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Mechanical Properties and Crystallographic Texture of Symmetrical and Asymmetrical Cold Rolled IF Steels

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The crystallographic texture developed during cold rolling and subsequent annealing of interstitial free sheet steels aims to increase conformability. For this, it is necessary to obtain partial α-fiber and continuous and homogeneous γ-fiber texture components. In this work, the influence of symmetric (SR) and asymmetric (AR) cold rolling on crystallographic texture and mechanical properties of an interstitial free steel (IF) was investigated. Symmetric cold rolling yields α- and γ-fibers, which are enhanced as deformation increases. Moreover, α-fiber weakening occurs due to recrystallizations, improving formability. The same fibers are produced by asymmetric cold rolling, but in this case, the γ-fiber is slightly shifted in psi, which is one of Euler angles second ROE's notation[1,2], and more homogeneous than in symmetric rolling. The best mechanical properties were achieved by asymmetric cold rolling/annealed with about 80% deformation.

Keywords: *IF Steels, Asymmetrical Cold Rolling, Texture, Mechanical Properties, Symmetrical Cold Rolling, Formability*

1. Introduction

Interstitial free steels (IF) are widely used in the automotive industry[3,4] thanks to their low tensile strength (100 to 350 MPa) and high formability. The industry tries to improve these properties even more, through appropriate thermomechanical processes such as cold rolling and annealing.

Cold rolling is one of the techniques used to obtain preferred orientations in the material that will improve its mechanical properties, especially the formability. Cold rolling may be symmetrical or asymmetrical. In the first case, the rolls have the same diameter, the same speed and the same friction coefficient. In the second, at least one of those conditions is different, leading to an additional shear strain, which may improve the mechanical properties and the formability[5].

By definition, the normal anisotropy coefficient (r_m or $\overline{r}$) is the planar average of r value, which is the ratio of the width strain ($\ln(w_0/w)$ to the thickness strain ($\ln(t_0/t)$ ($r = \ln(w_0/w)/\ln(t_0/t)$), obtained by a simple tensile test[6]. In this equation, w_0 and t_0 are the initial sample width and thickness, respectively, and w and t its width and thickness after about 15% of plastic deformation. This parameter is generally used to verify the ability of a sheet to undergo deep drawing. The larger this coefficient, the better is the formability[7,8]. This can be seen in Equation (1), where, r_0, r_{45}, r_{90} are r values obtained for samples removed 0, 45 and 90º degrees from the rolling direction and $\overline{r}$ is the normal anisotropy coefficient.

$$\overline{r} = \frac{r_0 + 2r_{45} + r_{90}}{4} \quad (1)$$

In ultra-low carbon steels, the preferred orientations are located in two main fibers: α (<110>//Rolling Direction-RD) and γ (<111>//Normal Direction-ND)[9], regardless of the rolling technique[10]. High formability is associated with a high fraction of γ-fibers and a low fraction of α-fibers[11].

If, r_0, r_{45} and r_{90} exhibit significant differences, the "earing phenomenon" can occur, due to the planar anisotropy (Δr) condition described by Equation (2)[12]:

$$\Delta \mathrm{r} = \frac{r_0 + r_{90} - 2r_{45}}{2} \quad (2)$$

The sheet formability is also influenced by the hardening coefficient (n), which, using Hollomon equation[13] ($\sigma = K\varepsilon^n$), is the slope of the $\ln(\sigma)$ versus $\ln(\varepsilon)$ curves in the plastic regime and numerically equal to the uniform elongation. This parameter is important for forming operations, because it measures the hardening ability of the material, i.e., its ability to homogeneously distribute deformation along the sheet surface before necking[14].

This work aims to compare the effect of symmetrical and asymmetrical cold rolling in the texture and mechanical properties of an IF steel.

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2. Experimental Procedure

A hot-rolled IF steel with 4.9 mm thickness produced by Companhia Siderúrgica Nacional (CSN) – Brazil was used in this research. Its chemical composition (wt.%) was: 0.002 %C, 0.104 %Mn, 0.011 %P, 0.06 %Ti, 0.009 %S, 0.003 %Ni, 0.001 %Sn, 0.035 %Al, 0.004 %N,0.002 %Nb and Fe is the balance.

Symmetrical (SR) and asymmetrical (AR) cold rolling were performed in a FENN MFG. Co, model D51710 Rolling Mill to 70, 80 and 90 % thickness reductions. The configuration for SR was two mill rolls with 133.70 mm diameter each (duo configuration). For the AR, upper and lower rolls with 40.18 mm and 31.72 mm diameter, respectively, were used. For analyzing the effect of annealing, after rolling, samples were annealed in a salt bath at 850 °C for 120 s and cooled in air. Finally, the samples were mechanical polished to half thickness and etched by a 5 % hydrofluoric acid (HF) and 95 % peroxide (H_2O_2) solution for 20s.

The X-ray measurements were performed on a PANalytical, X'Pert PRO MRD diffractometer using Co-Kα radiation and yielded (110), (200) and (211) pole figures. These experimental pole figures were processed with the help of popLA software and they are presented for 0º and 45º φ_2 sections using the Bunge notation.

In order to evaluate the mechanical properties of the annealed materials, 5 rectangular samples with dimensions of 15 x 100 mm, were cut for each processing condition, i.e., symmetric and asymmetric cold rolled followed by an 850ºC during 120 s annealing process, on three different angles with the rolling direction: 0°, 45° and 90°, totalizing 90 samples. The tensile tests were conducted on an EMIC DL 10000 machine with a 3mm/min loading rate, following the ABNT NBR 6892-1[15] standard, and the yield point (σ_e), tensile strength (σ_m) were evaluated. The ABNT NBR 16282[16] was followed for r_m, Δr and work hardening coefficient (n) determinations. The highest and the lowest values of each measurement were discarded and the average of the others was taken as the final result.

3. Results and Discussion

The φ_2 = 45º sections of the Orientation Distribution Function (ODF) for the symmetrical cold rolled and annealed samples are shown in Figure 1. α- and γ-fibers can be observed for 70, 80 and 90 % cold rolled samples. The volume fraction of α-fibers increases up to 90 % deformation, but the volume fraction of γ-fibers is smaller for 90 % deformation than for 80 % deformation. This may be related to the development of a new <110>//RD component, which inhibits the development of γ-fibers. The effect of annealing is to decrease the volume fraction of α-fibers and to increase the volume fraction of γ-fibers, thus increasing the formability of IF steels[17]. The graphs of Figure 2 illustrate the development of α- and γ-fibers for all symmetrical cold rolled and annealed samples.

Since the deformation of asymmetrically rolled samples is not homogenous over the sheet thickness, the texture was analyzed in three different sample positions: on the lower and upper surfaces and in the middle plane. Generally, the texture was the weakest in the lower surface and the strongest in the upper surface, where it was similar to that of symmetrically rolled samples. For comparison, Figure 3 shows the φ_2 = 45º ODF sections for the middle plane, where no components are observed at Φ = 54.7º, the original position of the γ-fiber. In this Figure 3, it can be seen the ODF sections for annealed 70, 80 and 90 % asymmetrically cold rolled samples. This is taken as evidence of a shift of the position of the γ-fiber, as reported by Tóth *et al*[18]. The graphs of Figure 4 show the volume concentration of α- and γ-fibers in asymmetrically rolled samples, before and after annealing. It can be seen that the volume fractions of α- and γ-fibers are smaller than in symmetrically rolled samples and that annealing decreases the volume fraction of α-fibers and thus increases formability.

Stress–strain curves of annealed symmetrically and asymmetrically cold rolled samples are shown in Figure 5. It can be observed that the yield (σ_e) and tensile (σ_m) strengths increase with deformation for both symmetrically (SRXX-Y) and asymmetrically (ARXX-Y) rolled/annealed samples, where XX denotes the deformation degree and Y is the angle with which the sample was taken. Asymmetrical rolling yielded larger values of σ_e and σ_m values for all deformations and angles, except for SR90-0 sample, whose σ_m was larger than that of asymmetrically rolled/annealed samples.

The larger tensile strength (σ_m) of asymmetrically rolled samples may be due to the fact that the larger shear stress associated with asymmetrical deformation leads to grain breaking and, consequently, to a smaller grain size in the rolled sample[19]. Wauthier et al.[20] reported that this phenomenon could be observed by EBSD. The values of σ_m and σ_e in this work are larger than those reported by other authors[21, 22].

As shown in Table 1, the work hardening coefficient n decreases with increasing deformation, as might be expected if deformation becomes more and more nonhomogeneous as thickness reduction progresses. The decrease is approximately linear and, in the case of asymmetric rolling, can be described by Eq. 3, where $\%x$ is the percentage relative thickness reduction and the coefficient of determination is 0.95.

$$n = 0.9741 - 0.0095\%x \qquad (3)$$

Table 2 shows the normal and planar anisotropy of the annealed samples. The values are lower than the expected for this type of material[23-25]. The largest value of r_m was 1.45 for the SR90 samples. Annealed asymmetrically rolled samples reached even lower values of r_m values, around 1.0.

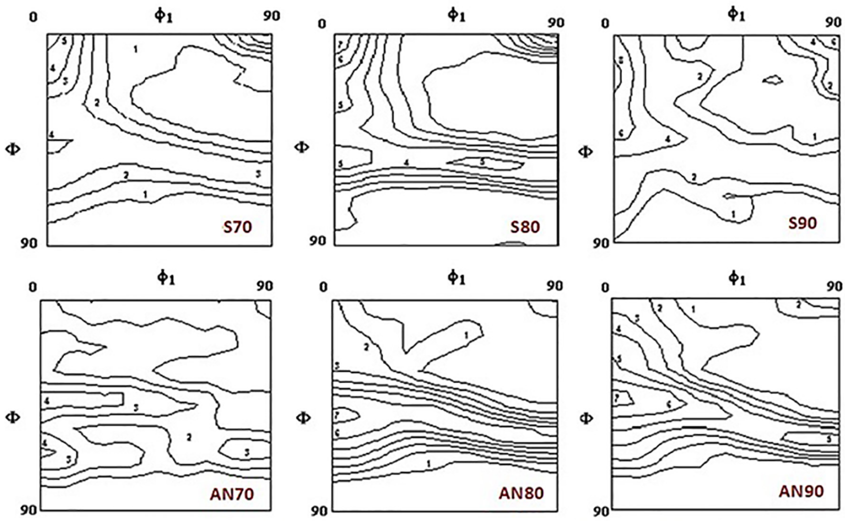

Figure 1: ODF section of φ2 = 45º for IF steel samples symmetrically cold rolled (S) for 70, 80 and 90% and after annealing (AN).

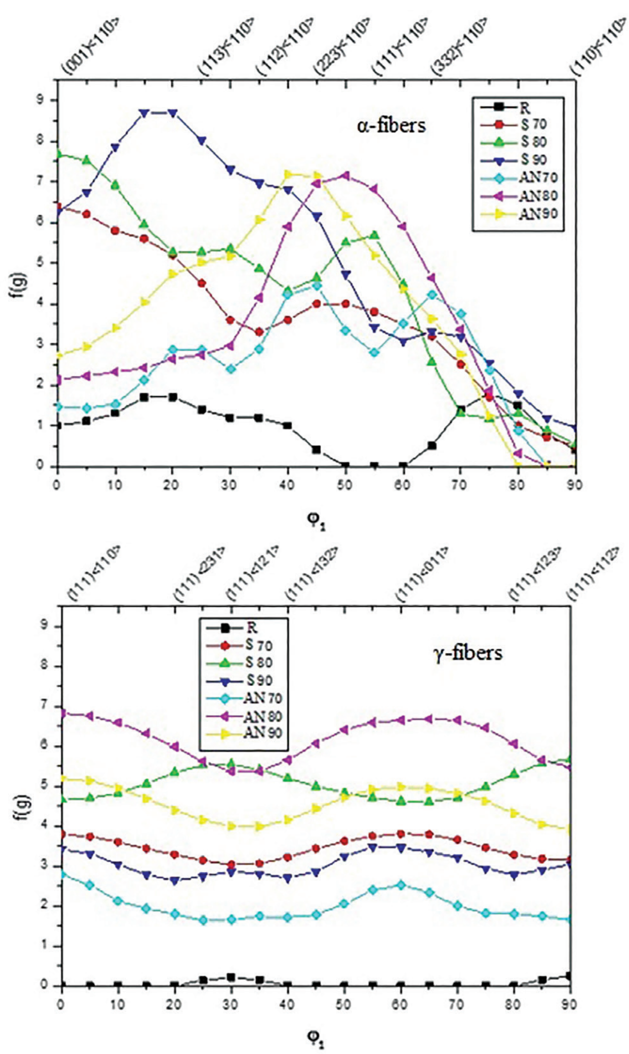

Figure 2: α- and γ-fibers plots for IF steel samples 70, 80 and 90 % symmetrically cold rolled (S) and after annealing (AN).

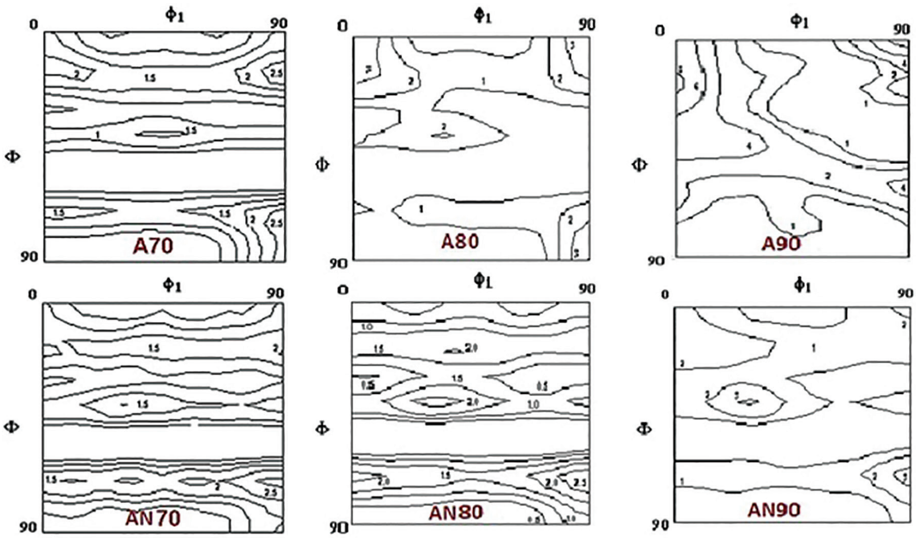

Figure 3: ODF section of φ2 = 45º for IF steel samples asymmetrically cold rolled (A) for 70, 80 and 90 % and annealed (AN).

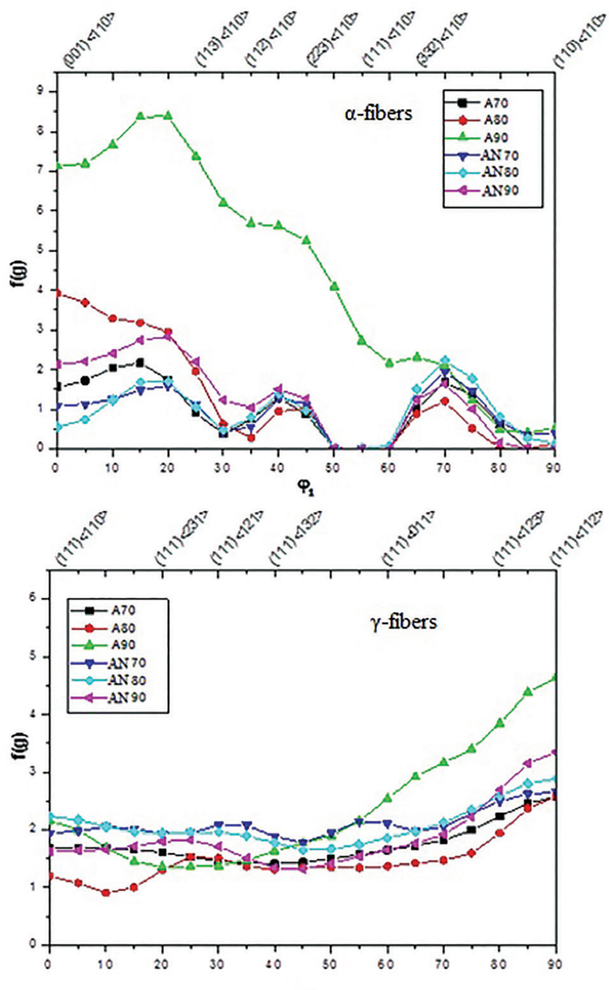

Figure 4: α- and γ-fiber plots for 70, 80 and 90 % asymmetrically cold rolled (A) and after annealing (AN) the IF steel samples.

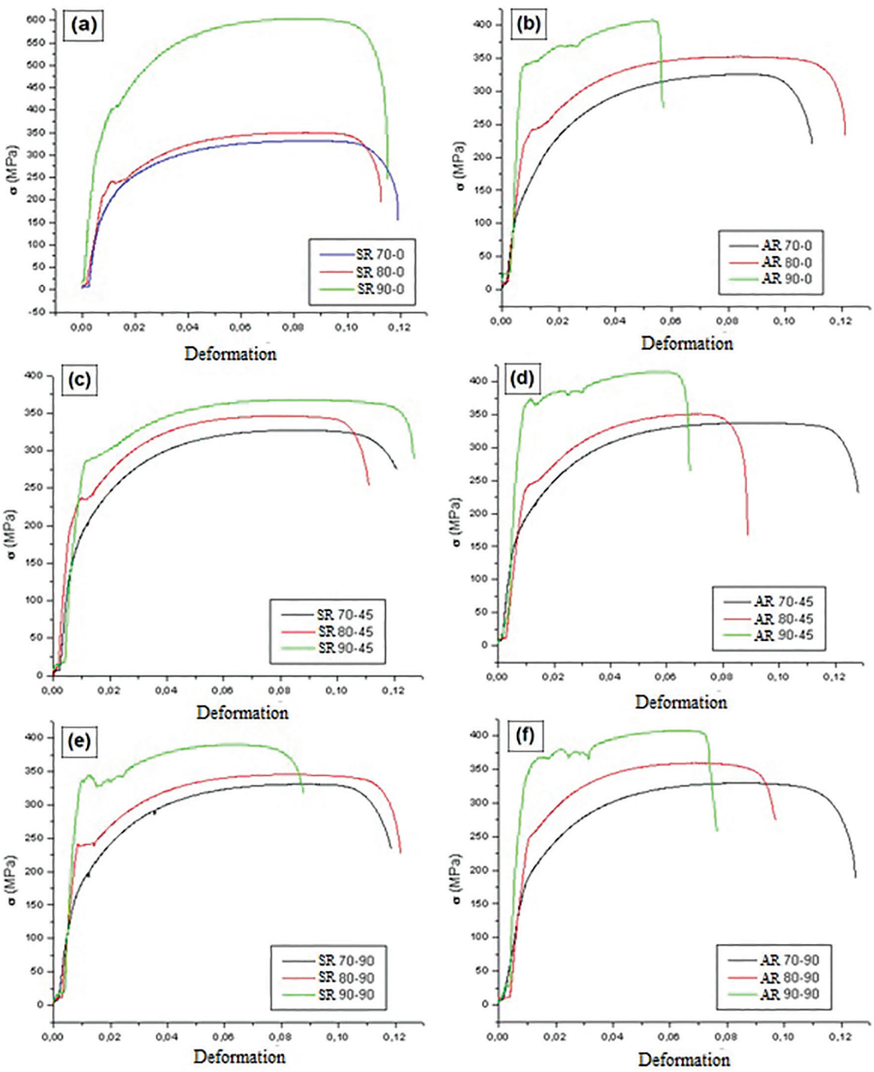

Figure 5: Engineering stress vs strain curves of annealed symmetrically rolled samples, (a) 0º RD, (c) 45º RD, (e) 90º RD and annealed asymmetrically rolled samples, (b) 0º RD, (d) 45º RD e (f) 90º RD.

Table 1: Work hardening coefficient (n) of annealed symmetrically and asymmetrically cold rolled samples.

	Hardening coefficient (n)								
Cold rolling (%)		70%			80%			90%	
Rolling angle	0	45	90	0	45	90	0	45	90
Symmetric	0.318	0.302	0.301	0.245	0.236	0.211	0.252	0.182	0.153
Asymmetric	0.326	0.309	0.281	0.222	0.250	0.226	0.133	0.105	0.111

Table 2: Normal plastic anisotropy ($\bar{r}$) and planar anisotropy (Δr) of annealed symmetrically (SR) and asymmetrically cold rolled samples (AR).

	Normal plastic anisotropy	Planar anisotropy
SR 70	1.29	-0.45
SR 80	1.22	-0.26
SR 90	1.45	-0.39
AR 70	1.25	0.24
AR 80	0.99	0.21
AR 90	1.06	-0.28

For all annealed symmetrically cold rolled samples and for the AR90 sample (annealed asymmetrically ones) negative values of planar anisotropy were found, while positive values were found for the AR70 and AR80 samples. The ideal planar anisotropy from the point of view of formability should be around zero, but the lowest value found in this work was 0.26 for AR80 sample. This Δr values indicates that deep drawing test samples will show “ears” at X and Y degrees with rolling direction.

4. Conclusions

The results of the present work lead to the following conclusions:

(i) The symmetrically cold rolled and annealed samples presented a typical texture of low carbon steels, consisting of partial α-fibers and continuous γ-fibers;

(ii) The volume fraction of γ-fibers increased with deformation up to a thickness reduction of 80 %. A decrease in the volume fraction of γ-fibers was observed for a 90 % thickness reduction, possibly due to the appearance of new <110>//RD components;

(iii) The texture induced by asymmetric rolling was smaller than the texture induced by symmetric rolling, but the volume fraction of α-fibers was considerably reduced by annealing, thus increasing formability;

(iv) In the case of asymmetrically rolled/annealed samples, texture components were not found in the original position of γ-fibers, $\Phi = 54.7°$, but fibers were formed between $60 < \Phi < 75°$, suggesting a displacement of γ-fibers;

(v) All deformations increased the values of the yield and strength stress; the largest increases of σ_e and σ_m were observed in asymmetrically rolled samples.

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