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Procedia Materials Science 1 (2012) 118 – 125

Procedia Materials Science

www.elsevier.com/locate/procedia

11th International Congress on Metallurgy & Materials SAM/CONAMET 2011.

Application of dual phase steels in wires for reinforcement of concrete structures

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Abstract

Dual Phase steels (DP) are part of the Advanced High Strength Steels (AHSS) family and consist in a ferritic matrix with a fraction of dispersed martensite between 5 and 50%, which gives the material a good combination of strength and ductility, with a significant capacity to absorb energy. Steel wires called in Argentina ATR500N, are used to manufacture steel welded framework, wires mesh and lattice girders for reinforcement of concrete structures and their mechanical requirements have defined in this country by the IRAM-IAS U500 526 standard. The current manufacturing process uses a wire rod of low carbon steel, hardened by cold working, producing a low ductility and low yield strength to tensile strength ratio product, although meet the requirements of the standard. The objective of the present work is to develop DP steels for ATR500N product, starting from the raw material used today and compare their mechanical properties to the commercial product. Several grades of DP steels were obtained and characterized microstructural and mechanically. Expressions of technological interest were developed, relating properties with fraction of martensite. Certain DP steels were slightly hardened by cold working and compared with the commercial ATR500N product. The DP steels developed fully satisfy the requirements of the standard and, in addition, a significantly higher elongation, hardening exponent and yield strength to tensile strength ratio. These characteristics are interesting for earth-quake resistant applications. A new manufacturing route could be developed for ATR500N product.

Keywords: Dual Phase steels; rod wire; ATR500; mechanical properties

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doi:10.1016/j.mspro.2012.06.016

1. Introduction

DP steels are part of the advanced high strength steels family, which in recent times have taken a great technological interest. They consist of a ferritic matrix with a dispersed fraction of martensite between 5 and 50%, giving the material outstanding mechanical characteristics in terms of combination of strength and ductility. This unique combination of properties, coupled with the high capacity of energy absorption makes them attractive to use for structural purposes, especially for seismic resistance applications (Kelesternur et al. 2009; Maffei et al. 2007). The mechanical properties of Dual Phase steels are controlled by metallurgical factors, such as the volume fractions of the martensitic and ferritic phases, the carbon content of martensitic phase, the grain sizes of the martensite and ferrite and the individual resistances of both martensitic and ferritic phases (Tamura et al., 1973; Hance et al., 2005; Movahed et al., 2009). The resistance of those phase, is also affected by the chemical composition of steel. In this sense, the possibility of obtain a dual structure in different diameters or thicknesses and technological aspects such as weldability, are defined by such a composition (Lorusso, 2009). Within the family of steel used in reinforced concrete structures, the ATR500N wires are used to manufacture welded mesh and lattice girders, and their mechanical requirements are defined in our country by the IRAM-IAS U500 526. These products are manufactured from a rod wire of low carbon steel, which is subsequently hardened by cold working to achieve the required properties. This manufacturing process generates a product having a very low remaining hardening capacity and low ductility. In particular, for structures built in seismic areas, ductility of steel and work hardening rate are relevance aspects in terms of energy absorption capacity of reinforced concrete structures (Maffei et al., 2007).

Nomenclature

DP	Dual Phase Steel
M	Martensite fraction
F	Ferrite fraction
$R_{0,2}$	0.2% Offset Yield Stress
R_m	Ultimate Tensile Strength
A%	Elongation
n	Strain Hardening Coefficient
EUL	Extension Under Load

The present work is framed within a research project that seeks to develop commercial products for structural steel in the construction industry, through the use of DP steels with improved mechanical properties, compared to conventional steels, developing more efficient alternative manufacturing routes. The aim of this work is to obtain a DP steels for ATR500N product, starting from the raw material currently used (rod wire) and benchmark their mechanical properties obtained for the product, with conventional steels.

2. Experimental

In a first stage, the raw material (5.5 mm rod steel wire) used for the manufacture of steel wires for reinforcement of concrete structures (ATR500N) was characterized. Chemical composition was determined by optical emission spectrometry (OEE). Critical transformation temperatures (AC1 and AC3) were obtain by linear thermal dilatometry (LTD) - heating rate 15 °C/min - and microstructural analysis was performed, using a light microscope (LM). Vickers microhardness (HV1) was also determined according to ASTM E 384-10, and tensile tests were conducted according to ASTM E 8-09. Mean values of the 0.2% offset yield stress (R0.2), ultimate tensile strength (Rm) and elongation (A%) were determined. In a second stage, from this raw material (wire rod), different Dual Phase (DP) steel grades were obtained by heat treatment at different intercritical temperatures (795, 810, 820 and 840° C) with 15 minutes of retention and subsequent water cooling. Microstructural characterization was performed using (LM) and (SEM) on these steels, as well as mean grain size measurement according to ASTM E 112-10, phase quantification analysis according to ASTM E 562-08. Mechanical properties were determinate in tensile tests. Also, microstructural characteristics and mechanical properties of commercial ATR500N products were evaluated from two different manufacturers. Several DP grades were tensile deformed by introducing different levels of plastic deformation under load (1%, 1.5% and 2% EUL). This was done to simulate the hardening effect in the ribbed of ATR500N. Subsequently, the same tensile properties were studied and the resulting mechanical properties were obtained for each DP steel grade. These properties were compared with those obtained for ATR500N commercial product and its standard requirements, and then a Hollomon analysis (Hollomon, 1945) was done on the different materials studied. Finally, the failure mode was characterized for different steel grades examined.

3. Results and discussion

Table 1 shows the chemical composition and the critical temperatures of the raw material (rod wire).

Table 1. Chemical composition (%wt) and critical temperatures (ºC) of the rod wire.

Sample	C	Mn	Si	P	S	Ac_1	Ac_3
Rod wire	0.08	0.77	0.21	0.017	0.012	732	873

Figure 1 shows the microstructures of the rod wire (a) and the ATR500N (b), in longitudinal sections.

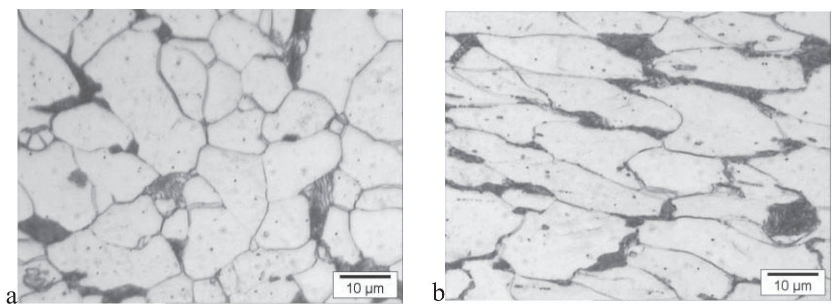

Fig.1. (a) microstructure of the rod wire and (b) commercial ATR500N

The rod wire is produced by hot rolling and subsequent air cooling. The observed microstructure is consistent with this manufacturing process, showing the presence of equiaxed ferrite grains of average size 15 microns, with a small fraction of pearlite. Also, the microstructure of commercial ATR500N, shows the same constituents but cold deformed, according to the process itself. Figure 2 shows microstructure of DP steels obtained for different heat treatment temperatures. In all cases, a dual microstructure composed of equiaxed grains of ferrite (F) and martensite (M), whose fraction increases with the heat treatment temperature is observed.

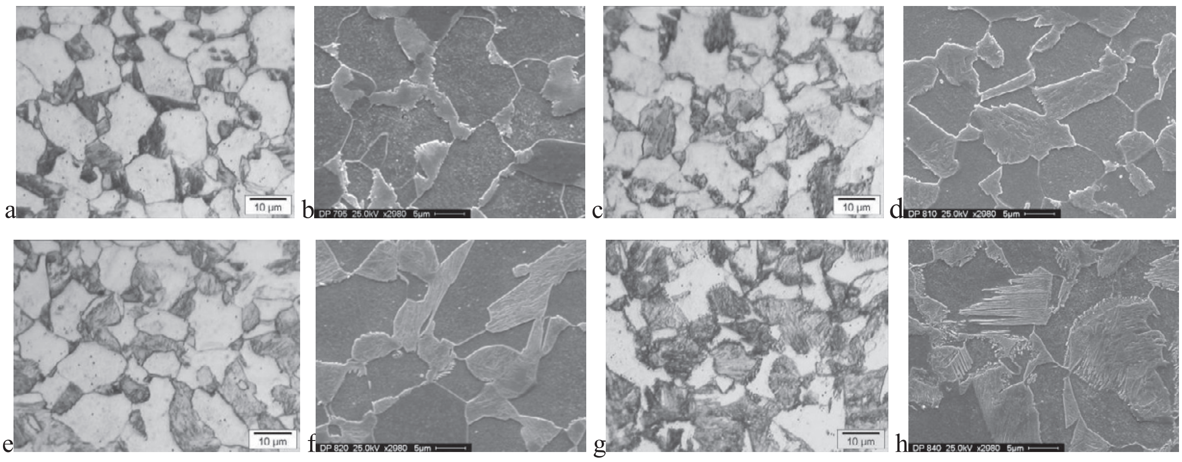

Fig. 2. LM and SEM images of DP steel microstructures obtained: a-b DP 795, c-d-DP 810, e-f DP 820, g-h-DP 840.

Figure 3 shows the stress-strain curves obtained from tensile test for the rod wire, the commercial ATR500N and DP steel family tested.

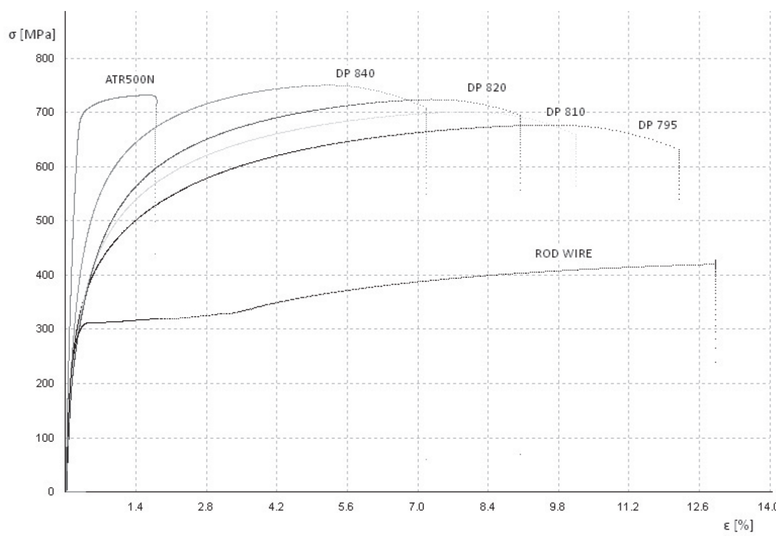

Fig.3. Stress-strain curves of the rod wire, commercial ATR500N and DP steels family.

DP steels seems to reach similar tensile strength to the commercial product, but with a higher elongation. Hence, it is observed an increase in the resistance of both, the ATR500N and the DP steels, respect to the rod wire. However, DP steels presented a lower yield point, even than the standard requirements. To obtain the yield requirements values according to the standard ones and, bearing in mind that for the product´s manufacture needed a final cold plastic deformation stage for the adherence nerves to concrete realization, there were conducted several plastic deformations by tensile tests, applying a 1%, 1,5% and 2% of extension under load (EUL). From the results, the 2% EUL value seams to be an interesting value of deformation for both, DP 810 and DP 820 steels, because of its best properties combination.

In Table 2, the mechanical properties obtained for the rod wire material, the commercial ATR500N product and its standard requirements are reported, as well as the phase analysis results with its standard deviation; microVickers hardness (1000g) values with its standard deviation, and the tensile results for the different DP steels analyzed.

Table 2. Martensite fraction, microVickers hardness (1kgf) and tensile properties of : rod wire material, different DP steels, commercial ATR500N product and its standard requirements.

Sample	M [%]	HV1	R0,2 [MPa]	Rm [MPa]	Rm/R0,2	A_{10d} [%]
Rod wire	-	139±5	304	426	1.40	32.7
DP 795	25±5	184±1	333	656	1.97	14.9
DP 810	40±5	226±2	337	675	2.00	13.5
DP 820	50±5	252±8	356	693	1.95	12.5
DP 840	65±5	268±2	407	698	1.72	10.5
DP 810 (2%EUL)	40±5	227±2	588	689	1.17	12.7
DP 820 (2%EUL)	50±5	261±4	633	698	1.19	9.5
ATR 500N Commercial*	-	240±14	670	708	1.06	7.8
Standard requirements	-	-	500^{+}	550^{+}	1.03^{+}	6.0^{+}

*Mean values of two product manufacturers; $^{+}$ Minimum values

For DP steels, there is an increase in hardness and resistance, as well as a decrease of elongation and the yield strength-to-tensile strength ratio, with increasing martensite. Figure 4 shows the evolution of microhardness and tensile properties with the martensite fraction of DP steels.

Experimental equations obtained are technologically useful for defining processing parameters to obtain the DP steels, depending on the required properties. The correlation coefficients obtained (R2) were greater than 0.83, indicating a very good fit. Furthermore, doing a Hollomon analysis (Hollomon, 1945), for the different DP steels grades, the hardening exponent (n) and the resistance constant (k) were obtained. Table 3 presents the n and log k values obtained for the different steels studied.

For both, the rod wire and DP795 (M25%), it was showed a single-stage (n1) value. For M50% around (DP810-820-840), there was a two-stage behavior (n1 and n2), where the exponent value for the first stage is higher than the second one. This behavior of two-stage hardening has been reported in the literature (Hance et al., 2005; Movahed et al., 2009) and could be related to the activation of different hardening mechanisms for DP steels. The first hardening stage, can be related to the plastic deformation of the ferrite, while the second, would be co-related to the plastic deformation of both phases. For the DP with subsequent plastic deformation (DP810-2%EUL and DP820-2%EUL), a single-stage was found.

Other authors (Mazinani et al., 2007) reported that the plasticity of the martensite is favored when its strength is diminished by increasing the phase fraction and decreased its carbon content or when the martensite morphology changes from equiaxed to banded, by the effect of deformation.

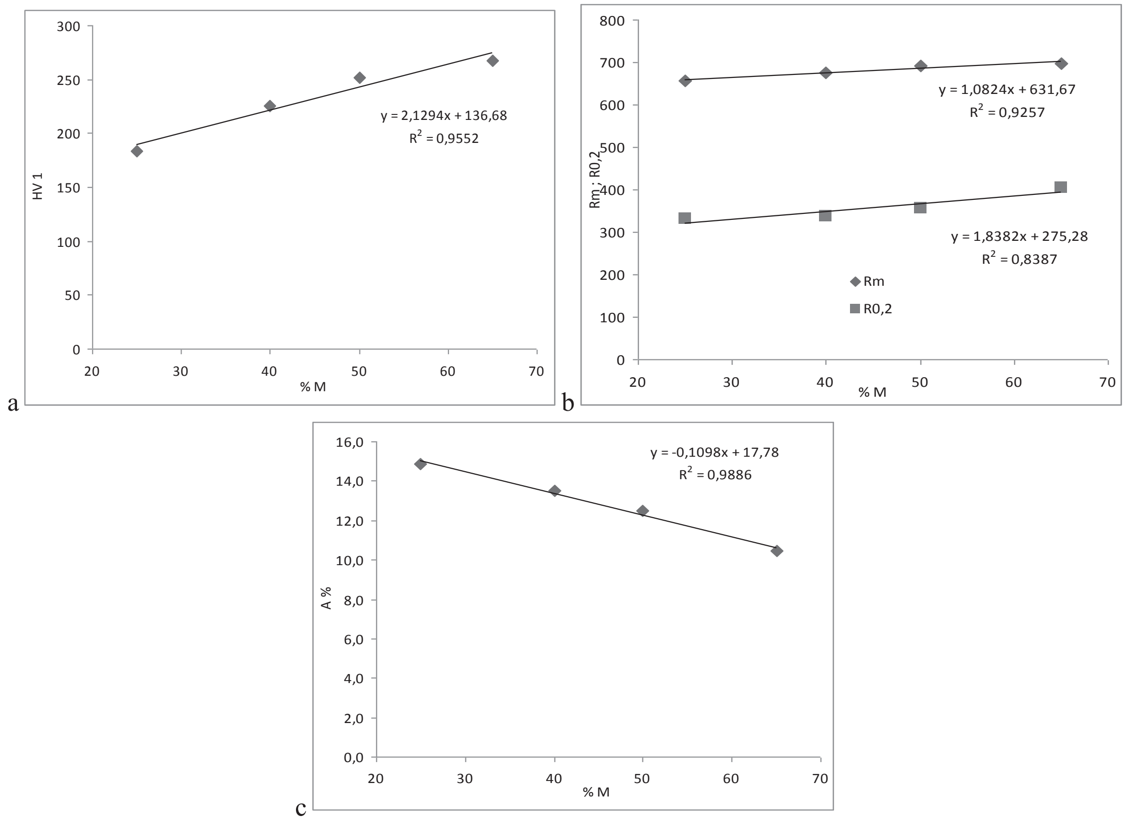

Fig. 4. Effect of martensite fraction on: a)-MicroVickers hardness, b)-0.2% Offset Yield Stress and Tensile Strength and c)- Elongation

Table 3. n and log k values, obtained by the analysis of the different studied steels.

Sample	M [%]	n_1	n_2	log k_1	log k_2
Rod wire	-	0.25	-	2.91	-
DP 795	25±5	0.22	-	3.11	-
DP 810	40±5	0.33	0.20	3.36	3.11
DP 820	50±5	0.38	0.20	3.47	3.13
DP 840	65±5	0.28	0.16	3.35	3.11
DP 810 (2%EUL)	40±5	0.09	-	2.98	-
DP 820 (2%EUL)	50±5	0.07	-	2.98	-
ATR 500N Commercial*	-	0.04	-	2.94	-

Figure 5, shows the εverd - σverd curves for DP810(2% EUL) and DP820(2% EUL) steels.

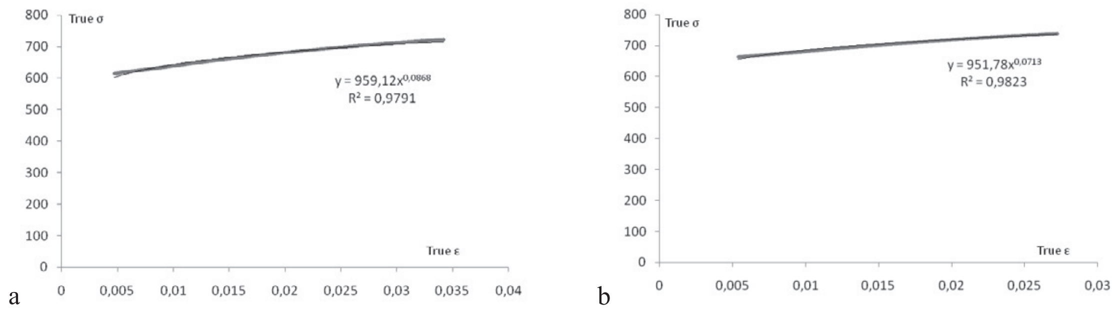

Fig. 5. True σ -ε diagrams: a) - DP810(2% EUL) and b) - DP820(2% EUL) steels.

From these curves Hollomon expressions were obtained that allowed modeling the mechanical behavior of these steels. It is observed that the R2 coefficients are higher than 0.97; indicating a very good fit.

In Figure 6, we present SEM images of the fracture surfaces of a) commercial ATR500N and b) DP 810-2%EUL. In both cases, the fractures presented ductile characteristics, as well as DP 820-2%EUL steel.

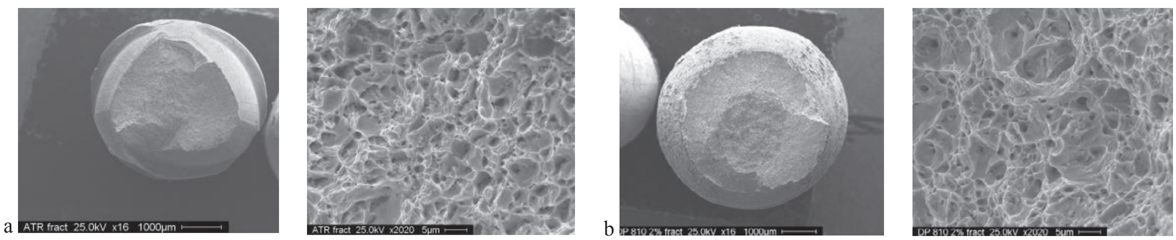

Fig. 6. SEM images of fracture characteristic for: a)- commercial ATR500N and b)- DP810(2% EUL) steels

Table 4 shows the analysis of the DP810(2% EUL) and DP820(2% EUL) steels behavior, relative to the commercial ATR500N and its standard requirements. In order to the regulatory requirements, the DP steels properties exceeded the minimum requirements widely, meeting all established values.

Table 4. Analysis of the DP810(2% EUL) and DP820(2% EUL) steels behavior , relative to the commercial ATR500N and its standard requirements.

Material	DP810(2% EUL)		DP820(2% EUL)	
Property	ATR requirements	ATR commercial	ATR requirements	ATR commercial
Δ R0,2 [%]	+18	-12	+27	-6
Δ Rm [%]	+25	-3	+27	-1
Δ Rm/R0,2 [%]	+14	+10	+16	+12
Δ A10d [%]	+112	+63	+58	+22
Δ n [%]	-	+125	-	+75

In particular, for both DP, there was a significant increase in elongation, 112% and 58% for DP810(2% EUL) and DP820(2% EUL), respectively. The remaining values are between 14 and 27% above those required for both DP degrees. This combination of properties (high ductility and strength), is associated with a high capability for energy dissipation, which is of great interest in reinforced concrete structures, especially for applications in seismic zones.

Regarding the commercial ATR, there was a slight decrease in the yield strength values (6-12%) and tensile strength (1-3%), and a significant increase in elongation values (22-63%), the yield strength to tensile strength ratio (10-12%) and the hardening exponent, n1 (75-125%) for both steels.

The manufacture route of these materials eliminates the cold stage of reduction of the diameter and would only have a single-deformation stage, for the ribbed formation.

Also, the dual structure is produced by controlled forced cooling from hot rolling, which could result in simplifying the process and its operating costs. At the same time, it was observed that the process was robust, as changes in austenitizing temperature (fraction of martensite) would not significantly affect the properties of the final product. These results could be optimized by varying slightly the chemical composition of the DP obtained. Take into account the considerations mentioned, this could be an interesting alternative to the conventional route used to produce ATR500N.

4. Conclusions

From raw material currently used for producing ATR500N, Dual Phase steels, with a variable martensite fraction, there were obtained expressions to quantify the resulting properties as a function of the martensite fraction. Applying a slight cold deformation on the DP steels obtained, materials that meet satisfactorily the ATR 500N regulatory requirements were produced. The materials obtained had a greater capacity for energy absorption, ultimate elongation and hardening exponent than current commercial products, although a slight decrease in resistance. In this sense, these results present a special interest in earthquake resistant structures. Furthermore, a good robustness of the manufacture process was observed, which is important from a technological standpoint, being an interesting alternative route to produce ATR500N.

Acknowledgments

The authors of this paper wish to thank the staff of the Mechanical Centre of National Institute of Industrial Technologyand the University of Buenos Aires for their assitance and financial support.

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