LABORATORY STUDIES OF A DUAL-PHASE STEEL WITH 0.53% MN STRUCTURES

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Abstract: *This article presents the results of research conducted to determine the influence of heating temperature on the structure of a dual-phase steel with low manganese content (0.53% Mn). The ferrite-martensite structures were obtained by intercritical quenching (heating to temperatures located between 750 and 850 °C, followed by cooling in water), andthe metallographic analyses revealed the volume fraction of martensite in these structures; to evaluate the influence of the structure, and therefore of the heating temperature, on some mechanical properties, the carbon content of martensite was calculated and the Vickers hardness was measured.*

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

1. Introduction

Global legislators have passed more stringent vehicle safety (crash), fuel economy and tailpipe emissions regulations in recent years, while considering further, aggressive targets for the next decade. For these reasons, automakers are searching for new materials and engineering capabilities to meet requirements that often conflict. As an example, structural applications require materials characterized by high strength and stiffness, often achieved with greater thickness. But fuel economy and emissions are positively impacted when the component thickness is reduced. The new vehicle designs with complex geometries are aesthetically pleasing, but difficult to form and join, compromised further by thickness decrease to achieve mass reduction targets. Therefore, automakers need materials that balance performance, safety, fuel efficiency, affordability and the environment, while maintaining designs that are appealing to customers. The steel industry continues to develop new grades of steel, defined by ever-increasing strength and formability capabilities, continually reinventing this metallic material to address these opposing demands. Thus, "Advanced High-Strength Steels" (AHSS) made 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. Advanced High-Strength Steels (AHSS) are complex, sophisticated materials, with carefully selected chemical compositions and multiphase structures resulting from precisely controlled heating and cooling processes [1-4].

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 Dual-Phase steels (DP), materials extensively used to manufacture crumple zone to the body structure of a vehicle, closures, hood, doors, front and rear rails, beams and cross members, sills, cowl inner and outer, crush cans, shock towers, fasteners, and wheel. These materials' structure is formed by a soft and ductile ferrite matrix in which martensite (10 to 35 %, according to European Standard EN 10020:2000) and a small amount of residual austenite (1 to 2 %) are homogeneously dispersed; they have a stress-strain curve continuous, low yield strength and high tensile strength (a very small $R_{p0.2}/R_m$ ratio), and their work hardening is very fast to small stress. The dual-phase steels have, 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 recent years, to reduce costs of steels and therefore, finally, of vehicles, research has been done on alloys in which the manganese content was less than 1 % (0.5 to 1 % Mn).One of the technologies for making these steels is "intercritical quenching"; the structure obtained by applying this method is influenced by both the chemical composition of the steel and the technological parameters of the heat treatment, especially the heating temperature. At the same time, the mechanical and technological properties depend on the quantitative ratio and the morphology of the structural components that are formed as a result of the thermal processing process. Therefore, to obtain the desired ferrite-martensite structure, the influence of heat treatment parameters on the quantity, morphology, distribution and properties of the two phases must be known [1-9].

The study of both dual-phase steels production technologies by intercritical quenching and structures and properties of these materials began at “Stefan cel Mare” University of Suceava (Romania) in 1992, and over the years research has been carried out on several categories of alloys [10,11]; here, in recent years, studies have been made on dual-phase steels with low manganese content [12-14], in this article being presented the influence of the heating temperature (from intercritical quenching) on the structure of a dual-phase steel with 0.53% Mn.

2. Materials and methods

The chemical composition of the studied alloy (denoted $DP_{0.53Mn}$) was determined with a FOUNDRY-MASTER Xpert Spectrophotometer (Oxford Instruments Analytical GmbH, Germany), Table 1, and the initial structure of this alloy was composed of 87.10% ferrite and 12.90% pearlite [13].

Table 1. The chemical composition of the $DP_{0.53Mn}$ steel.

Chemical elements (wt. %)			
C	Mn	Si	P
0.094	0.530	0.085	0.003
S	Cr	Mo	Ni
0.004	0.029	0.005	0.042
Al	Cu	Fe	
0.003	0.065	balance	

The critical points 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 = 725.50˚C and Ac_3 = 900.40 ˚C [13].

To obtain the ferrite-martensite structure, specific to a dual-phase steel, samples of the $DP_{0.53Mn}$ alloy were subjected to intercritical quenching; the heating temperatures (T_Q) were chosen according to the position of the critical points in the solid-state phase transformation (Ac_1 and Ac_3) and had values between 750 and 850˚C (750, 770, 790, 810, 830 and 850 ˚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, and the cooling was conducted in water (without mechanical agitation) with the temperature of 20 ˚C.

After quenching, metallographic analyses were performed with a LEXT OLS4100 Laser Microscope (Olympus Corporation, Japan). The surfaces needed for these analyses were obtained by processing the samples (five samples for each version of intercritical quenching) with Hot Mounting Press OPAL

410 and Grinding/Polishing Machine SAPHIR 530 (ATM GmbH, Germany). 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, the martensite appeared as "dark" regions on micrographics, and the ferrite beads as the "white" regions [15]. Five micrographs were performed on each sample, and the volume fraction of martensite (V_M) was then determined on them (with OLYMPUS Stream MOTION Image Analysis Software).

The metallographic analyses were completed by measuring the Vickers hardness of the quenched samples (to evaluate the influence of the structure on the properties of dual-phase steel). The determination of hardness was made with a MicroHardness Tester DuraScan 70 (Emco Prüfmaschinen-Test GmbH, Austria), following the provisions of EN ISO 6507-1: 2018, "Metallic materials - Vickers hardness test - Part 1: Test method"; the test load of the Vickers indenter was 9.8 N (1 kgf), five hardness measurements being performed on each sample (Figure 1).

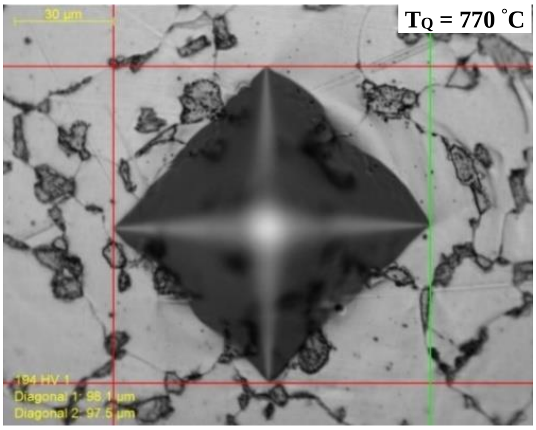


Figure 1. *Determination Vickers hardness.*

The mechanical properties of a dual-phase steel are influenced also by the carbon content of martensite (C_M), not only by the volume fraction of (V_M) of this phase [6-9,11,12,14,16-18]. The carbon content of martensite (C_M) can be determined by X-ray diffraction analysis or it can be calculated with different equations, one of them being proposed by *G. R. Speich* and *R.L. Miller* [6,12,17]:

$$C_M = C_o + \frac{\rho_F}{\rho_M} \cdot \left(\frac{100}{V_M} - 1 \right) \cdot (C_o - C_F) \quad (1)$$

in which: C_M is the carbon content of the martensite; C_o – the carbon content of the steel; C_F - the carbon content of the ferrite, (C_F = 0.002%); V_M – the volume fraction of martensite; ρ_F – the density of the ferrite; ρ_M – the density of the martensite, (ρ_F/ρ_M = 1.025) [6,12,17]; with equation (1) the carbon content of martensite (C_M) in the structures obtained by intercritical quenching was calculated.

3. Results and discussions

The mechanical properties of a dual-phase steel are fundamentally influenced by the volume fraction of martensite in the structure, the morphology and distribution of this phase, structural characteristics, which in turn are influenced, in particular, by the heating temperature in the range between critical points Ac_1 and Ac_3. Raising the heating temperature causes an increase in the volume fraction of martensite and a decrease in the amount of ferrite in the structure of dual-phase steel; the heating in the intercritical range (Ac_1 - Ac_3) leads to a ferrite-austenite structure and raising the heating temperature in this range causes an increase in the volume fraction of austenite, a phase which then by high rate cooling turns into martensite. The structure obtained by intercritical quenching from temperatures close to the critical point Ac_1 contains martensite islands (M), relatively isolated from each other (many of the islands being elongated), situated (usually) at the boundaries of the ferrite grains. Most of these islands are located in regions where, in initial structure, has been pearlite (P); by heating (over point Ac_1), the pearlite was transformed into austenite (A), from which, through quenching, martensite was obtained (P $\rightarrow$ A $\rightarrow$ M).The martensite islands (M) that are located in regions other than those where pearlite existed (in the initial structure), resulted from an austenite (A) formed following the allotropic transformation of the ferrite (F): F → A → M; raising the heating temperature in the intercritical range leads to an increase in the volume fraction of martensite formed in this way (F → A → M).The mechanical properties of a dual-phase steel (in particular those of strength) are also influenced by the carbon content of martensite (C_M), which decreases with increasing the volume fraction of this phase (V_M), hence with increasing heating temperature (T_Q); the variation of the volume fraction of martensite (V_M) in structure has two contradictory effects on the mechanical characteristics (especially on ultimate tensile strength), namely: on the one hand, the strength properties increase with increasing the volume fraction of martensite (V_M), and on the other hand, the carbon content of martensite (C_M) decreases, and hence its strength decreases with an increase in the volume fraction of martensite (V_M). From the above it follows that the heating temperature is an essential parameter in a technology for the production of dual-phase steels; it determines the amount of austenite formed in an alloy with certain chemical composition and finally the volume fraction of martensite in the structure (as well as the carbon content and the properties of this phase) [6-9,11,12,14,16-20].

In the case of the studied steel ($DP_{0.53Mn}$), the results of the metallographic analyses and the hardness tests performed are presented in Table 2.

Table 2. Results of the metallographic analyses and the hardness tests (average values).

T_Q, °C	750	770	790	810	830	850
V_M, %	17.04	18.75	23.38	29.03	37.46	47.60
C_M, %	0.533	0.503	0.403	0.325	0.251	0.198
HV1	188	195	201	207	212	214

Raising the heating temperature (T_Q) in the intercritical range (Ac_1 - Ac_3), from 750 to 850 °C, led to an increase in the volume fraction of martensite (V_M) in the structures, from 17.04% to quenched samples from 750 °C at 47.60% to those quenched at 850 °C (Figure 2). The volume fraction of martensite (V_M) resulted by quenching from 830 and 850 °C (37.46% and 47.60% respectively) exceeds the maximum value (of 35%) provided for dual-phase steels in the European Standard EN 10020: 2000. In the structures obtained by quenching from 750 °C, around 12.90% martensite was formed from austenite obtained by eutectoid transformation of pearlite from the initial structures (P → A → M); the difference up to 17.04% martensite (ie 4.14%) resulted from an austenite formed by allotropic transformation of the ferrite (F → A → M). As the heating temperature increased, the difference between the volume fraction of martensite obtained by the P → A → M mechanism and that resulting from the F → A → M mechanism also increased, reaching a percentage of 34.70% in the structures obtained by quenching from 850 °C.

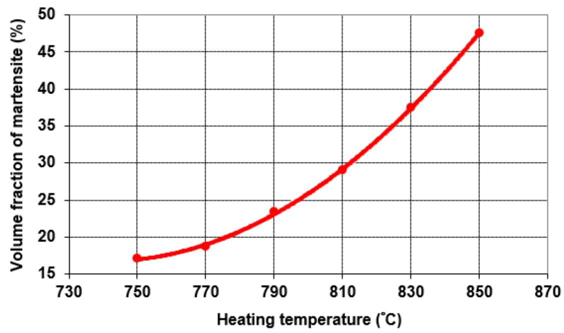


Figure 2. *Influence of the heating temperature on the volume fraction of martensite.*

The martensite of the structures formed by quenching from 750 °C is in the form of small islands, situated mainly at the boundaries of the ferrite grains (Figure 3), most of them being located in regions in which, in initial structure, has been pearlite. The increase in the volume fraction of martensite, due to the rise in heating temperature, was accompanied by an increase in the size of the islands of this phase (which become thicker and less elongated), as well a tendency of their connection and the formation of a network around the ferrite grains (Figure 3).

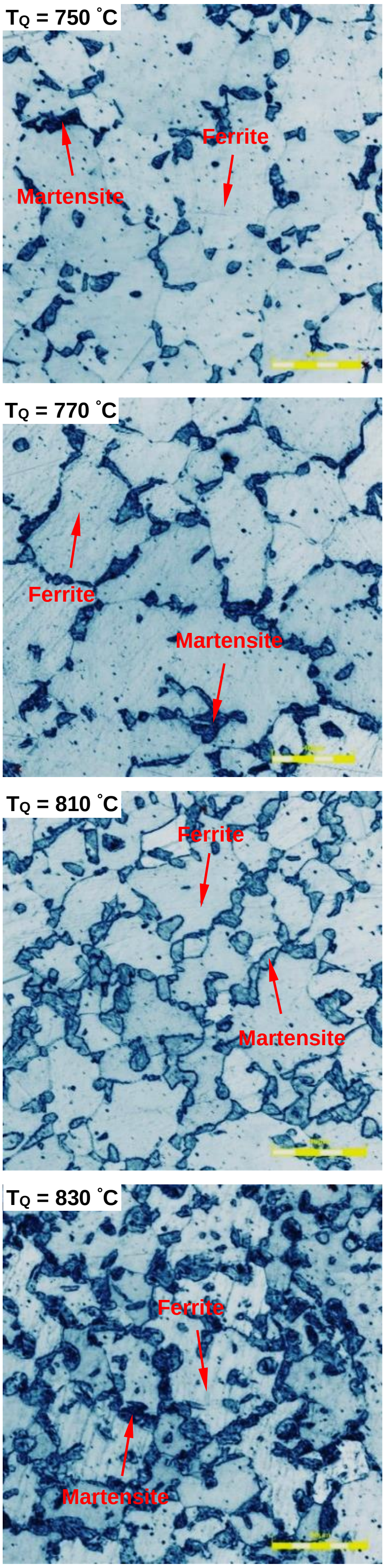
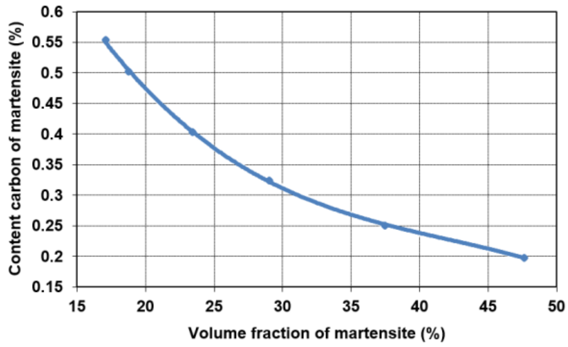
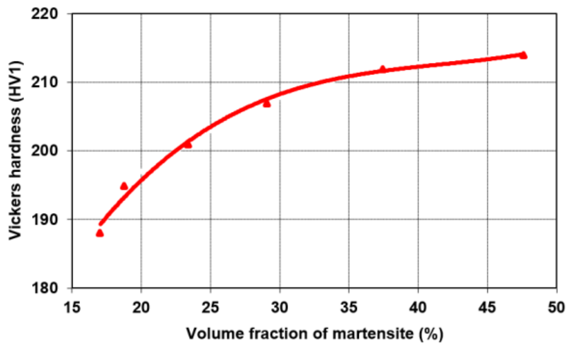


Figure 3. *Microstructures of the $DP_{0.53Mn}$ steel (laser micrographs).*

The carbon content of martensite (C_M) decreased with increasing volume fraction of martensite in the structure (Figure 4.a) from 0.553% for V_M = 17.04% (T_Q = 750 ˚C) to 0.198% for V_M = 47.60% (T_Q = 850 ˚C); this fact was also reflected in the evolution of Vickers hardness, hence of the mechanical characteristics (of the strength ones) of the dual-phase steel, depending on the values of V_M (Figure 4.b). The obtained results show that the two contradictory effects of martensite on the mechanical properties are more visible at a volume fraction of this phase (V_M) higher than 35% (Fig. 4.b); thus, for V_M between 17.04% (C_M = 0.553%) and approx. 35% (C_M = 0.269%), the variation of Vickers hardness is more intense, than for V_M between 35% (C_M = 0.269%) and 47.60% (C_M = 0.198%).



a



b

Figure 4. *Influence of the volume fraction of martensite on the carbon content of martensite (a) and the Vickers hardness (b).*

4. Conclusions

Raising the heating temperature (T_Q) in the intercritical range (Ac_1 - Ac_3), from 750 to 850 ˚C, led to an increase in the volume fraction of martensite (V_M in the structures, from 17.04 to

47.60% and the increase Vickers hardness (HV1) of dual-phase steel with low manganese content studied.

However, the increase in the volume fraction of martensite determined the decrease of the carbon content of this phase (C_M), which influenced the evolution of the mechanical characteristics (of the strength ones) depending on the values of V_M; in this alloy, the contradictory effects of increasing the volume fraction of martensite in structures of the dual-phase steels (the strength properties increase with increasing the volume fraction of martensite, but the carbon content of martensite decreases, and hence its strength decreases) were more visible at values of V_M greater than 35%.

The martensite of the structure obtained by quenching from 750 $^{\circ}$C (the heating temperature closest to the critical point Ac_1) was in the form of small islands, situated mainly at the boundaries of the ferrite grains. The increase in the volume fraction of martensite, due to the rise in heating temperature, was accompanied by an increase in the size of the islands of this phase, as well a tendency of their connection and the formation of a network around the ferrite grains.

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