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Dual-phase steels with low manganese content. Structures and mechanical properties

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This article are presented the results of studies conducted to determine the influence of the intercritical heating temperature on the structure and mechanical properties of the dual-phase steels with low manganese content (0,511% Mn, respectively 0,529% Mn). The ferrite-martensitic structures, specific for dual-phase steels, were obtained by intercritical quenching, which consisted of heating the samples to temperatures located between critical points Ac_1 and Ac_3 (760, 780, 800, and 820 °C), followed by cooling in water. With the help of metallographic analyses, the volume fraction of martensite and ferrite microhardness from the structures were determined, and by tensile testing, the ultimate tensile strength and the total elongation were established. The results obtained for the two dual-phase steels with low manganese content were compared with those determined in previous research, performed on a dual-phase steel with 1.90% Mn.

Keywords: dual-phase steel, intercritical quenching, ferrite-martensite structure, mechanical properties

INTRODUCTION

“Advanced High-Strength Steels” (AHSS) developed for the automotive industry uniquely satisfy safety, efficiency, emissions, manufacturability, durability, and cost requirements; these alloys are characterized by structures and metallurgical properties that allow automakers to meet the diverse functional requirements of today’s vehicles. The AHSS family includes, in addition to Complex-Phase (CP), Ferritic-Bainitic (FB), Martensitic (MS), Transformation-Induced Plasticity (TRIP), Hot-Formed (HF), Twinning-Induced Plasticity (TWIP), and the dual-phase steels (DP), alloys extensively used to manufacture crumple zone to the body structure of a vehicle, closures, hood, doors, front and rear rails, beams and cross members, cowl inner and outer, crush cans, shock towers, fasteners, and wheel; it is estimated that in the coming years (until 2030), a percentage of 30 to 32% of the body of a car will be made of dual-phase steels. These materials, in general, a percentage of carbon less than 0.12 %, a content of manganese between 1.0 % and 3.5 %, and elements such as V, Cr, Mo, Si, Nb, Ti are to be found in chemical composition in proportions situated below 1%; in the last years, to reduce cars costs, there have been studied steels in which the content of manganese was less than 1 % (0.5 to 1 % Mn). One of the technologies applied to produce these steels is intercritical quenching, the structure resulting from the application of this technology being influenced by both the chemical composition of the steel and the technological parameters of the heat treatment, especially the heating (quenching) temperature. At the same time, the mechanical properties depend in a decisive way on the quantitative ratio and the morphology of the structural components that are formed as a result of the thermal processing process, [1-14]. Therefore, the influence of the heat treatment technological parameters on the structure and properties of a dual-phase steel must be established.

The dual-phase steels have been studied at the Faculty of Mechanical Engineering, Mechatronics and Management from University "Stefan cel Mare" of Suceava since 1992, and over the years researches has been conducted on several categories of alloys, [14, 15]; in recent years, research has been carried out on dual-phase steels with low content of manganese, [12, 13, 16, 17], in this article being presented results obtained for two such alloys.

EXPERIMENTAL DETAILS

The chemical compositions of the two studied alloys (denoted DPS-A and DPS-B) were determined with a FOUNDRY-MASTER Xpert Spectrophotometer (Oxford Instruments Analytical GmbH, Germany), they being (wt. %), [6, 10]:

- DPS-A: Fe, 0.087 C, 0.511 Mn, 0.091 Si, 0.0036 P, 0.0039 S, 0.029 Cr, 0.005 Mo, 0.049 Ni, 0.003 Al, 0.082 Cu, 0.003 V, 0.003 W;
- DPS-B: Fe, 0.101 C, 0.529 Mn, 0.091 Si,

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0.0032 P, 0.0037 S, 0.036 Cr, 0.005 Mo, 0.015 Ni, 0.003 Al, 0.015 Cu, 0.011 Pb, 0.003 V, 0.003 W.

The initial structures of these alloys were composed of 85.30% ferrite and 14.70% pearlite for DPS-A steel, respectively 83.90% ferrite and 16.10% pearlite for DPS-B steel, [13, 17].

In intercritical quenching applied to hypoeutectoid steels, knowing the critical points Ac_1 and Ac_3 is particularly important, the success of these heat treatments depending on the accuracy of this data. In the case of the studied alloys, the critical points in solid-state phase transformation (Ac_1 and Ac_3) required to establish heating temperatures at the intercritical quenching, were determined by dilatometric analyses performed with a DIL 402 Expedis-SUPREME Dilatometer (NETZSCH Gerätebau GmbH, Germany), the values obtained being: Ac_1 = 724.00 °C and Ac_3 = 899.40 °C for DPS-A steel, Ac_1 = 725.10 °C and Ac_3 = 898.90 °C for DPS-B steel, [13, 17-19].

In order to obtain ferrite-martensite structure characteristic to dual-phase steels, samples of the two alloys were subjected to intercritical quenching at which the heating temperatures (T_Q) had the following values, (established according to position of the critical points in the solid-state phase transformation): 760, 780, 800 and 820 °C. The heating was conducted in an electric laboratory furnace Nabertherm LT 40/11/P330 (Nabertherm GmbH, Germany), at constant values of the T_Q temperature, for 30 minutes. The cooling was performed in water with the temperature of 20 °C (without mechanical agitation), in an LBS 2 bath (Falc Instruments S.R.L., Italy), [13, 17].

After quenching, the samples were subjected to metallographic analyses in order to determine the volume fraction of martensite (V_M) in the structures, the morphology, and distribution of this phase; the analyses were performed with a LEXT OLS4100 Laser Microscope, (Olympus Corporation, Japan) and OLYMPUS Stream MOTION Image Analysis Software. The ferrite-martensite structures were highlighted by the following metallographic etchant: picric acid 4 % solution in alcohol (etching time - 60 seconds) and then nital 2% (etching time - 5 seconds); after the metallographic etchant, on micrographics, the martensite appeared as "dark" regions and the ferrite beads as the "white" regions, [20]. These analyses were completed by measuring the ferrite microhardness, determinations that were made with a MicroHardness Tester DuraScan 70 (Emco Prüfmaschinen-Test GmbH, Austria), the test load of the Vickers indenter being 0.098 N (0.01 kgf). Five micrographs and five microhardness measurements were performed on each metallographic sample.

In order to determine the influence of heating temperatures (T_Q) from the intercritical quenching on mechanical properties, specimens with ferrite-martensite structures obtained by applying the heat treatments described above were subjected to tensile testing, which determined the ultimate tensile strength (R_m) and the total elongation (A_5). These tests have been carried out on a QUASAR 600 universal testing machine (Cesare GALDABINI SpA, Italy). Cylindrical specimens with a diameter of 5 mm and an initial length between markers (in the calibrated portion) of 25 mm were used (ten samples for each heating temperature).

RESULTS AND DISCUSSIONS

In a dual-phase steel, the mechanical characteristics are influenced by both the volume fraction of martensite, and the properties of the ferrite, [2-5]; therefore, in order to analyse the influence of the intercritical heating temperature on the mechanical properties of the DPS-A and DPS-B steels, on samples intercritical quenched, the volume fraction of martensite (V_M) and the ferrite microhardness (HV0.01), were determined, the results being presented in Tab.1, Figs. 1 and 2.

Raising the heating temperature (T_Q) has led to an increase in the volume fraction of martensite (V_M) in structures (Tab.1 and Fig.1), because raising the T_Q temperature in the intercritical range (Ac_1 - Ac_3) has determined an increase in the volume fraction of austenite, phase which, by quenching has turned into martensite; thus, in the DPS-A steel samples, the volume fraction of martensite (V_M) increased with 16.79 percent, from 20.19% (T_Q = 760 °C) to 36.98% (T_Q = 820 °C), whereas in the samples of DPS-B steel it increased with 16.03 percent, from 22.10% (T_Q = 760 °C) to 38.13% (T_Q = 820 °C).

In the structures obtained by quenching from T_Q = 760 °C (Fig.3) the martensite was in the form of small islands, situated mainly at the boundaries of the ferrite grains. Most of these martensite islands were located in regions where, in initial structure, has been perlite; by heating (over Ac_1) the pearlite was dissolved into austenite, which, through quenching was transformed into martensite. Through this mechanism has formed a volume fraction of martensite (V_M) of approx. 14.70% in the case of DPS-A steel, respectively 16.10% in the case of DPS-A steel, i.e. the equivalent of the volume fraction of pearlite from the original structures.

Table 1. Volume fraction of martensite and ferrite microhardness (average values)

T_Q, ˚C	760		780		800		820	
Steel	DPS-A	DPS-B	DPS-A	DPS-B	DPS-A	DPS-B	DPS-A	DPS-B
V_M, %	20.19	22.10	23.83	25.51	29.41	30.40	36.98	38.13
HV0.01	170.43	184.77	182.37	194.63	188.54	199.28	192.11	202.53

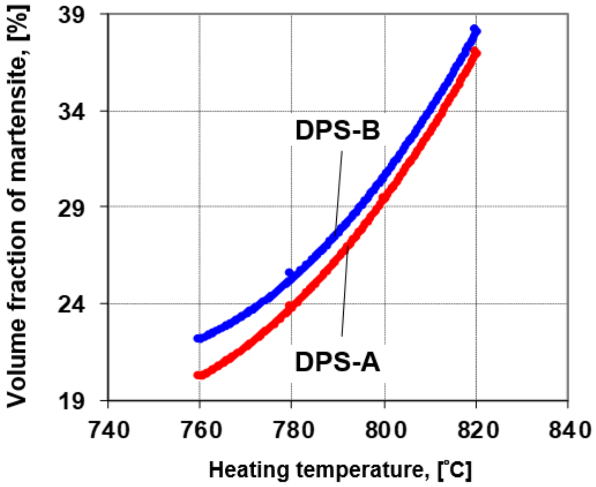

Fig.1. Influence of the heating temperature on the volume fraction of martensite.

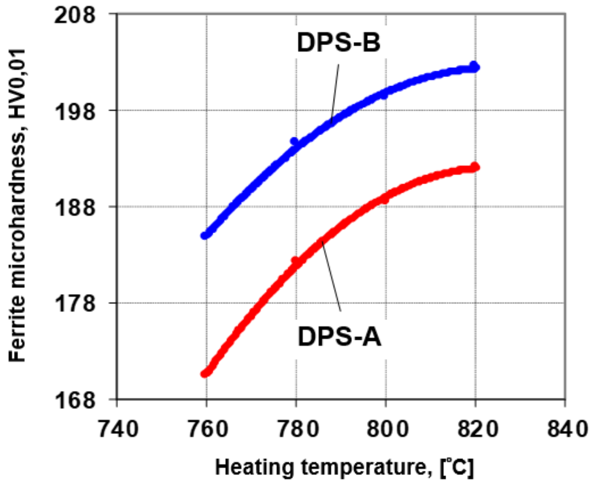

Fig.2. Influence of the heating temperature on the ferrite microhardness.

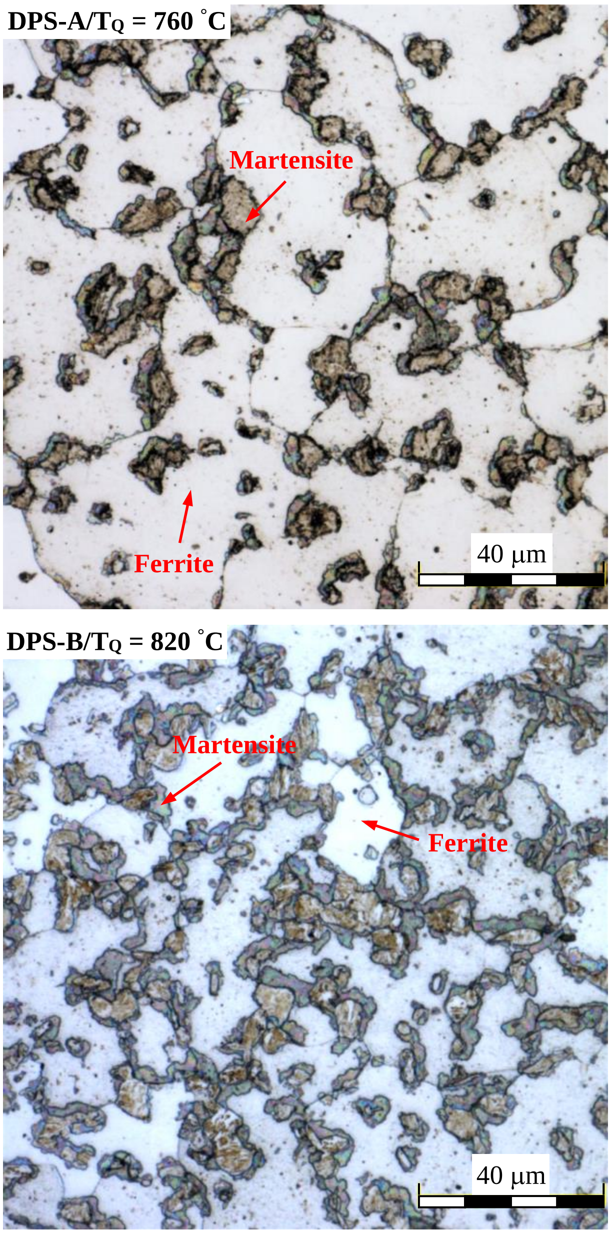

Fig.3. Structures of the dual-phase steels.

Other martensite islands (the difference up to 20.19% for DPS-A steel, respectively 22.10% for DPS-B steel, Tab.1) have been formed from the austenite obtained by the allotropic transformation of the ferrite. Raising the heating temperature (T_Q), from 760 ˚C at 780, 800 and 820 ˚C determined an increase in the volume fraction of austenite that was formed by the allotropic transformation of the ferrite, which generated an increasing volume fraction of martensite that resulted by quenching. In the same time with the rising of the volume fraction of martensite in structures (and decreasing the volume fraction of ferrite), an increase in the size of the martensite islands is observed (Fig.3), as well as a tendency of their connection and the formation of a network around the ferrite grains.

The raising of the heating temperature (T_Q) also determined an increase of ferrite microhardness (Tab.1 and Fig.2). The increasing ferrite microhardness was caused, most probably, by an increase in the amount of interstitial atoms (C, N) and density of dislocations in the crystal lattice ofthis phase, [5, 13, 17, 21].

The results obtained from the tensile testing applied to the intercritical quenched specimens are presented in Tab.2 and Figs.4 - 7.

Table 2. Ultimate tensile strength and total elongation (average values)

T_Q, ˚C	760		780		800		820	
Steel	DPS-A	DPS-B	DPS-A	DPS-B	DPS-A	DPS-B	DPS-A	DPS-B
R_m, MPa	631	638	661	673	684	699	701	718
A_5, %	24.46	23.29	22.01	20.95	20.08	19.29	19.04	18,59

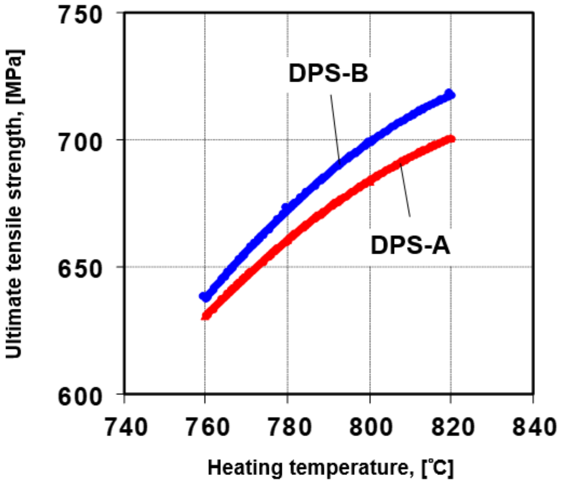

Fig.4. Influence of the heating temperature on the ultimate tensile strength.

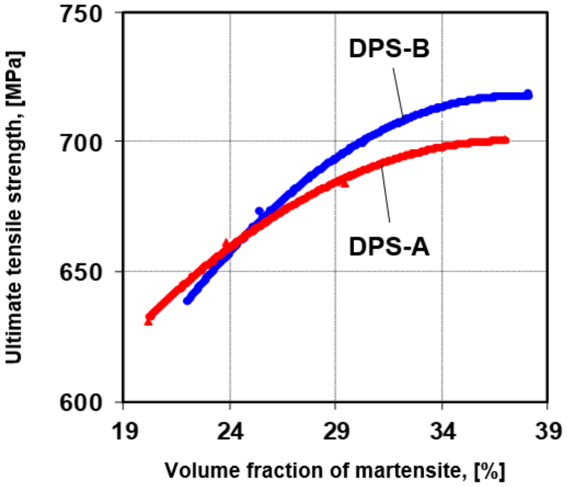

Fig.6. Influence of the volume fraction of martensite on the ultimate tensile strength.

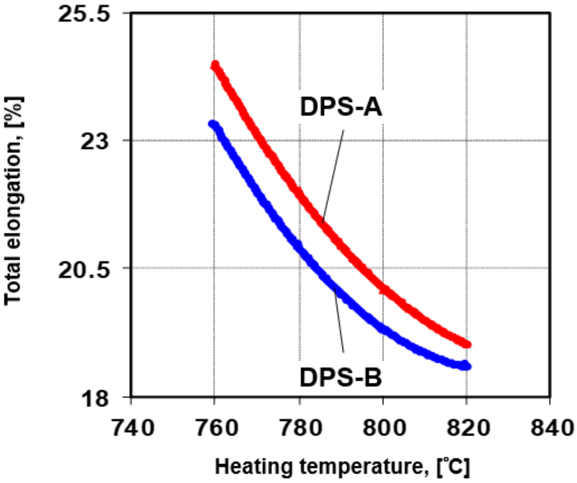

Fig.5. Influence of the heating temperature on the total elongation.

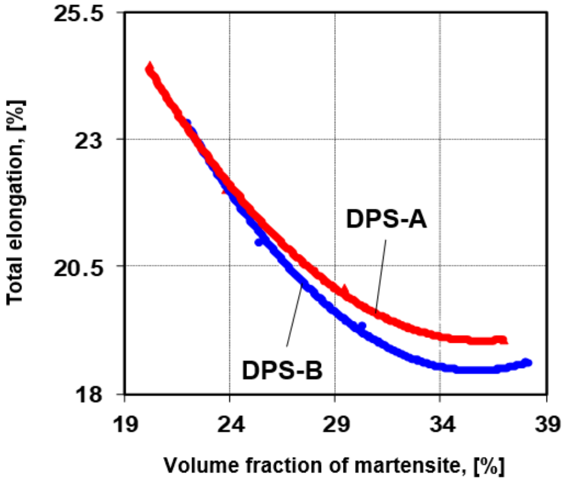

Fig.7. Influence of the volume fraction of martensite on the total elongation.

Raising the heating temperature (T_Q), so the increase in the volume fraction of martensite (V_M) and ferrite microhardness (HV0.01), has led to increasing of the strength characteristics (R_m) and the decrease of deformability (A_5). Thus, the ultimate tensile strength (R_m), determined for the specimens made of the DPS-A steel, increased with 70 MPa, from 631 MPa (T_Q = 760 ˚C) to 701 MPa (T_Q = 820 ˚C), and the total elongation (A_5) decreased with 5.42 percent, from 24.46% (T_Q = 760 ˚C) to 19.04% (T_Q = 820 ˚C); in the case of DPS-B steel specimens, the ultimate tensile strength (R_m) increased with 80 MPa, from 638 MPa (T_Q = 760 ˚C) to 718 MPa (T_Q = 820 ˚C), and the total elongation (A_5) decreased with 4.70 percent, from 23.29% (T_Q = 760 ˚C) to 18.59% (T_Q = 820 ˚C).

The slightly higher carbon and manganese content of DPS-B steel (compared to DPS-A steel) determined the obtaining of slightly higher values of the volume fraction of martensite in the structure, with effect on the ultimate tensile strength and total elongation; for example, for T_Q = 760 ˚C the ultimate tensile strength was 638 MPa compared to 631 MPa and the total elongation was 23.29% compared to 24.46%, and for T_Q = 520 ˚C the ultimate tensile strength was 718 MPa compared to 701 MPa and the total elongation of 18.59% compared to 19.04%.

The results obtained for the two dual-phase steels with low manganese content (DPS-A and DPS-B) were compared with those determined from previous research (Tab.3, [14, 15]), performed on dual-phase steel with 1.90% Mn (0.09% C, 1.90% Mn, 0.06% Si, 0.10% Cr, 0.09% Ni, 0.03% Mo, 0.012% Al, 0.15% Cu, 0.019% P, 0.011% S), alloy noted $DPS_{1.90Mn}$ in this article. The higher manganese content determined a lower position of the critical points A_{c1} and A_{c3} (A_{c1} = 703 ˚C, A_{c3} = 839 ˚C) compared to the DPS-A and DPS-B alloys and for this reason, the intercritical quenching of $DPS_{1.9Mn}$ steel was performed from temperatures between 740 and 820 ˚C (compared to 760 – 820 ˚C for DPS-A and DPS-B alloys).

Table 3. The volume fraction of martensite and mechanical properties for the $DPS_{1.90Mn}$ (average values).

T_Q, ˚C	V_M, %	R_m, MPa	A_5, %
740	25.10	883	16.68
760	42.51	957	15.18
780	57.10	1018	14.04
800	68.32	1086	12.99
820	78.10	1135	12.06

There are important differences between the two data sets (Tabs.1 – 3, Figs.8 and 9), differences determined by the very different manganese content of the two categories of steels. In $DPS_{1.9Mn}$ steel, the position of the critical points A_{c1} and A_{c3} led to the obtaining, by intercritical heating, of a higher amount of austenite, which determined the formation, on quenching, of a higher the volume fraction of martensite; thus, for the temperature range 760 – 820 ˚C, the volume fraction of martensite in the structure was higher by percentages between 22.32 and 41.12%. Because of this, the values of ultimate tensile strength and total elongation at DPS-A and DPS-B steels were much different from those of $DPS_{1.90Mn}$ steel; the total elongation was higher with percentages between 9.28 and 6.98% and the ultimate tensile strength was lower with values between 326 and 434 MPa.

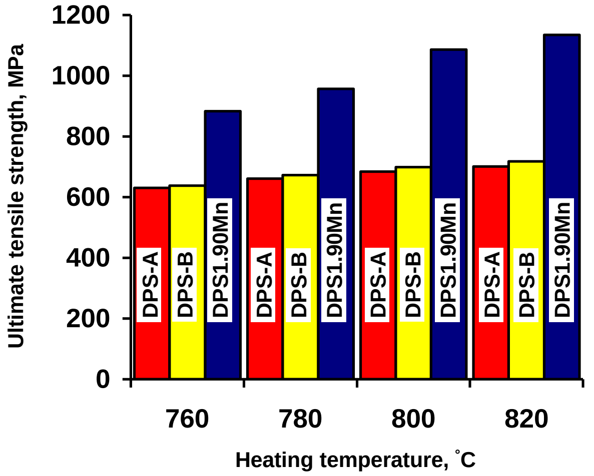

Fig.8. Influence of the heating temperature on the ultimate tensile strength of the dual-phase steels (DPS-A, DPS-B, and $DPS_{1.9Mn}$).

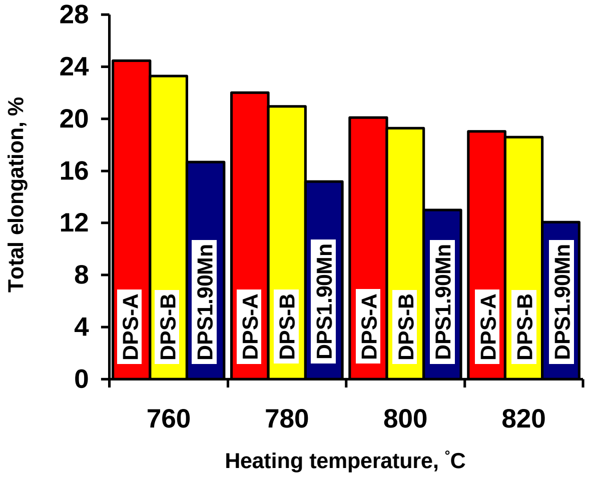

Fig.9. Influence of the heating temperature on the total elongation of the dual-phase steels (DPS-A, DPS-B, and $DPS_{1.9Mn}$).

CONCLUSIONS

The increase of the heating temperature in the intercritical range (Ac_1 - Ac_3), between 760 ˚C and 820 ˚C, led to the increase of the volume fraction of martensite and the ferrite microhardness in the structures resulting from intercritical quenching; this fact has increased the mechanical strength and reduced the deformability of the dual-phase steels.

The slightly higher carbon and manganese content of DPS-B steel (compared to DPS-A steel) determined the obtaining of slightly higher values of the volume fraction of martensite in the structure, with effect on the ultimate tensile strength and total elongation; the ultimate tensile strength was higher by 7 to 17 MPa, and the total elongation was lower by percentages between 1.17 and 0.45%.

Compared to the mechanical properties of a dual-phase steel with 1.90% Mn (a "classic" dual-phase steel), low manganese steels (0.511% Mn and 0.529% Mn) had much different values of the ultimate tensile strength and total elongation; the ultimate tensile strength was lower by 326 to 434 MPa, and the total elongation was higher by percentages between 9.28 and 6.98%.

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NOMENCLATURE

Ac_1 - critical point, °C;
Ac_3 - critical point, °C;
T_Q - heating temperatures from the intercritical quenching, °C;
V_M - the volume fraction of martensite, %;
HV0.01 - ferrite microhardness;
R_m - ultimate tensile strength, MPa;
A_5 - total elongation, %;
DPS-A - dual-phase steel with 0.511% Mn;
DPS-B - dual-phase steel with 0.529% Mn;
$DPS_{1.90Mn}$ - dual-phase steel with 1.90% Mn.

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