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TOUGHNESS ANISOTROPY IN HSLA STEELS

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Abstract. *This paper presents a study concerning the toughness 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 tension and Charpy impact tests. It has been concluded that mechanical resistance has higher values in the longitudinal direction for both steels, and the inverse occurs for ductility. This could be explained with the microstructure preferential orientation with rolling direction. The higher tensile strength found in dual-phase steel is related to the presence of martensite islands, and the higher yield strength found in ferrite-perlite grain-refined steel is related to the fine structure observed. The higher toughness is a ferrite-perlite grain-refined steel characteristic, and this could be explained with the presence of only globular-oxide type inclusions, which reduces fracture nucleation sites, and does not promote fracture easy-propagation. Sulfide type inclusions found in dual-phase steel, associated with globular-oxide ones, give to this material a more brittle behavior. Toughness anisotropy is clearly noted, and in both cases the highest values are found in the longitudinal direction, related to the preferential inclusion alignment achieved in rolling. The lowest DBTT found in both steels, however, could be related to the very fine structure found .*

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

1. INTRODUCTION

This paper presents a study concerning the toughness anisotropic behavior of two high-strength low-alloy steels having ferrite-martensite (dual-phase) and ferrite-perlite grain-refined structures. The anisotropic behavior results from a preferably grain orientation or inclusions mechanical alignment after deformation processes, and the quantification of this phenomena was possible through the attainment of the mechanical properties and Charpy impact tests.

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).

***Charpy* impact test:** The brittle fracture of steels is the main cause of several historical accidents, like those with the *Liberty ships* in II World War (PETCH, 1961). Since the 50's programs have been studying this problem, and nowadays the *Charpy* impact test, regulated by ASTM E23-96 and in Brazil by NBR 6157, is the most important tool to determine the brittle behavior of metals and alloys.

The brittle fracture macroscopic behavior is related to the absence of plastic deformation, and the most usual microscopic fracture mechanism is cleavage, which is the separation of the lowest density planes in a crystallographic structure, and it occurs when there are not active slip systems capable to promote plastic deformation. Considering plastic deformation in metals and alloys as a thermally activated process, at "low" temperatures cleavage will occur. For carbon and low-alloy steels, cleavage is the fracture mechanism at temperatures below 25°C (ANDERSON, 1994).

The simplest way to characterize a brittle fracture is quantify how much energy it absorbs to happen: generally speaking, brittle fractures absorb low energy. On the other hand, ductile fractures, which are related to large amounts of plastic deformation, absorb high-energy values. This energy is called the toughness of the material, and its measurement, as a temperature function is the fundamental of *Charpy* impact test. The absorbed energy is plotted against the test temperature and a "ductile-to-brittle transition temperature" (DBTT) could be determined as the maximum temperature where the cleavage fracture is the most important fracture mechanism. One way to determine the DBTT is assume that it happens at the mean energy value between the maximum energy value (at the upper shelf energy in the energy *vs.* temperature diagram) and minimum energy value (at the lower shelf energy in the energy *vs.* temperature diagram) (ANDERSON, 1994).

Not only cleavage could impose a brittle fracture to steel. The presence of brittle inclusions and carbides, or weak interfaces between them and the metallic matrix, associated with mechanical fibering imposed by metalworking (as in rolling), could reduce the total absorbed energy and promote brittle fractures. Large grain sizes are another occurrence that could reduce the total absorbed energy, considering that fracture (specially the cleavage one) has to be nucleated at each grain boundary, and this nucleation is a process that absorbs energy (PETCH, 1961; ANDERSON, 1994).

All these factors give to *Charpy* test conditions to quantify the ductile-to-brittle transition, and the toughness anisotropy imposed by metalworking, simply conducting tests with specimens obtained in different orientations related to the principal direction of mechanical work

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 and reduced (2,5 mm thickness) Charpy V-notch specimens were token oriented longitudinal and transversal to the rolling direction, as showed in Fig. 1. Tension tests were performed to determine tensile strength, yield strength and total elongation in 50 mm, and impact tests were carried out following NBR 6157.

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

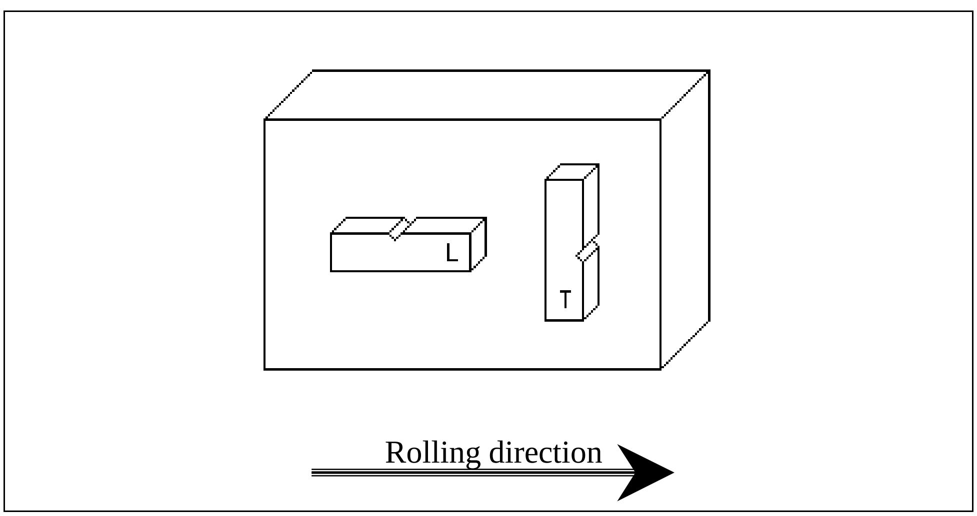

Figure 1: Specimen groups orientation relative to rolling direction. L: longitudinal; T: transversal.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In Tables 2 and 3 the mechanical properties for each material are described. It can be seen that mechanical resistance has higher values in the longitudinal direction for both steels, and the inverse occurs for ductility. This could be explained with the microstructure preferential orientation with rolling direction, and the texture formed during rolling and phase transformations. The higher tensile strength found in dual-phase steel is related to the presence of martensite islands, as can be seen in Fig. 2. The ferrite-perlite grain-refined steel, however, shows higher yield strength, probably related to the fine structure observed in Fig. 3.

Figures 4 and 5 show the inclusions found in those steels, with micrographs took normal to the sheet plane. Dual-phase steel (Fig. 4.) has globular-oxide and sulfide type inclusions, while ferrite-perlite grain-refined steel has only globular-oxide type ones.

Figure 6 shows the absorbed energy as a test temperature function for the two steels studied, in the longitudinal and transversal orientations. The toughness anisotropy is clearly noted, specially for the ferrite-perlite grain-refined steel. In both cases, the highest energy values are found in the longitudinal direction, and this fact can be related to the preferential inclusion alignment achieved with rolling (Fig. 4 and 5). The higher toughness, however, is a ferrite-perlite grain-refined steel characteristic.

In Table 4 the upper and lower energy shelf for each sample series are showed, as well as the mean energy value and the related ductile-to-brittle transition temperature (DBTT). Once again the ferrite-perlite grain-refined steel shows higher toughness, described with higher energy values and the lowest DBTT.

The higher toughness found in ferrite-perlite grain-refined steel could be explained with the inclusions type found. In ferrite-perlite grain-refined steel, the presence of only globular-oxide type inclusions (Fig. 5) reduces fracture nucleation sites, and does not promote fracture easy-propagation. However, sulfide type inclusions found in dual-phase steel, associated with globular-oxide ones (Fig. 4), give to this material a more brittle behavior. The lowest DBTT found in both steels, however, could be related to the very fine structure found (Fig. 2 and 3): grain boundaries are surely fracture stops, making cleavage fracture difficult to happen.

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

Sample orientation	Longitudinal	Transversal
Yield strength (MPa)	$418_{\pm16}$	$401_{\pm15}$
Tensile strength (MPa)	$705_{\pm4}$	$701_{\pm3}$
Elongation in 50 mm (%)	$21_{\pm1}$	$23_{\pm1}$

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

Sample orientation	Longitudinal	Transversal
Yield strength (MPa)	$535_{\pm15}$	$505_{\pm2}$
Tensile strength (MPa)	$581_{\pm8}$	$564_{\pm10}$
Elongation in 50 mm (%)	$25_{\pm1}$	$27_{\pm1}$

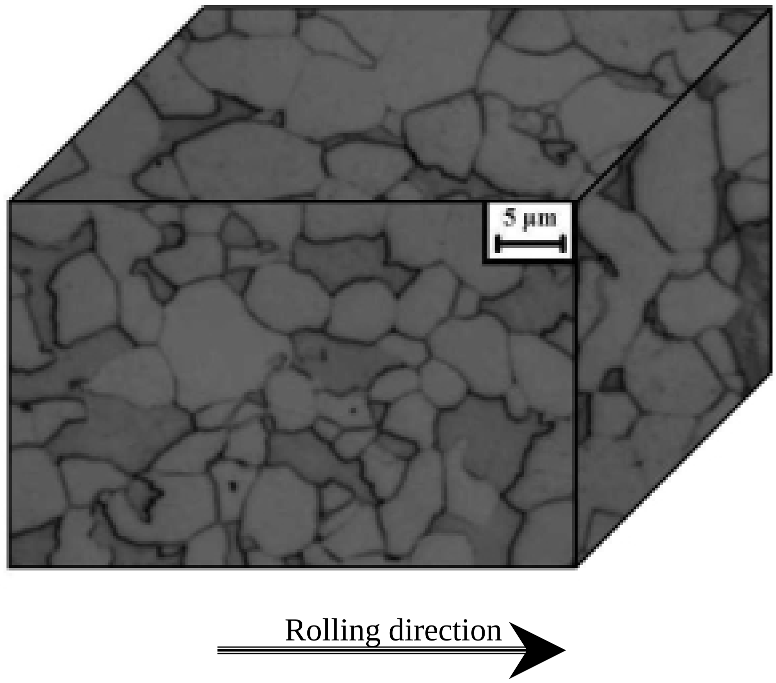

Figure 2. Dual-phase steel microstructure showing ferrite and martensite (dark).
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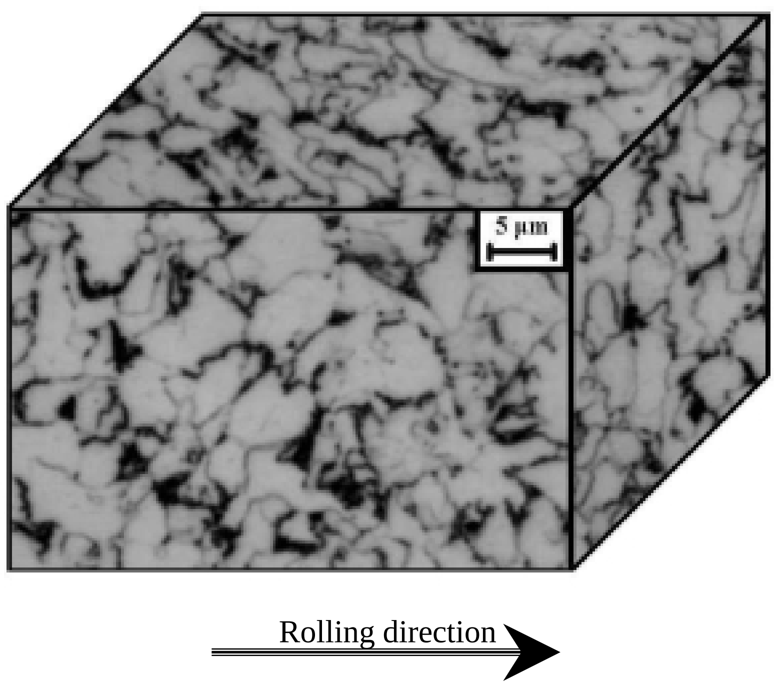

Figure 3. Ferrite-perlite grain-refined steel microstructure showing ferrite and perlite (dark).
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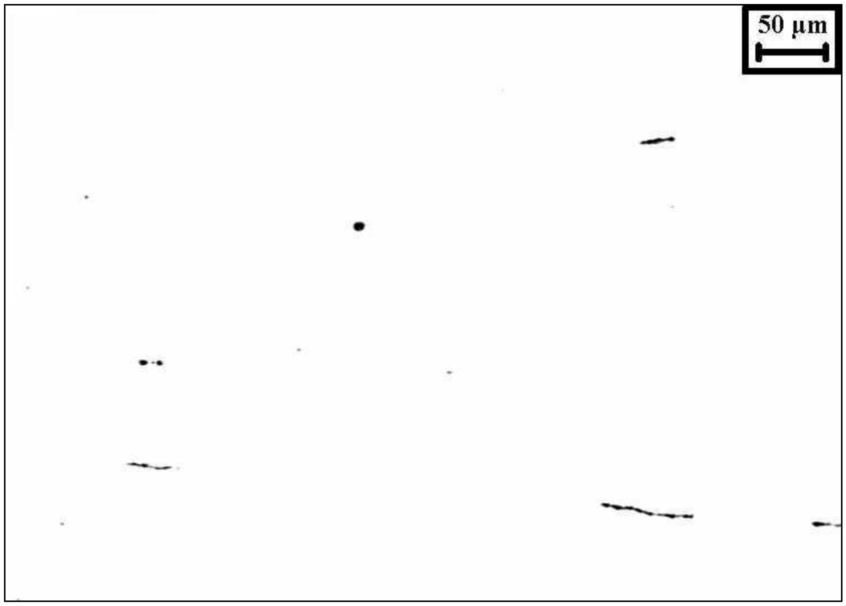

Figure 4. Dual-phase steel, in-plane view, showing globular-oxide and sulfide type inclusions. As polished.

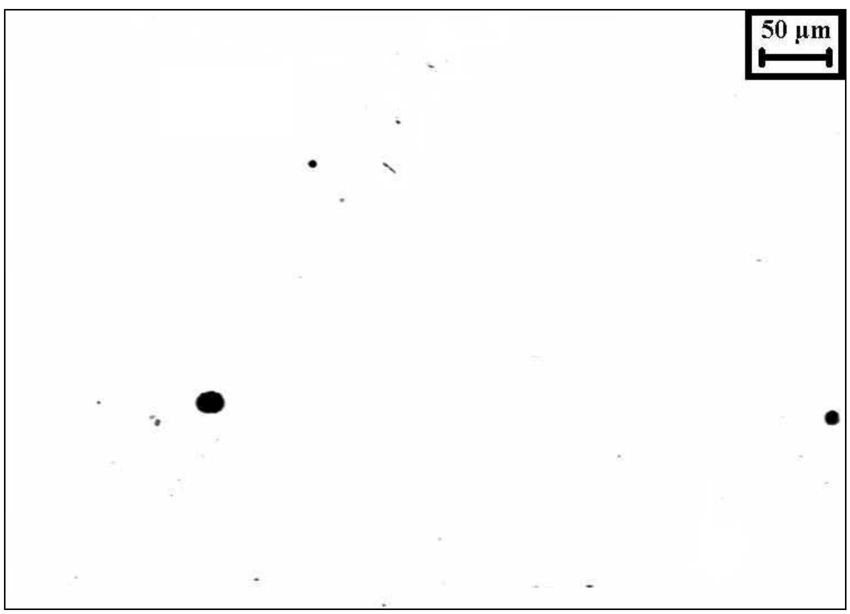

Figure 5. Ferrite-perlite grain-refined steel, in-plane view, showing globular-oxide type inclusions. As polished.

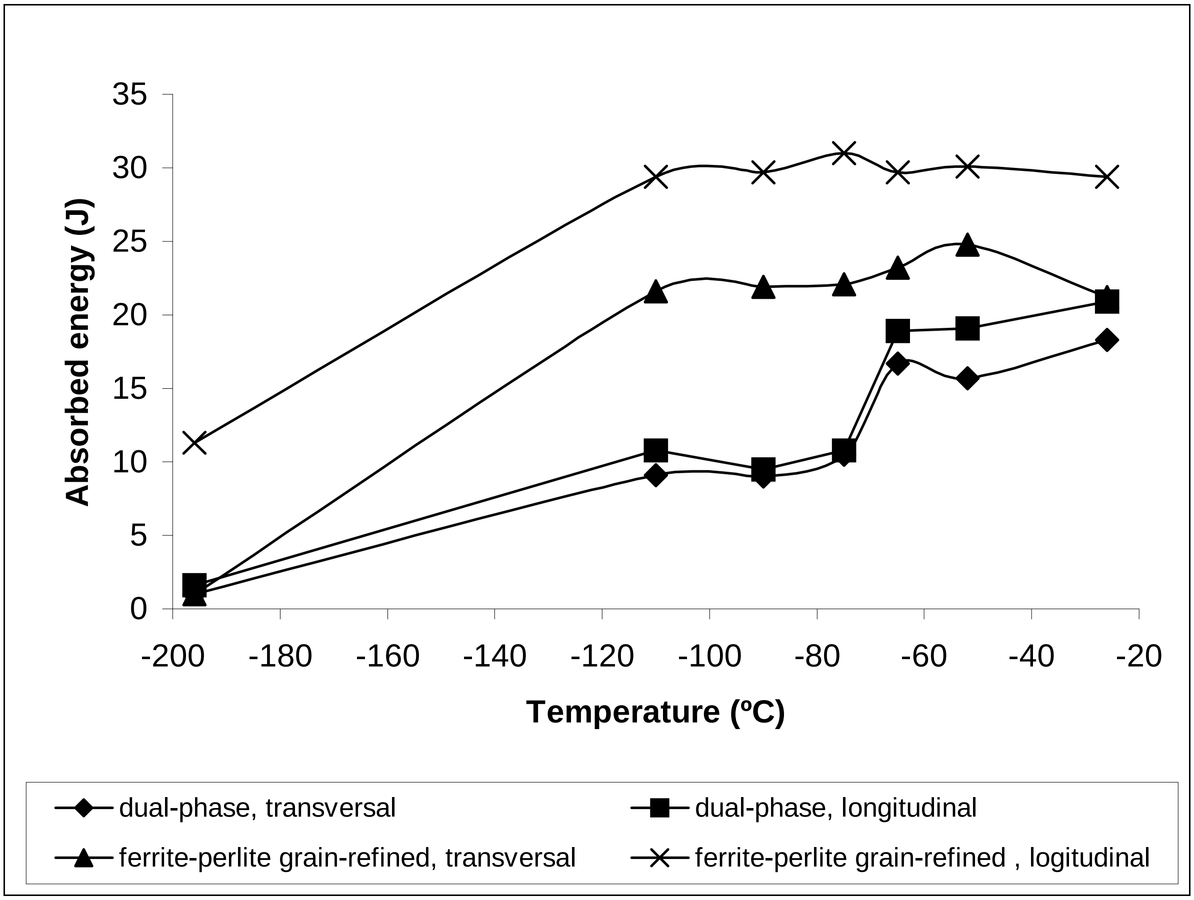

Figure 6. Charpy absorbed energy as a test temperature functions for the materials studied.

Table 4. Dual-phase and ferrite-perlite grain-refined steel upper and lower energy shelf, mean energy and related ductile-to-brittle transition temperatures (DBTT).

	Energy (J)			
Material	Upper shelf	Lower shelf	Mean value	DBTT (°C)
Dual-phase, longitudinal	20,0	1,0	10,5	-110
Dual-phase, transversal	17,6	1,0	9,3	-110
Ferrite-perlite, longitudinal	30,0	11,0	20,5	-155
Ferrite-perlite, transversal	24,0	1,0	12,5	-155

4. CONCLUSIONS

(1) Mechanical resistance has higher values in the longitudinal direction for both steels, and the inverse occurs for ductility. This could be explained with the microstructure preferential orientation with rolling direction, and the texture formed during rolling and phase transformations.
(2) The higher tensile strength found in dual-phase steel is related to the presence of martensite islands. The ferrite-perlite grain-refined steel, however, shows higher yield strength, probably related to the fine structure achieved.
(3) The higher toughness is a ferrite-perlite grain-refined steel characteristic, described with higher energy values and the lowest DBTT, and this could be explained with the presence of only globular-oxide type inclusions, which reduces fracture nucleation sites, and does not promote fracture easy-propagation.
(4) Sulfide type inclusions found in dual-phase steel, associated with globular-oxide ones, give to this material a more brittle behavior.
(5) The toughness anisotropy is clearly noted, and in both cases, the highest toughness values are found in the longitudinal direction, related to the preferential inclusion alignment achieved in rolling.
(6) The lowest DBTT found in both steels, however, could be related to the very fine structure found.

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