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## Effect of carbon content on microstructure and mechanical properties of dual phase steels

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### Abstract

Dual-Phase steels (DP) are constituted by a ferrite matrix with a martensite fraction, giving a good combination of strength, ductility, capacity of energy absorption and strain hardening. Mechanical properties are controlled by martensite and ferrite fractions, martensite carbon content, grain sizes and strength of both phases. The carbon content affects the martensite hardness and the hardenability. This work studied the effect of carbon content on microstructure and mechanical properties of DP steels. Samples of steels with different carbon content were heat treated at different intercritical temperatures, obtaining DP steels with different fractions of martensite. Microstructural characterization, microhardness and tensile test were made for each condition. Increasing carbon content and martensite fraction hardness and strength were increased. The best properties combination was reached for steels with a carbon content of 0.1 to 0.15% and 50% of martensite. Stress relationships obtained were from 1.55 to 2.25.

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*Keywords:* Dual Phase steels; carbon content; martensite; microstructure; mechanical properties

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## 1. Introduction

Dual Phase steels (DP) are part of the Advanced High Strength Steels (AHSS) family, and were developed to increase steel strength and formability with enhanced capacity of energy absorption. It was observed that quenching from an intercritical temperature produces ferritic-martensitic microstructures and improves the mechanical properties (Hayami et al. (1977)). Application of DP steels allowed the automotive industry to reduce thickness without lose formability or capability of energy absorption on impact. DP steels had a strong development in the 80's, but it was limited by the high production costs (Honeycombe (1982)). Nowadays it is possible to achieve efficient productions of these steels at a reasonable cost, thanks to current technological advances, being widely used in automotive industry for making structural components (International Iron and Steel Institute (2005)).

DP steels microstructure consists of martensite islands surrounded by a ferrite matrix. Small quantities of bainite, perlite and/or retained austenite may be present (Davenport (1979)). The martensitic phase increases strength, while ferrite matrix, generally continuous, gives excellent ductility. When the steel is subjected to a stress state, strain concentrates in this ferritic phase, obtaining a high strain hardening rate. This property, plus the good elongation that these steels have, gives a tensile strength much higher respect to conventional steels with similar yield strength (Lorusso et al. (2009)).

Many models were proposed to explain the behavior of DP steels (Gerbase et al. (1979), Crawley et al. (1981), Speich et al. (1981), Sherman et al. (1981), Kumara et al. (2008), Dzupon et al. (2007)). Mechanical properties are controlled by many metallurgic factors, like the volume fraction of martensite (VM) and ferrite (VF), the carbon content of martensitic phase, grain size of martensite and ferrite, and the strength of both phases (Tamura et al. (1973), Hance (2005), Mohaved et al. (2009), Maffei et al. (2007)), strongly affected by the chemical composition of the steel.

An increase of the intercritical temperature increases the fraction of austenite formed, which transforms into martensite during rapid cooling, improving hardness and strength. However, there is a balance between two opposite effects: for low martensite fractions, carbon content of this phase is high, while with increasing the fraction, carbon content decreases. This carbon content of martensite controls the hardness of the phase and hence affects the final properties of material. It has been reported that there is a range of martensite fractions (35-50%) in which mechanical properties of DP are optimized, associated to a balance between martensite fraction and hardness of both phases (Maffei et al. (2007), Mohaved et al. (2009)).

The composition also defines the possibility to obtain the dual structure in different diameters or thickness and technological aspects like weldability (Maffei et al. 2007). Although it has been generated a large amount of information, there are still discussions about the evolution of mechanical properties of these steels with carbon content.

The aim of this work was study the influence of the carbon content on the obtained microstructure and mechanical properties of DP from conventional structural steels.

### Nomenclature

DP	Dual Phase Steels
AHSS	Advanced High Strength Steels
M	Martensite Volume Fraction
C	Carbon content
IHT	Intercritical Heat Treatment
Ac <sub>1</sub>	Lower critical temperature
Ac <sub>3</sub>	Upper critical temperature
HV <sub>1</sub>	Vickers Microhardness
Rp <sub>0.2</sub>	0.2% offset yield strength
Rm	Tensile strength
A%	Elongation to fracture (expressed in percentage)
SR	Stress Relationship (Rm/Rp <sub>0.2</sub> )

## 2. Experimental procedure

To achieve these objectives, bars of four different conventional carbon steels were used, with nominal carbon contents between 0.05 and 0.35 wt%. Analyzed materials are structural steels for reinforced concrete commonly used in construction industry (ATR 500, AL220, AND 420S and ADN 420). This work is part of a project that studies the applicability of Dual Phase steels as an alternative in manufacturing of some steel products used in this industry.

For each analyzed steel, it was determined the chemical composition, through Optical Emission Spectrometry and the critical temperatures  $A_{c1}$  and  $A_{c3}$  through Linear Thermal Dilatometry, using a heating rate of  $15^{\circ}\text{C}/\text{min}$ .

From the obtained results, samples of each material were heat treated at different intercritical temperatures to obtain DP steel grades with different M. Holding time at temperature was 30 minutes, followed by water quench, according to Figure 1. Table 1 shows the heat treatments done for each material, with its nominal C provided by the manufacturer. Temperatures were chosen to cover a wide range of M. It should be noted that the C limits the minimum M that can be obtained, according to equilibrium diagram. Due to the effect of C in hardenability, the maximum M that can form uniformly in all the section is related with the chemical composition. These issues limited the martensite fractions obtained for each analyzed material.

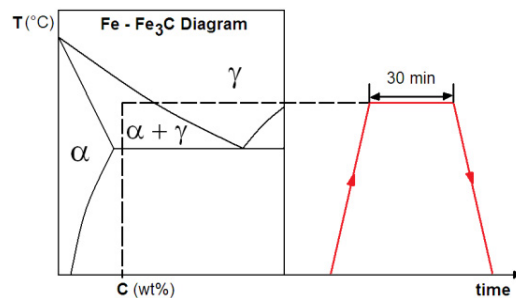


Fig. 1. Intercritical heat treatments (IHT) employed to obtain DP.

Table 1. Intercritical temperatures applied on heat treatments for DP

Identification	%C (wt%)	Intercritical temperatures ( $^{\circ}\text{C}$ )
S1	0.05	795; 810; 820; 840
S2	0.10	740; 750; 760; 770; 780; 790; 800; 820; 840; 860; 880
S3	0.20	740; 760; 780; 800; 820
S4	0.35	740; 750

On each obtained DP it was made a microstructural analysis through Light Microscope (LM). M was quantified by quantitative metallography according to ASTM E562. Mechanical properties were measuring for each DP condition, determining Vickers microhardness ( $HV_1$ ) according to ASTM E384 and tensile tests according to ASTM E8M, obtaining  $R_p 0.2$ ,  $R_m$  and  $A\%$ . Fracture surfaces were observed through optical stereomicroscopy (SLM).

## 3. Results and analysis

### 3.1. Chemical composition and critical temperatures

Table 2 shows the results of chemical analysis and the transformation critical temperatures for the analyzed materials.

The carbon content increased from material S1 to S4 from 0.08 to 0.38. Also, for S3 and S4 steels manganese and silicon contents were higher to that of the S1 and S2 steels. Phosphorus and sulfur contents were similar for all the studied materials.

Table 2. Chemical composition of analyzed material (wt%) and critical temperatures (°C)

Material	C	Mn	Si	P	S	Ac <sub>1</sub>	Ac <sub>3</sub>
S1	0.08	0.77	0.21	0.017	0.012	732	873
S2	0.11	0.69	0.21	0.025	0.021	733	865
S3	0.20	1.45	0.40	0.015	0.028	720	776
S4	0.38	1.43	0.37	0.024	0.033	736	805

It was found that increasing in carbon percentage decreased the temperature range in which austenite and ferrite coexists, according to equilibrium phase diagram (fig. 1). This implies that materials with the highest carbon contents are more sensitive to temperature variations in heat treatments. Also the lower critical temperature was about 730°C for all materials. Moreover, increasing Mn and Si contents in S3 and S4 steels implied an additional decrease on Ac<sub>3</sub>. It is worth to note that critical temperatures were just reference values for IHT, because heating rate on samples in the heat treatment furnace is different to the one employed in their determination. It has been reported an increase in critical temperatures for the heat treatment conditions used (Lorusso (2009)).

### 3.2. Microstructural characterization

Figures 2, 3, 4 and 5 show the microstructures of DP obtained through IHT at different temperatures for S1, S2, S3 and S4 steels, respectively. Ferrite is the white phase and martensite is the brown one.

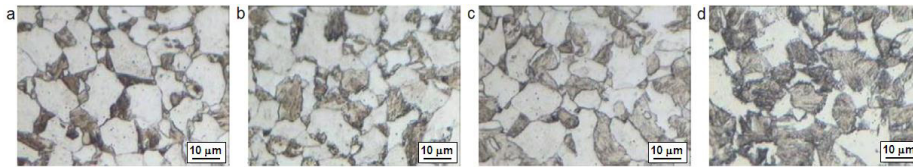


Fig. 2. Microstructures of DP obtained from material S1 at the temperatures: (a) 795°C; (b) 810°C; (c) 820°C; (d) 840°C.

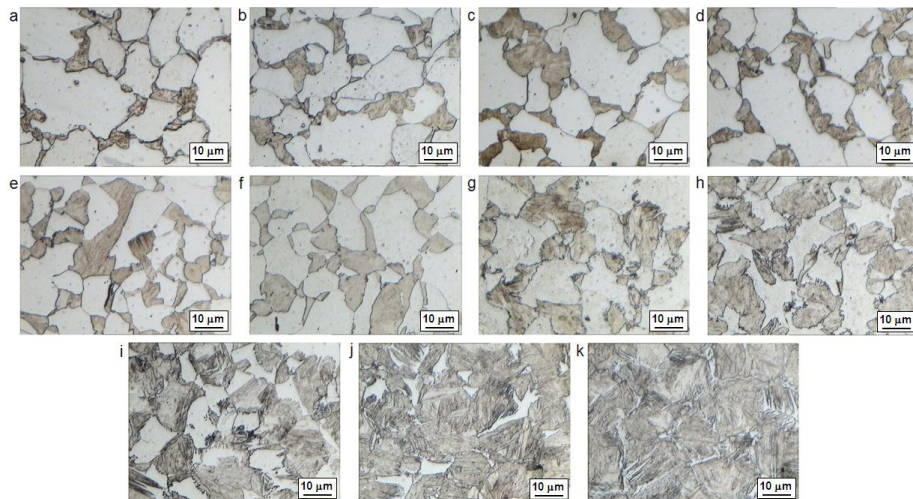


Fig. 3. Microstructures of DP obtained from material S2 at the temperatures: (a) 740°C; (b) 750°C; (c) 760°C; (d) 770°C; (e) 780°C; (f) 790°C; (g) 800°C; (h) 820°C; (i) 840°C; (j) 860°C; (k) 880°C.

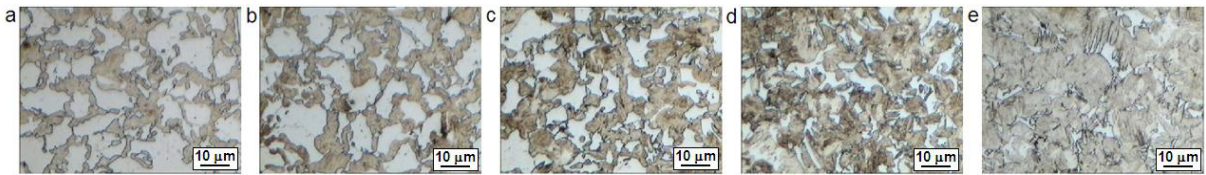


Fig. 4. Microstructures of DP obtained from material S3 at the temperatures: (a) 740°C; (b) 760°C; (c) 780°C; (d) 800°C; (e) 820°C.

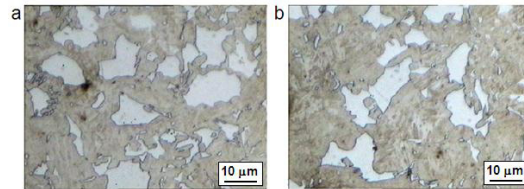


Fig. 5. Microstructures of DP obtained from material S4 at the temperatures: (a) 740°C; (b) 750°C.

In all cases it was observed a dual structure consisting of equiaxial grains of ferrite and martensite islands.  $M$  increased with increasing temperature IHT, associated to a higher austenite fraction formed. Also, it is worth to note that S3 steel presented smaller sizes of ferritic phase than the rest of analyzed materials. Table 3 shows  $M$  measured on each case.

Table 3.  $M$  measured for the different conditions

Sample	Steel	Temperature [°C]	$M$ [%]
S1-25	S1	795	25 ± 5
S1-40	S1	810	40 ± 5
S1-50	S1	820	50 ± 5
S1-65	S1	840	65 ± 5
S2-23	S2	740	23 ± 3
S2-27	S2	750	27 ± 3
S2-29	S2	760	29 ± 3
S2-31	S2	770	31 ± 3
S2-37	S2	780	37 ± 3
S2-40	S2	790	40 ± 3
S2-45	S2	800	45 ± 3
S2-50	S2	820	50 ± 3
S2-69	S2	840	69 ± 3
S2-85	S2	860	85 ± 3
S2-89	S2	880	89 ± 3
S3-50	S3	740	50 ± 3
S3-62	S3	760	62 ± 1
S3-76	S3	780	76 ± 5
S3-86	S3	800	86 ± 2
S3-96	S3	820	96 ± 2
S4-74	S4	740	74 ± 4
S4-80	S4	750	80 ± 1

It can be observed that for the steel S1, M was between 25-50%; for S2 was between 23-90%, being the wider range obtained. For steel S3, M was between 50-96%, and finally for S4, only two fractions of martensite could be achieved: 74 and 80%. These results show the strong influence of C on the viability to obtain DP structures.

Figure 6 shows, for each alloy (with determined C), the evolution of M obtained according to intercritical temperature employed.

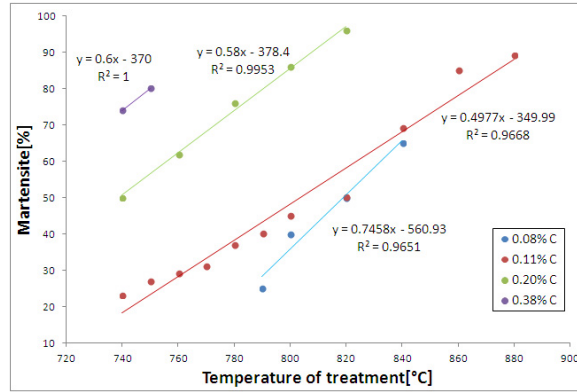


Fig. 6. Martensite percentage as a function of heat treatment temperature for each material

It was observed that, for the same temperature, M increased with increasing carbon content. The highest difference was observed for between steels S2 and S3. It were obtained linear expressions to adjust the experimental data with a very good agreement ( $R^2 > 0.96$ ). The evolution of M with IHT temperature (slope of curves) was similar for all analyzed materials, reaching an average value of 0.6 %/°C.

3.3. Mechanical properties

Figures 7a to 7d shows stress-strain curves obtained for the different DP, for each alloy.

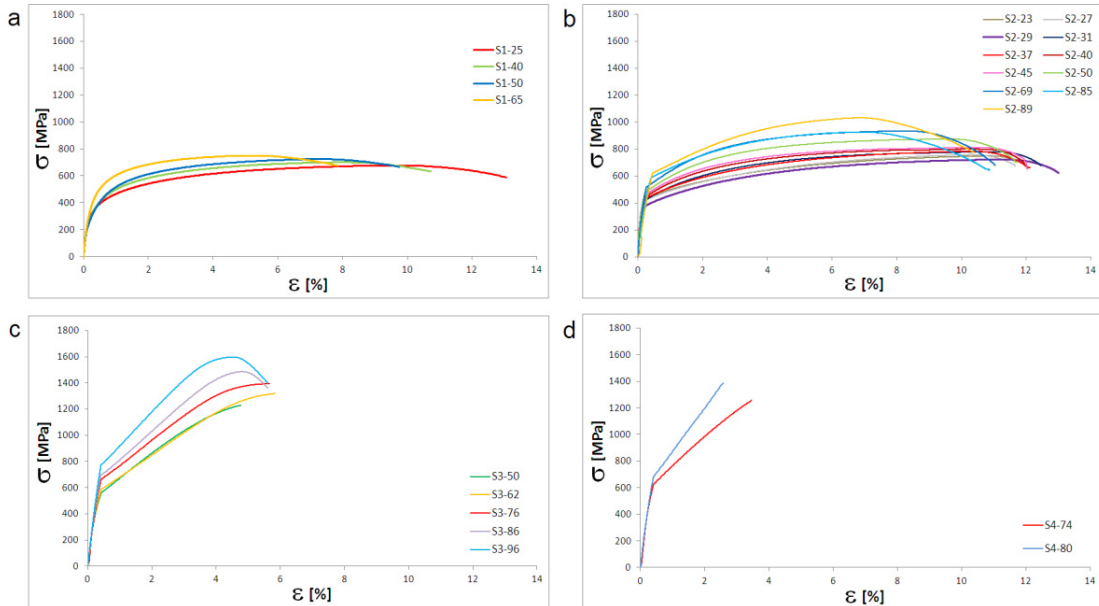


Fig. 7. DP Stress-strain curves obtained for materials: (a) S1 (0.08%C); (b) S2 (0.11%C); (c) S3 (0.20%C); (d) S4 (0.38%C).

The behaviors of different DP showed in Figure 7 are consistent with literature reports and can be explained from partition of stresses and strains between both phases, based on the modified law of mixtures (Hance (2005), Kuang et al. (2009)). In all cases it was observed a continuously yield behavior which is characteristic of this kind of dual structures attributable to the presence of high density of free dislocations in ferrite/martensite interfaces, due to austenite/martensite transformation (Sherman et al. (1981), Kumara et al. (2008), Matlock et al. (1979)). Moreover, it was generally observed a high strain hardening, typical of these materials. This aspect is usually evaluated by the stress relationship index ( $R_m/R_{p0.2}$ ). Values over 2 are considered as remarkable.

Tables 4, 5, 6 and 7 show the results of microhardness and tensile tests obtained.

Table 4. Microhardness and tensile properties of DP obtained for material S1 (0.08%C)

Sample	HV1	Rp0.2 [MPa]	Rm [MPa]	Rm/Rp	A [%]
S1-25	184 ± 1	333	656	1.97	14.9
S1-40	226 ± 2	337	675	2.00	13.5
S1-50	252 ± 8	356	693	1.95	12.5
S1-65	268 ± 2	407	698	1.71	10.5

Table 5. Microhardness and tensile properties of DP obtained for material S2 (0.11%C)

Sample	HV1	Rp0.2 [MPa]	Rm [MPa]	Rm/Rp	A [%]
S2-23	191 ± 7	405	714	1.76	17.4
S2-27	196 ± 3	392	715	1.82	18.0
S2-29	203 ± 3	366	712	1.94	16.5
S2-31	209 ± 3	384	745	1.94	14.2
S2-37	212 ± 6	391	744	1.90	18.3
S2-40	215 ± 3	405	767	1.89	16.3
S2-45	231 ± 6	421	789	1.87	16.4
S2-50	250 ± 6	435	839	1.93	16.1
S2-69	266 ± 5	502	914	1.82	15.7
S2-85	303 ± 6	592	925	1.56	14.1
S2-89	361 ± 9	632	1032	1.63	11.9

Table 6. Microhardness and tensile properties of DP obtained for material S3 (0.20%C)

Sample	HV1	Rp0.2 [MPa]	Rm [MPa]	Rm/Rp	A [%]
S3-50	328 ± 7	569	1228	2.16	3.7
S3-62	350 ± 9	588	1318	2.24	4.3
S3-76	381 ± 6	675	1393	2.06	5.8
S3-86	429 ± 9	719	1486	2.07	7.7
S3-96	434 ± 5	815	1597	1.96	8.9

Table 7. Microhardness and tensile properties of DP obtained for material S4 (0.38%C)

Sample	HV1	Rp0.2 [MPa]	Rm [MPa]	Rm/Rp	A [%]
S4-74	511 ± 3	649	1257	1.94	1.8
S4-80	521 ± 5	728	1389	1.91	0.6

In all cases, it was observed an increase of HV, Rp0.2 and Rm with increasing M, consistent with an increasing in the IHT temperature. Increasing M, A% decreased in materials with low carbon content (S1 and S2), and increased in material S3. However, the highest elongation values were obtained for the steel S2, with 0.11%C. SR values were between 1.56 and 2.24.

Figure 8 shows the evolution of mechanical properties with M, for different C. In each case, correlation equations were obtained. These expressions could be of technological interest because allow to estimate the M required to obtain a DP with certain properties. Correlation coefficients R<sup>2</sup> were satisfactory in all cases.

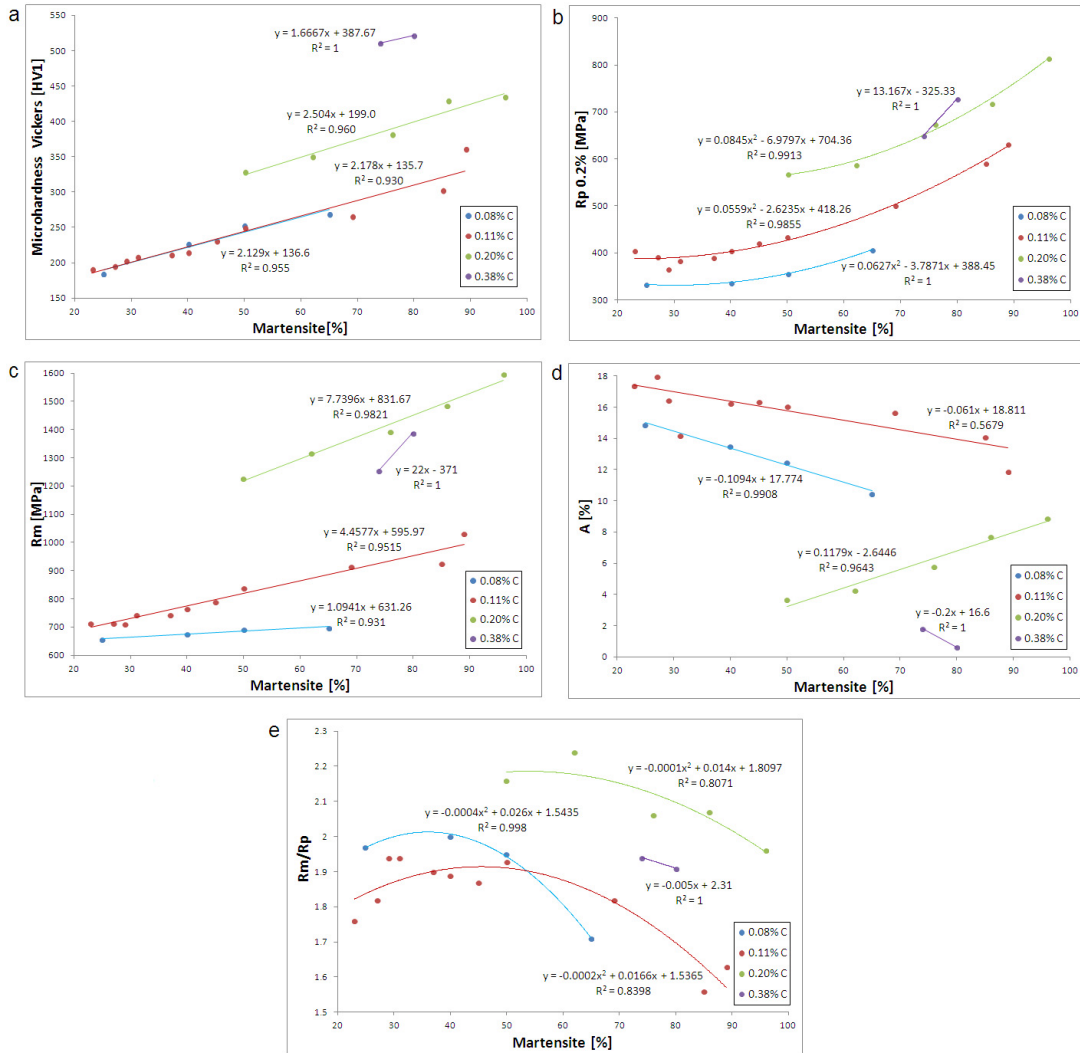


Fig. 8. Mechanical properties of DP vs. M for different C: (a) HV; (b) Rp 0.2%; (c) Rm; (d) A%; (e) SR.

Hardness increased with M, associated to an increase of the carbon content in martensite phase. It can be observed that in all cases the rate of variation of hardness with M was almost the same. Results for steels S1 and S2 were very similar, according to the similar C in both alloys.

Rp0.2% and Rm also increased with increasing C. The variation of the obtained curves for Rp0.2% with M was similar for all C and it was fitted with a non-linear curve. This phenomenon that has been reported by many authors (Tamura et al. 1973; Mohaved et al. 2009; Speich et al. 1979). Rm with M varied linearly, although the slope of the



curve increased with the carbon content of the alloy. Rm for steel S3 was slightly higher than for S4, despite the difference in carbon content.

As a general trend A% decreased with increasing C, as well as A% decreased with M for a certain carbon content in the steel, except for steel S3 where A% increased with increasing M. This anomalous behavior could be attributed to a balance of two effects: a decreasing of carbon content in martensite with increasing the volume fraction, and plasticity adopted by the martensite due to the stress partitioning in the DP (Kuang et al. 2009). It has been reported in literature that martensitic phase does not deform plastically until necking occurs in DP with low M (Kang et al. 2007). For high M (>50%), martensite is the matrix and supports most of the load, with small or none deformations of ferritic phase (Hance (2005)).

SR showed high values that varied from 1.55 to 2.25, presenting a maximum value for M between 40 and 60%. Related with carbon content, maximum values were obtained for S3 steel, being always higher than 2.

Several authors report that the best combination of properties in DP is usually obtained for about 50% of martensite fraction (Kang et al. 2007). Figure 9 shows the mechanical properties obtained for the different materials, with M=50%.

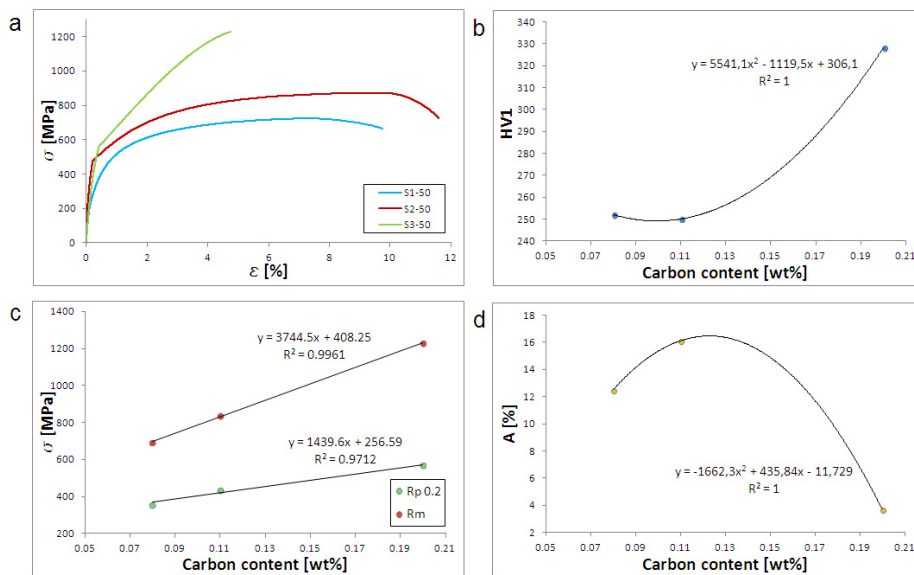


Fig. 9. Mechanical properties of DP steels with 50% martensite: (a) stress-strain curves; (b) HV; (c) Rp0.2% and Rm, (d) A%.

HV, Rp0.2% and Rm increased with increasing C, while A% presented a maximum value (16-18%) between 0.1 and 0.15% of carbon. HV presents a strong increase for C=0.20%, from 250 to 330 HV. For this range of C, Rp0.2% is about 400 to 500 MPa, Rm is 700 to 1200 MPa and SR is 1.93 to 2,16. Ferritic grain size was also measured, being minimum for material S3 (8  $\mu\text{m}$ ). The best combination of properties was achieved for steel S2, with C=0.10%. Figure 10 shows fracture surfaces of tensile test samples S2-50 and S3-50.

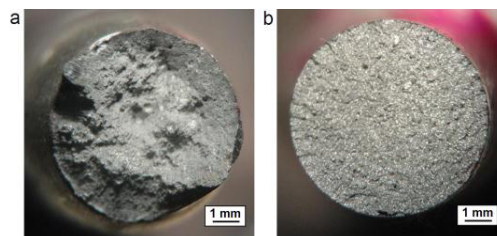


Fig. 10. Fracture surfaces of samples: (a) S2-50; (b) S3-50.

It can be noted that sample S2-50 (Figure 10.a) presented a ductile fracture surface, while for sample S3-50 (Figure 10.b) fracture was brittle. These samples correspond to the highest and the lowest elongation of samples with 50% martensite, making evident the strong influence of C in ductility and fracture behavior of DP.

#### 4. Conclusions

From steel bars with carbon contents between 0.08 and 0.38%, Dual Phase steels were obtained through intercritical heat treatments. Ferritic-martensitic microstructures were obtained, with martensite volume fractions varying from 23 to 96%, for the different carbon content materials. Hardness, 0.2% offset yield strength and tensile strength increased with increasing martensite fraction and carbon content. The stress relationships were high (1.55-2.25) in all cases, achieving maximum values for 40-50% of martensite. Elongation to fracture decreased with increasing carbon content, although the evolution with martensite fraction shows the same tendency except for C (0.20%) steel, which presented an increase of elongation with increasing martensite fraction, with  $M > 50\%$ . The ferritic grain size could also affect the obtained properties. Experimental expressions were obtained to estimate the resulting properties according to martensite fraction and carbon content.

It was observed that for DP steels with low carbon content (0.08 and 0.11%C), the volume fraction of martensite had a higher influence in elongation to fracture, due the decreasing carbon content of the martensite with the increase in its fraction. The opposite occurred for DP with 0.2%C. The best combination of mechanical properties in the analyzed DP can be obtained with carbon content between 0.1 and 0.15% and 50% martensite.

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