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ANISOTROPY INDEXES DETERMINATION IN HSLA STEELS

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Abstract. *Materials which structure has a preferably grain orientation after deformation processes are called anisotropic materials, since they could present, for example, different behavior when deformed (like variation in the thickness of sheets in a specific direction after metal forming). This paper presents a study concerning the anisotropic behavior of two high-strength low-alloy steels, having ferrite-martensite (dual-phase) and ferrite-perlite grain-refined structures. The anisotropic behavior quantification was possible through the determination of the mechanical properties and the normal and planar anisotropy indexes. It has been concluded that the more accentuated anisotropic behavior of ferrite-perlite grain-refined steels is microstructure-dependent, and the elevated mechanical resistance values, associated with high ductility, are related to the very refined structures found in the two steels, and the presence of martensite islands in the dual-phase steel. This paper confirms previous work, concluding that anisotropy indexes determination is more precise when performed in high uniform plastic deformations. Considering the combination of mechanical resistance, elongation and favorable anisotropy indexes, the dual-phase steel is the best candidate for sheet metal forming, unless welding is necessary, where ferrite-perlite grain-refined steels are the best choice.*

Key words: *Anisotropy, HSLA steels, mechanical properties, ferrite-perlite grain-refined steels, dual-phase steels.*

1. INTRODUCTION

This paper shows the mechanical properties and anisotropic behavior of two high-strength low-alloy steels (HSLA), with dual-phase and ferrite-perlite grain-refined structures. It consists on the determination of tensile strength, yield strength and total elongation in specimens got in three different orientations related to the rolling direction. After that, normal and planar anisotropy indexes were calculated, and the parameters to determine them precisely were discussed.

Anisotropy: In a metallic material, physical and mechanical properties can show differences when the measurements are taken in various orientations, related for example to a principal direction of mechanical work; when it happens, the material is called anisotropic (SLATER, 1977). The crystallographic anisotropy and texture affect the mechanical resistance and the uniform elongation of metals and alloys. In metallic sheets, the crystallographic texture is closely related to the metalworking procedure, and the mechanical properties change a lot, for example, if measured in the longitudinal and transversal orientations related to the rolling direction. Generally speaking, tension tests in metallic sheets are performed in three different orientations: longitudinal (identified as 0°), transversal (90°) and 45° related to the rolling direction (DIETER, 1981).

Normal anisotropy index: The ratio between width real elongation (ε_w) and thickness real elongation (ε_w) defines the normal anisotropy index r (DIETER, 1981).

$$r = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\ln\left({}^{w}\!/_{w_o} \right)}{\ln\left({}^{t}\!/_{t_o} \right)} \qquad (1)$$

where *wo* and *to* are the initial width and thickness respectively and *w* and *t*, the width and thickness at a fixed plastic deformation respectively.

If a material has r-values near unit, it seems that deformations are proportional, and the behavior is isotropic. On the other hand, r value higher than unit shows a particular behavior: the deformation in width is higher than in thickness, and it is desired in sheet metal forming. The thickness measurements are less precise than width and length ones in thin sheets; to avoid the imprecision that could be caused by those measurements, using the constant volume relation Eq. 1 can be rewritten:

$$r = \frac{\ln\left({}^{w}\!/_{w_o} \right)}{\ln\left({}^{l_o w_o}\!/_{l\ w} \right)} \qquad (2)$$

where lo is the initial length and l the length at a fixed plastic deformation respectively.

The r anisotropy index can be determined for the three principal orientations related to the rolling direction mentioned before, giving values identified as $r_{0°}$, $r_{45°}$ and $r_{90°}$. A mean normal anisotropy index (r_m) can now be determined, using Eq. 3 (DIETER, 1981; SLATER, 1977).

$$r_m = \frac{r_{o°} + 2.r_{45°} + r_{90°}}{4} \qquad (3)$$

The mean normal anisotropy index is closely related to sheet forming behavior: r_m values higher than unit results on limited thickness reduction, compared with length and width deformation; however, if r values in all directions are the unit, r_m will be equal to unit too, and these are parameters to determine the material's isotropic behavior. In body-centered cubic metals, the maximum r_m value is estimated to be 3 (SLATER, 1977).

Planar anisotropy index: The in-plane deformation differences during sheet metal forming can be calculated by the planar anisotropy index (Δr); it can be determined using Eq. 4 (DIETER, 1981; SLATER, 1977):

$$\Delta r = \frac{r_{o°} - 2.r_{45°} + r_{90°}}{2} \qquad (4)$$

If Δr is equal to zero, there is no difference between the deformation behavior in any direction: if fact, null Δr is another isotropy condition. If the absolute value of Δr is different from zero, during deep drawing "earing" formation will occur (SLATER, 1977).

HSLA steels: The high-strength low-alloy steels have high yield strengths, combined with high toughness and lower ductile-to-brittle transition temperatures, than mild carbon steels in the as-hot-rolled condition. Those characteristics are found in these steels related to very fine structure, like those found in the ferrite-perlite grain-refined or dual-phase steels, associated with inclusion shape-controlling (METALS, 1990).

Ferrite-perlite grain-refined steels are obtained through the formation, by controlled rolling, of a very fine, and consequently high-strength, polygonal ferrite and perlite microstructure. This microstructure allows high toughness and weldability (METALS, 1990). Dual-phase steels, on the other hand, have a microstructure with 80 to 90% polygonal ferrite and 10 to 20% martensite islands with low yield strength, continuous yielding behavior and high work-hardening rate (SPEICH, 1990), allowing very good results in sheet metal forming (METALS, 1990). The dual-phase steels weldability, however, is not so good as the ferrite-perlite ones, due to the formation of high carbon martensite or perlite in the heat affected zone (BATRA, 1993).

2. EXPERIMENTAL PROCEDURE

The studied materials (dual-phase and ferrite-perlite grain-refined HSLA steels) were provided as 3.1 mm thickness sheets. In Table 1, the studied materials chemical compositions are presented. Tension test specimens were taken oriented at 0°, 45° and 90° to the rolling direction, as showed in Fig. 1, and tension tests were performed to determine tensile strength, yield strength and total elongation in 50 mm. Anisotropy tests were carried out following ASTM E517. This procedure, however, do not determine the deformation at which anisotropy indexes have to be calculated, and considering this fact two deformation values were chosen, in the uniform plastic deformation region: one at a tension a little higher than the yield strength, and another near the tensile strength. Anisotropy indexes were calculated using Eq. 2 to 4, and all procedures were repeated at least 3 times to assure results statistical distribution.

Table 1. Dual-phase and ferrite-perlite grain-refined steel chemical composition.

	Element (weight %)					
Material	C	Si	Mn	Al	P	S
Dual-phase	0.11	0.30	1.11	0.038	0.017	0.014
Ferrite-perlite grain-refined	0.11	0.12	1.10	0.041	0.017	0.015

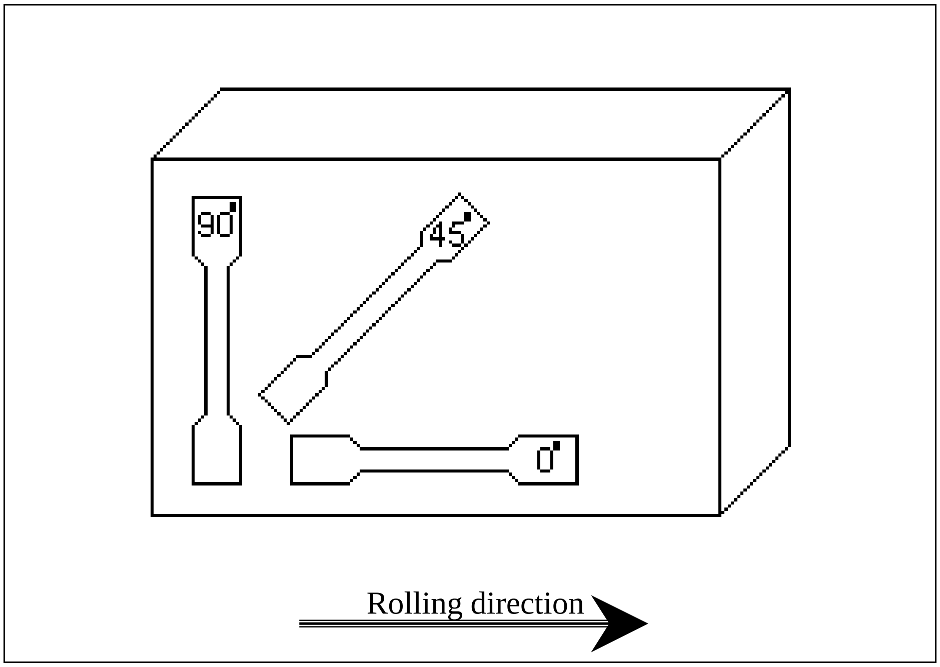

Figure 1: Specimen groups orientation relative to rolling direction.

3. RESULTS AND DISCUSSION

In Tables 2 and 3 the mechanical properties for each material are given. It was found that ferrite-perlite grain-refined steel has sharp yield point, promoted by *Cotrell atmospheres* (COTTRELL, 1955). In Table 4, the anisotropy index $\underline{r}$, calculated for two different plastic deformations values, and the mean normal and planar anisotropy indexes are showed. Figures 2 and 3 show the microstructure of each material studied.

Table 2. Dual-phase steel mechanical properties related to sample orientation.

Sample orientation	0º	45º	90º
Yield strength (MPa)	$418_{\pm 16}$	$401_{\pm 15}$	$401_{\pm 15}$
Tensile strength (MPa)	$705_{\pm 4}$	$708_{\pm 3}$	$701_{\pm 3}$
Elongation in 50 mm (%)	$21_{\pm 1}$	$22_{\pm 2}$	$23_{\pm 1}$

Table 3. Ferrite-perlite grain-refined steel mechanical properties related to sample orientation.

Sample orientation	0º	45º	90º
Yield strength (MPa)	$535_{\pm 15}$	$491_{\pm 5}$	$505_{\pm 2}$
Tensile strength (MPa)	$581_{\pm 8}$	$566_{\pm 11}$	$564_{\pm 10}$
Elongation in 50 mm (%)	$25_{\pm 1}$	$28_{\pm 1}$	$27_{\pm 1}$

Table 4. Dual-phase and ferrite-perlite grain-refined steels anisotropy indexes at plastic deformations values indicated.

Material and plastic deformation produced	r_{0°	r_{45°	r_{90°	r_m	Δr
Dual-phase, 2%	$2.97_{\pm 3.01}$	$0.45_{\pm 0.07}$	$1.72_{\pm 3.90}$	1.40	1.89
Dual-phase, 7%	$0.73_{\pm 0.14}$	$1.10_{\pm 0.04}$	$1.12_{\pm 0.34}$	1.01	-0.18
Ferrite-perlite grain-refined , 4%	$0.85_{\pm 0.16}$	$1.32_{\pm 0.12}$	$0.60_{\pm 0.13}$	1.02	-0.59
Ferrite-perlite grain-refined , 6%	$0.80_{\pm 0.02}$	$1.00_{\pm 0.13}$	$0.64_{\pm 0.03}$	0.86	-0.28

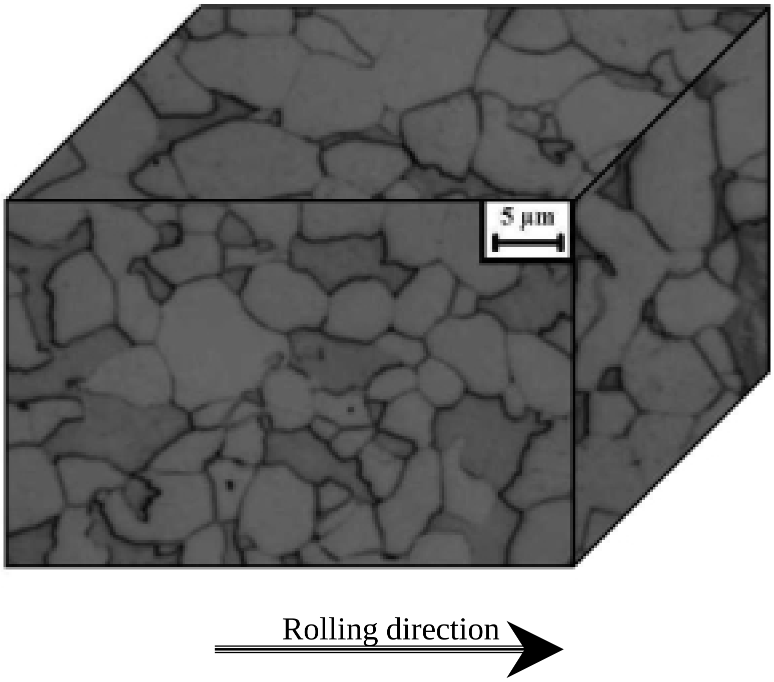

Figure 2. Dual-phase steel microstructure showing ferrite and martensite (dark).
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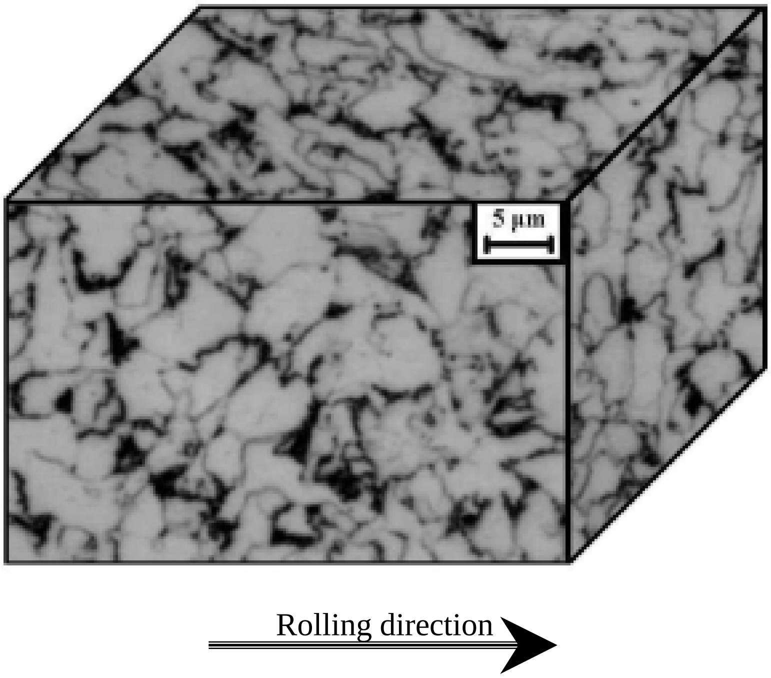

Figure 3. Ferrite-perlite grain-refined steel microstructure showing ferrite and perlite (dark).
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The mechanical properties showed in Tables 2 and 3 reflects the anisotropic behavior of the two steels studied, and one could note that the lowest elongation and the highest yield strength values were found in samples 0° oriented to the rolling direction. The dual-phase steel tensile strength, however, did not show this behavior, and its maximum value were found in samples oriented 45° related to the rolling direction. The high mechanical resistance, associated to elevated ductility, found in those steels could be related to the very refined structure showed in Fig. 2 and 3, and the presence of martensite islands in the dual-phase steel.

When the anisotropy indexes for dual-phase steels were calculated in two different uniform plastic deformations, the results showed special characteristics. At low plastic deformation, the standard deviations are higher than at high plastic deformation, showing that precise values could only be determined if deformations near tensile strength were produced. It was confirmed in the tests performed with ferrite-perlite grain-refined steels: with increased plastic deformation values, the standard deviation tends to decrease its value. This fact confirms earlier work (MAGNABOSCO, 1998), concerning that precise anisotropy indexes determination happens only with large uniform plastic deformation.

Considering the anisotropy indexes calculated at higher plastic deformations (7% for dual-phase steel and 6% to ferrite-perlite grain-refined steel), one could note that dual-phase steel has a isotropic behavior concerning the relation between in-plane and thickness deformation, because the mean normal anisotropy index (r_m) values is near unit; in addition, the negative planar anisotropy index (Δr) calculated shows tendency to “earing” during deep-drawing. However, the anisotropy indexes calculated to the ferrite-perlite grain-refined steel presents a more sharply defined anisotropic behavior: the r_m shows the tendency of thickness reduction during deformation (which is not recommended to sheet metal forming) and the higher Δr value (in absolute numbers) results in more accentuated “earing”. This more accentuated anisotropic behavior could be related to ferrite-perlite grain-refined crystallography, as stated before.

Considering the combination of mechanical resistance, elongation and favorable anisotropy indexes, the dual-phase steel is the best candidate to sheet metal forming, and it will not be only if welding of formed parts are needed (as stated before, ferrite-perlite grain-refined steels have good weldability).

4. CONCLUSIONS

(1) The more accentuated anisotropic behavior of ferrite-perlite grain-refined and dual-phase steels is microstructure-dependent.

(2) The elevated mechanical resistance values of those steels, associated with high ductility, are related to the very refined structures, and the presence of martensite islands in the dual-phase steel.

(3) The anisotropy indexes determination is more precise when performed in high uniform plastic deformations value.

(4) Considering the combination of mechanical resistance, elongation and favorable anisotropy indexes, the dual-phase steel is the best candidate to sheet metal forming, and it will not be only if welding of formed parts are needed, where ferrite-perlite grain-refined steels are the best choice.

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