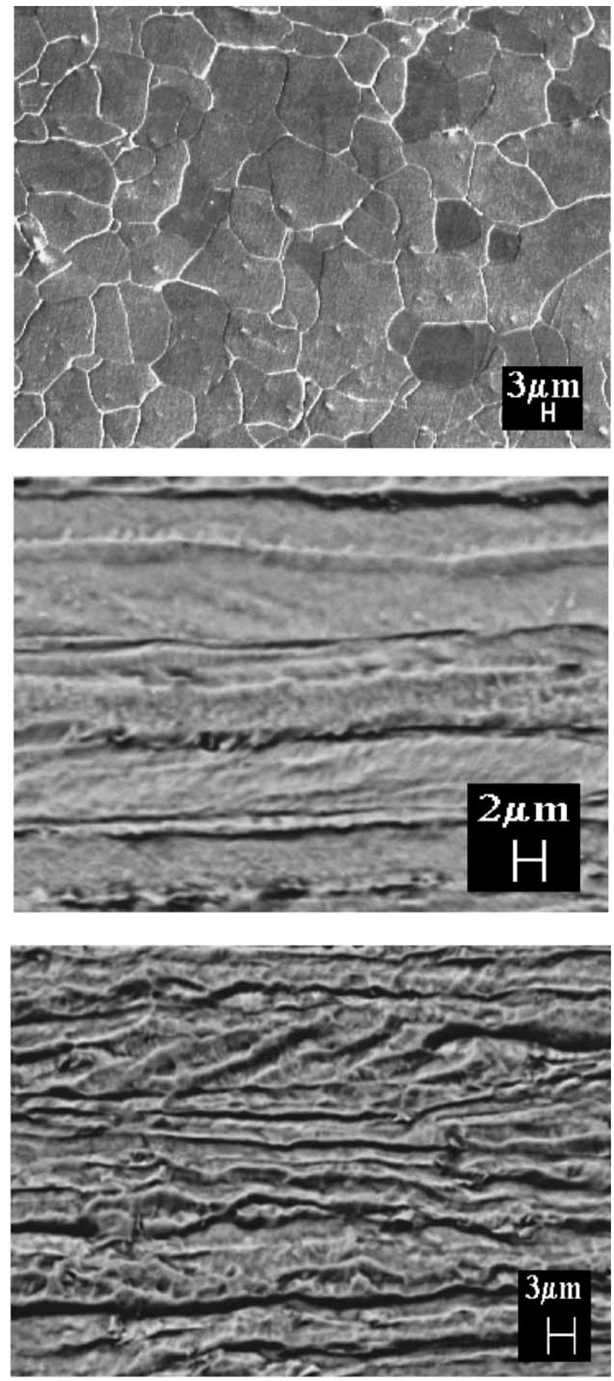

Fig. 1. Ferrite microstructure obtained in hot rolled plates, (b) and (c) flattened ferrite grains closely parallel to the sheet plane and inside the grains, some shear bands are observed.

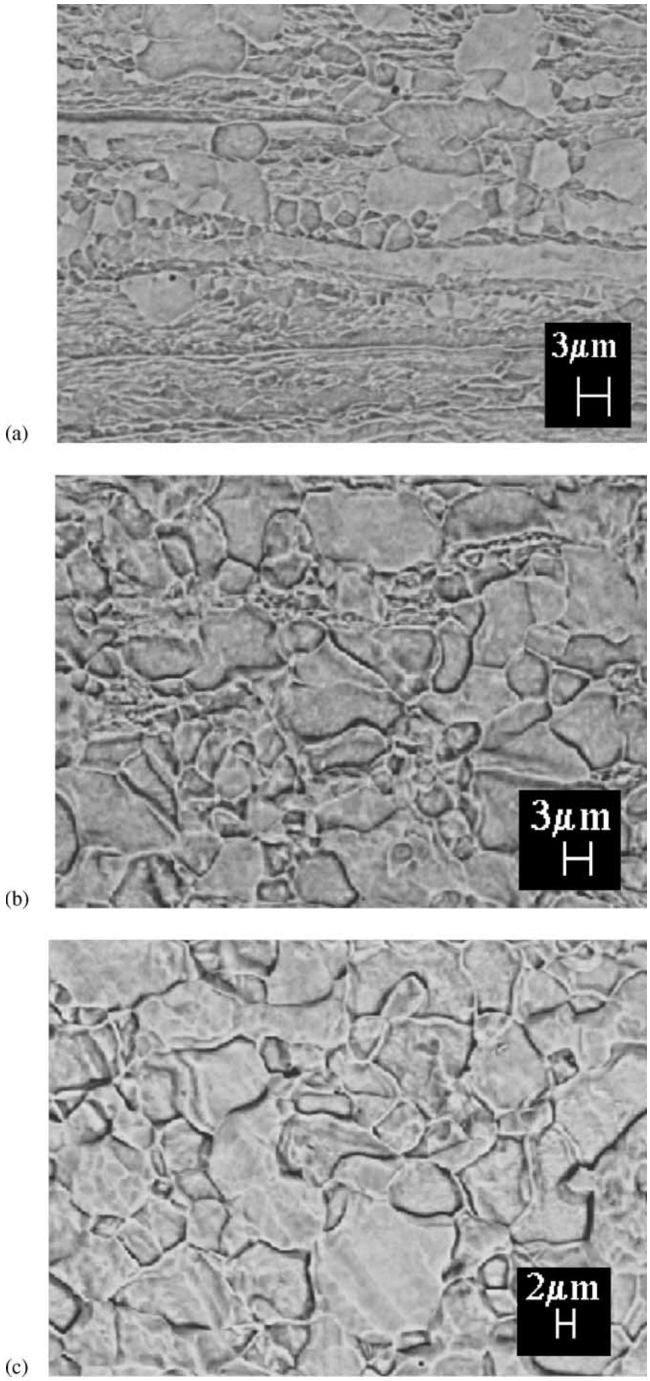

Fig. 2. (a), (b) Ferrite microstructure of partially recrystallized sheets (10%), where it can be observed that recrystallization initiates preferentially in the region of the original grain boundary and (c) fully recrystallized ferrite grains.

crystallization rate is significantly lower than the rate of recrystallization of Al-killed steels (i.e 100% of recrystallization in 20 s [2]). This delay in the recrystallization time is attributed to the contribution of chromium carbides (Fig. 2b), which retarded grain boundary migration by a pinning effect of Cr-precipitates [16]. The ferrite grain size achieved in samples with 100% of recrystallization was $11 \pm 0.6\,\mu m$,

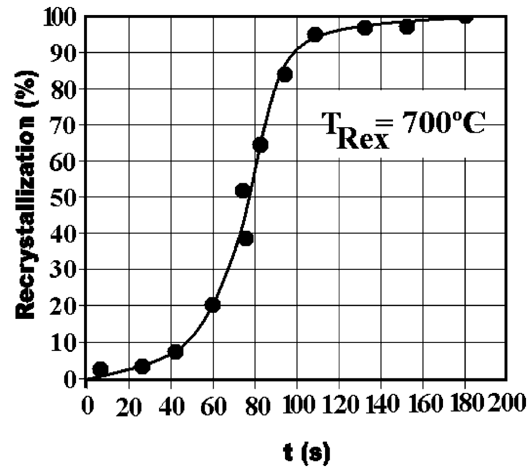

Fig. 3. Recrystallization curve for annealed coils at 700 °C.

and the microstructure observed in this condition, consisted of a nonequiaxed grain shape (Fig. 2c).

Fig. 4 shows {1 0 0} pole figures for the steel under study in the hot rolled, cold rolled and annealed conditions. It may be observed that, in the cold rolled sheet, a {5 5 4}<2 2 5> component near {1 1 1}<1 1 2> texture appeared which is a typical cold rolled texture for extra low carbon interstitial free steels. In a similar fashion, the annealed sheet showed an appreciably strong texture than in the as cold rolled condition, from {5 5 4}<2 2 5> component near {1 1 1}<1 1 2> to {2 1 1}<0 1 1>. As reported in [16,17], during recrystallization, the pinning force exerted by precipitates on the grain boundaries is one of the most important factors controlling the recrystallization texture. For instance, Barnett and Kestens [18] report that for observations carried out in low carbon, ultra low carbon and interstitial free steels, regarding the presence of in-grain shear bands; the increasing density and severity of these in-grain shear bands lead to a bulk recrystallization texture dominated by {1 1 1}<1 1 2> near the normal direction–rolling direction (ND–RD), especially when chromium was added to the low carbon steel. Fig. 5 shows a STEM-photograph of a partially recrystallized microstructure, where the roll played by chromium-carbides precipitates in retarding the recrystallization rate of the low carbon Al-killed/Cr-stabilized steel and probably to the contribution in the formation of {1 1 1}<1 1 2> textures may be observed.

On the other hand, industrial considerations in automotive technology are: (i) to improve safety and fuel efficiency by reducing vehicle weight and (ii) to shorten the manufacturing process of body panels. To achieve those goals, interstitial free steels have been hot rolled in the austenite region. Reports show that when the finish discharge temperature was lower than the α/γ transformation temperature, the appearance of a coarse grain structure in hot bands and a decrease in the intensity of {1 1 1} texture in cold rolled and annealed sheets was observed, resulting in a deterioration of its drawability [19]. Further research [20] showed that

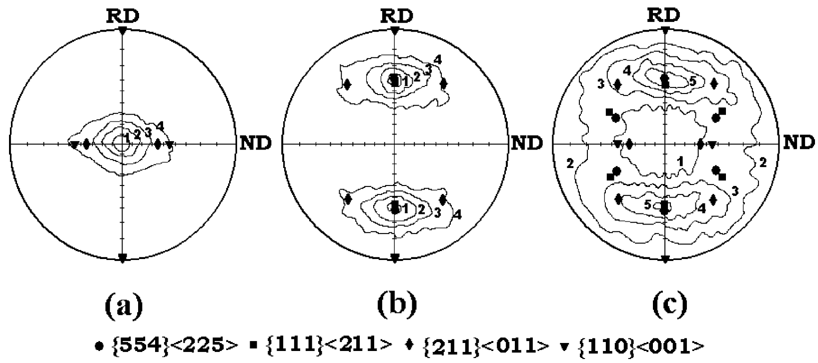

Fig. 4. {1 0 0} pole figures for the steel under study in (a) hot rolled, (b) cold rolled and (c) annealed conditions.

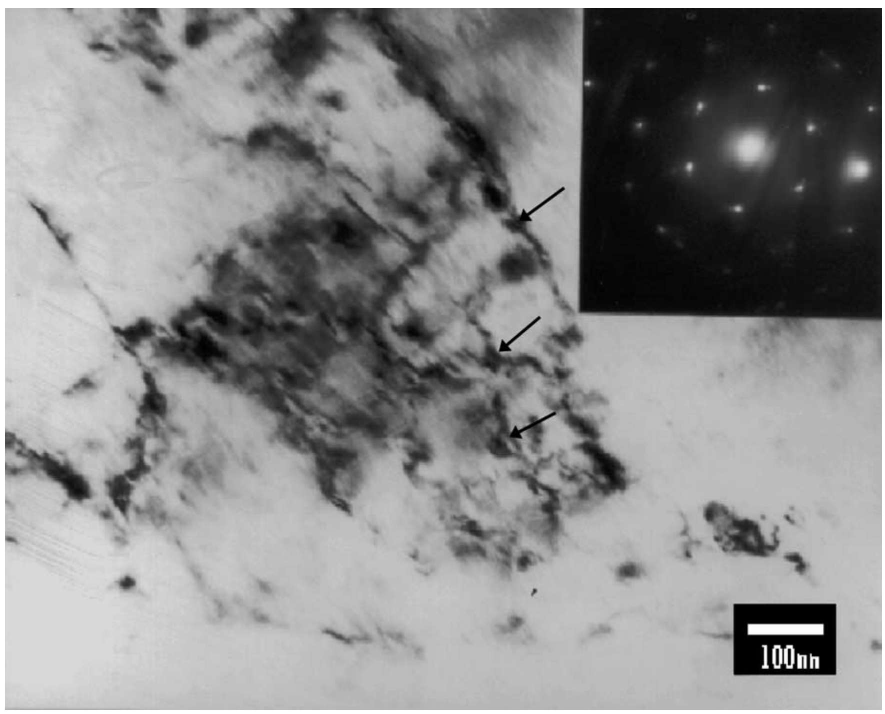

Fig. 5. TEM photograph of a partially recrystallized microstructure, where can be observed the roll played by chromium-carbides precipitates in retarding the recrystallization rate of the steel.

Table 2
Chemical composition and mechanical properties of several IF steels

Steel	C	N_2	Mn	Al	Si	P	S	Ti	Cr	Nb	Reference
A	0.0040	0.0020	0.16	0.043	0.008	0.010	0.010	0.078	–	0.003	[21]
B	0.0042	0.0010	0.15	0.043	0.010	0.007	0.013	0.068	–	0.004	[21]
C	0.0050	0.0070	0.08	–	0.10	0.022	0.002	0.23	17.20	–	[22]
D	0.0035	0.0310	0.14	0.045	0.002	0.009	0.008	0.054	–	0.010	[23]
E	0.0021	0.0039	0.24	0.011	0.026	0.098	0.008	0.024	–	0.041	[23]
F	0.0015	0.0025	0.12	0.030	–	0.005	0.006	0.01	–	0.02	[24]
G	0.0030	0.0030	0.35	0.03	–	0.05	–	0.020	–	0.035	[24]

Steel	YS (MPa)	TS (MPa)	El (%)	*r*	*n*	Reference
A	175.2	308.2	47.9	2.12	0.230	[21]
B	178.6	309.6	43.8	1.69	0.220	[21]
C	285.0	490.0	30	1.86	–	[22]
D	146.0	217.0	53.8	2.40	0.252	[23]
E	200.0	355.0	45.0	1.92	0.222	[23]
F	120.0	290.0	45.0	2.40	0.240	[24]
G	220.0	390.0	37	1.9	0.21	[24]

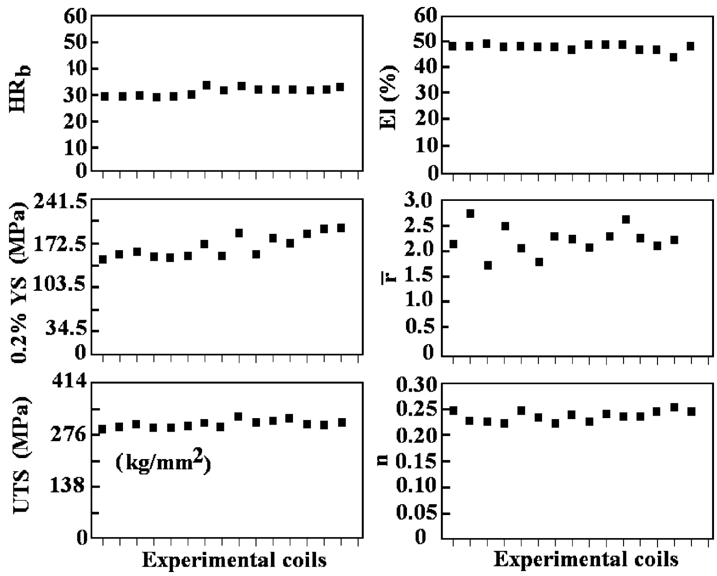

Fig. 6. Mechanical properties of annealed coils. (a) Hardness Rockwell b, (HR_b), (b) 0.2% of yield strength, (YS), (c) tensile strength, (TS), (d) percent of elongation, (El), (e) the average plastic anisotropy value, ($\bar{r}$) and (f) the strengthening hardening exponent, n.

hot rolling temperatures of interstitial free steels at 1050 °C resulted in similar values of the average plastic anisotropy ratio as compared to those IF steels hot rolled at 1200 °C. However, the resulting mechanical properties of annealed sheets may depend on the diversity of the steel composition, hot rolling process, finish discharge temperature, coiling, cold rolling process and annealing temperature. For instance, Table 2 shows some ultra low carbon steel compositions with their respective mechanical properties. As can be observed, the most commonly produced steel corresponds to the interstitial free steel with carbon contents up to 50 ppm and nitrogen contents from 20 to 310 ppm, which have been stabilized with Ti and/or Nb additions. And in spite of having similar compositions (i.e. steels A and B), only steels A, D and F fulfilled target properties required in the automobile industry (see Table 3). Regarding the steel under study, Fig. 6 shows experimental results obtained in 15 industrial coils after being annealed at 700 °C and with a fully recrystallized microstructure. Results are shown in terms of Rockwell B hardness, (HRB), 0.2% of yield strength, (YS), tensile strength, (TS), percent of elongation, (El), the average plastic anisotropy value, ($\bar{r}$) and the strengthening hardening exponent, (n). As shown in Table 3, the steel under study fulfills target properties dictated by the automobile industry. This achievement was obtained after introducing some technological modification to the steelmaking practice such as decarburization of molten steels by vacuum degassing, the use of 100% sponge iron and stabilizing the steel with chromium.

Table 3
Target properties to satisfy the requirements of the automobile industry together with the average properties of the steel under study

0.2% YS (MPa)	TS (MPa)	El (%)	*r*	*n*
138–173	242–345	46	>2	>0.21
172.5	300.6	47.1	2.2	0.237

4. Conclusions

1. The low carbon Al-killed/Cr-stabilized steel shows outstanding behavior in terms of mechanical properties suggesting its use as an annealed sheet in the automobile industry.
2. Automobile target properties were achieved in annealed sheets after employing low temperatures in the hot rolling (1100 °C instead of the typical 1250–1200 °C) and annealing (700 °C instead of the high recrystallization temperatures of 850 °C, normally needed in interstitial free steel) processes.
3. The use of low rolling and annealing temperatures may represent industrial advantages from the point of view of reducing energy consumption of at least 20–40 MCal/t per 100 °C.
4. The use of chromium instead of titanium or niobium elements to stabilize the low carbon steel (a part of the steelmaking practice and hot rolling schedules) was effective in retarding its recrystallization rate, enhancing formation of {1 1 1}<1 1 2> textures and in allowing $\bar{r}$ values >2.

Acknowledgements

The authors are grateful for the assistance of Mr. E. Caballero and Fis R. Reyes.

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