# THE INFLUENCE OF THE VOLUME FRACTION OF MARTENSITE ON THE ABSORBED ENERGY IN THE CHARPY PENDULUM IMPACT TEST OF A DUAL-PHASE STEEL WITH 1.15% Mn and 1% Cr

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**Abstract:** *In this article, the behavior of a dual-phase steel alloyed with manganese and chromium (0.182% C; 1.156% Mn; 1.004% Cr) during the Charpy pendulum impact test is presented, using standard test pieces with U and V notches.The ferrite-martensite structures (specific to dual-phase steel) were obtained by intercritical quenching, with heating at temperatures between 770 °C and 850 °C (for 30 minutes), followed by cooling in water without mechanical agitation. Through the analyses and tests carried out, the following were determined: the volume fraction of martensite in the structure (VM), the Vickers hardness of the steel (HV), the absorbed energy to break in the impact (KU2 and KV2).*

**Keywords:** *dual-phase steel; volume fraction of martensite; intercritical quenching; Charpy pendulum impact test; absorbed energy*

## 1. Introduction

Since the first mass-produced car (by the Oldsmobile Curved Dash in 1901), the automotive industry has made tremendous progress in terms of vehicle design, manufacturing technologies, materials used, performance etc. Over the years, the governments and parliaments of some countries or some international bodies (for example, European Union) have adopted increasingly higher safety and fuel economy standards; to meet the requirements of these standards at reasonable cost levels, car manufacturers have developed, among other things, new materials. In this way, the "Advanced High-Strength Steels" (abbreviated AHSS) were introduced to the automotive industry, materials that help engineers meet the requirements of safety, fuel efficiency, reduced environmental impact, machinability, durability and quality, at a low cost. This family of steels includes Dual Phase (DP), Complex-Phase (CP), Ferritic-Bainitic (FB), Martensitic (MS), Transformation-Induced Plasticity (TRIP), Hot-Formed (HF), and Twinning-Induced Plasticity (TWIP); they have a very high mechanical strength, associated with a high deformability (necessary to make auto body structures), with toughness and fatigue resistance, characteristics ensured by carefully selected chemical compositions and structures resulting from precisely controlled heating and cooling processes, [1-4]

*Dual-phase steels (DP)* are an important category of „advanced high-strength steels" (AHSS) widely used in the automotive industry, which were developed in the second part of the 20th century, when the "first oil crisis" (1973 ÷ 1974) required (especially in the U.S.) to reduce the weight of vehicles in order to make exploitation more economical; however, the decrease in the weight of the vehicle, in correlation with safety requirements and performance in operation, required the use of materials with higher strength, but with great deformability. At the beginning of the 70s of the 20th century, intense research was carried out for the production of „high-strength low-alloy steels" (HSLA), and in the middle of the decade, from the research led by M.S. Rashid, from General Motors, dual-phase steels were born, which at great strength, have good plasticity. They are obtained following thermal or thermomechanical processes, have a low carbon content and a structure made up of a soft and ductile ferrite matrix, in which are homogeneously dispersed, martensite and a small amount of residual austenite (1 to 2%). The stress-strain curve of dual-phase steels (as opposed to ferrite-pearlite ones) is continuous, without yield; their work hardening is very fast at small stresses, they have a low yield strength, a high tensile strength (a very small $R_{p0,2}/R_m$ ratio; is about 0.5), their deformability is much better than that of ferrite-pearlite steels, for similar tensile strengths. The superiority of these materials, compared to other steels, is determined not so much by their high strength or plasticity, but especially by the possibility of obtaining a high combination of these properties, a fact that allows the creation of parts with particularly complex shapes and with high mechanical strength (used to manufacture crumple zone to body structure of a vehicle, closures, hood, doors, front and rear rails, beams and cross members, sill, cowl inner and outer, crush cans, shock towers, fasteners and wheel), [1-8].

The appropriate use of a metallic material is closely related to the results of mechanical tests performed on samples subjected to stresses as close as possible to those in practice, and the mechanical characteristics that express the behavior of the metal or alloy at high deformation rates are of great importance for engineering applications; therefore, in order to characterize a metallic material, it is also subjected to *dynamic tests* (mechanical tests with high rate of load application), in addition to those to static stresses (e.g. tensile or hardness test). Typically, dynamic tests are carried out, realized by breaking some samples with a single blow by a rotating or free-falling mass. The most widespread dynamic test is the bending test performed on notched specimens (pendulum impact test), which indicates the deformation capacity of metallic materials under conditions of deformation rate, temperature and tensile state, [9-11]. Due to their high plasticity and strain hardenability, dual-phase steels are suitable for cold working (e.g. deep drawing, stretching, hydroforming etc.); however, during the processing, problems of cracking of the material were encountered. The development of dual-phase steels with increasingly higher mechanical strengths (current DP steels with strengths up to 1200 MPa) has led to an increase in the frequency of cracks in cold plastic deformation processing, which is a real concern of steel manufacturers automotive components; crack resistance has become a critical factor limiting the use of dual-phase steels with high mechanical strengths, [12-14]. Therefore, understanding the effects of microstructure on behavior under impact stress is essential for the development of new dual-phase steels.

The dual-phase steels have been studied at "Stefan cel Mare" University of Suceava since 1992, and over the years research has been carried out on several categories of alloys [7-8, 15-19]; this article presents the results of the studies carried out in this university to establish the influence of the volume fraction of martensite in the structure on the absorbed energy during the Charpy pendulum impact test of a dual-phase steel with manganese and chromium in the chemical composition..

## 2. Materials and Methods

The chemical composition of the studied alloy (denoted $DP_{Mn-Cr}$) was determined with a FOUNDRY - MASTER Xpert Spectrophotometer (Oxford Instruments Analytical GmbH, Germany), and it is presented in Table 1. The initial structure of this alloy was composed of 61.64% ferrite and 38.36% pearlite.

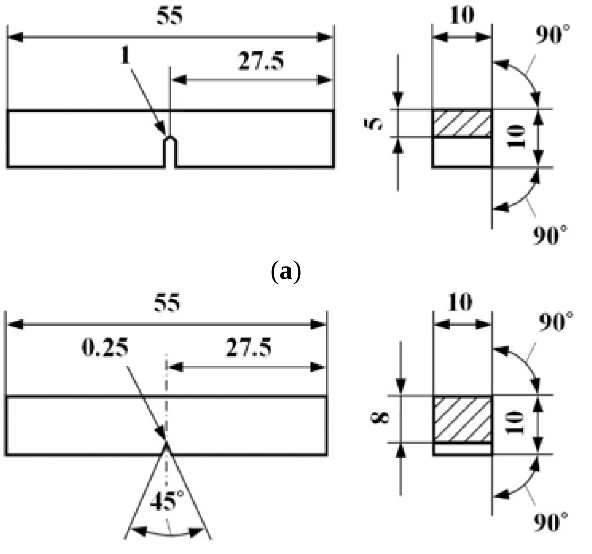
**Table 1:** *The chemical composition of the DPMn-Cr steel*

| **Chemical elements (wt. %)** | | | | |
|---|---|---|---|---|
| C<br>0.182 | Mn<br>1.156 | Cr<br>1.004 | Si<br>0.258 | Cu<br>0,217 |
| Mo<br>0,052 | Ni<br>0,205 | P<br>0,0162 | S<br>0,253 | Fe<br>balance |

The ferrite-martensite structures specific to dual-phase steels were obtained by applying the heat treatment of intercritical quenching to some samples made from the studied alloy. For the correct performance of this heat treatment, it is necessary to know the critical points Ac1 and Ac3 (for establishing the quenching temperatures). The values of these critical points were determined by dilatometric analyses performed with a DIL 402 Expedis-SUPREME Dilatometer (NETZSCH Gerätebau GmbH, Germany), being 738.90 °C for Ac1 and 841.10 °C for Ac3, and the heating temperatures (TQ) at intercritical quenching were set between 770 and 850 °C (770, 790, 810, 830 şi 850 °C). The heating was conducted in an electric laboratory furnace Nabertherm LT 40/11/P330 (Nabertherm GmbH, Germany), at constant values of the TQ temperature, for 30 minutes; the cooling was carried out in water (with the temperature of 20 °C), without mechanical agitation.

After quenching, the samples were subjected to metallographic analyses in order to determine the volume fraction of martensite ($V_M$) in the structures; the analyses were performed with a LEXT OLS4100 Laser Microscope, (Olympus Corporation, Japan) and OLYMPUS Stream MOTION Image Analysis Software. The surfaces needed metallographic analysis (seven samples for each version of intercritical quenching) were obtained by processing 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, on micrographics, the martensite appeared as "dark" regions and the ferrite beads as the "white" regions, [8, 17, 20, 21]. Five micrographs were performed on each metallographic sample.

In order to determine the influence of the volume fraction of martensite on on the absorbed energy in the impact tests, specimens with ferrite-martensite structures obtained by applying the heat treatments described above (batches of 10 specimens for each quenching temperature) were subjected to such tests. These have been carried out on a Pendulum Hammer type IMPACT 300 (Cesare GALDABINI SpA, Italy), following the provisions of EN ISO 148-1:2016 ("Metallic materials - Charpy pendulum impact test - Part 1: Test method"). Standard Charpy specimens were used (with with 55 mm long and of square section, with 10 mm sides), which had **U** and **V** notch in the center of the length; the **U**-notch had a depth of 5 mm and a root radius of 1 mm (Figure 1.a.), and the **V**-notch had an included 45° angle, a depth of 2 mm and a root radius of 0,25 mm (Figure 1.b.). The results obtained on Charpy specimens with **U** and **V** notch complement each other because the **U**-notch test shows the property of the metal material to avoid crack initiation, and the **V**-notch test shows the property of the metal or alloy to stop propagation of the crack initiated on the sharp tip, [9-11].



(**a**)

(**b**)

**Figure 1.** *The specimens for Charpy pendulum impact test: (**a**) specimen with U-notch; (**b**) specimen with V-notch, [11].*

Before carrying out the impact tests, the Vickers hardness was measured on the Charpy specimens (in compliance with EN ISO 6507-1:2018, "Metallic materials - Vickers hardness test - Part 1: Test method"); determinations were made with a MicroHardness Tester DuraScan 70 (Emco Prüfmaschinen-Test GmbH, Austria), the test load of the Vickers indenter being 5 kgf (49 N)

## 3. Results and discussions

The behavior under static and dynamic stresses of dual-phase steels is influenced, in particular, by the volume fraction of martensite ($V_M$) in their structure, [5-8, 15-20], and therefore, this structural parameter was first determined from the microstructures obtained by applying the intercritical tempering variants described above. Thus, on the micrographs taken at different points on the heat-treated samples (five points on each intercritical quenched sample), the volume fraction of martensite ($V_M$) was determined with the help of OLYMPUS Stream MOTION Image Analysis Software; the results obtained are reproduced in Table 2 and Figures 2, 3 and 4.

**Table 2.** *Volume fraction of martensite for $DP_{Mn\text{-}Cr}$ steel (average values).*

| **$T_Q$, ˚C** | **770** | **790** | **810** | **830** | **850** |
|---|---|---|---|---|---|
| **$V_M$, %** | 51,22 | 73,01 | 83,31 | 90,14 | 93,47 |

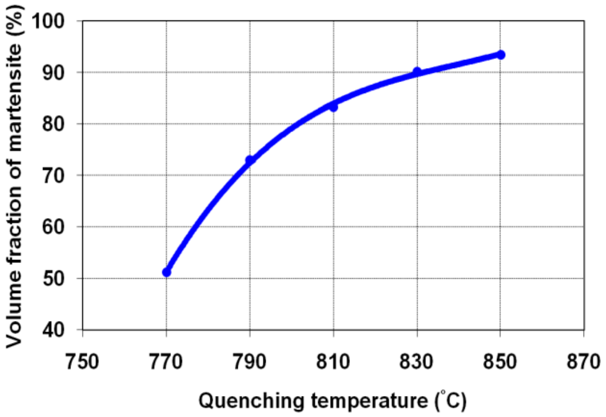
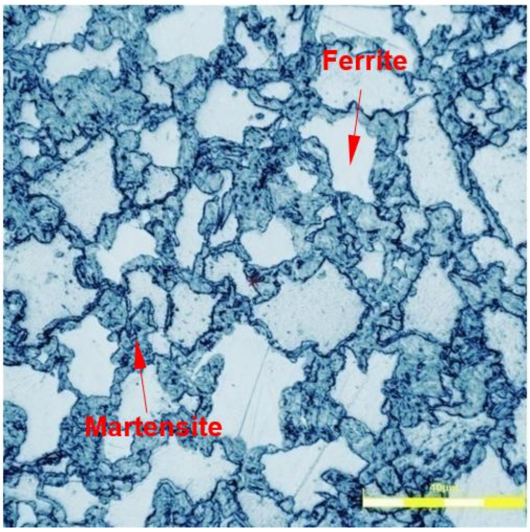


**Figure 2.** *Variation of volume fraction of martensite with quenching temperature.*



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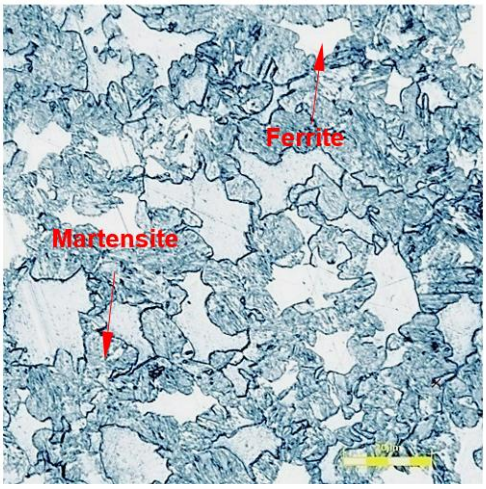
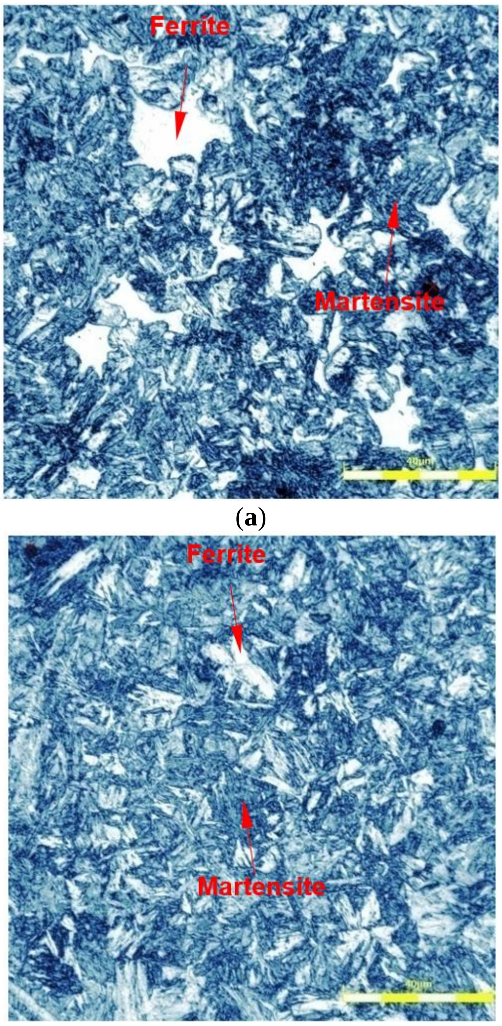


(**b**)

**Figure 3.** *Microstructures of the $DP_{Mn\text{-}Cr}$ steel (laser micrographs):*
*(**a**): $T_Q$ = 770 ˚C; (**b**) $T_Q$ = 790 ˚C*



(**a**)

(**b**)

**Figure 4.** *Microstructures of the $DP_{Mn\text{-}Cr}$ steel (laser micrographs):*
*(**a**): $T_Q$ = 810 ˚C; (**b**) $T_Q$ = 850 ˚C*

Raising the quenching temperature ($T_Q$) from 770 to 850 °C, led to the increase in the amount of austenite formed by heating, which caused the increase in the volume fraction of martensite (VM) in the structures; thus, the VM increased from 51.22% for TQ = 770 °C, to 93.47% for TQ = 850 °C. From Table 2. and Figure 4 it can be observed that the increase in the volume fraction of martensite ($V_M$) in the structures is steeper between 770 and 810 °C, after which the increase of this structural parameter becomes smoother (less steep).

To verify the influence of the volume fraction of martensite in the structure on some mechanical characteristics of the dual-phase steel, the metallographic analysis was completed with Vickers hardness tests. Eight hardness determinations were performed on each specimen intended for Charpy pendulum impact tests (two determinations each on four of the six faces of the specimen); the software used to determine the Vickers hardness (*ecos Workflow*) also allowed the approximation of ultimate tensile strength ($R_m$), the results obtained being presented in Table 3 and Figure 5.

**Table 3.** *Vickers hardness and ultimate tensile strength for $DP_{Mn\text{-}Cr}$ steel (average values).*

| **$V_M$, % ($T_Q$)** | **51,22 (770˚C)** | **73,01 (790˚C)** | **83,31 (810 ˚C)** | **90,14 (830˚C)** | **93,47 (850˚C)** |
|---|---|---|---|---|---|
| **HV5 ($R_m$)** | 242 (755MPa) | 253 (784MPa) | 270 (845MPa) | 306 (958MPa) | 339 (1064 MPa) |

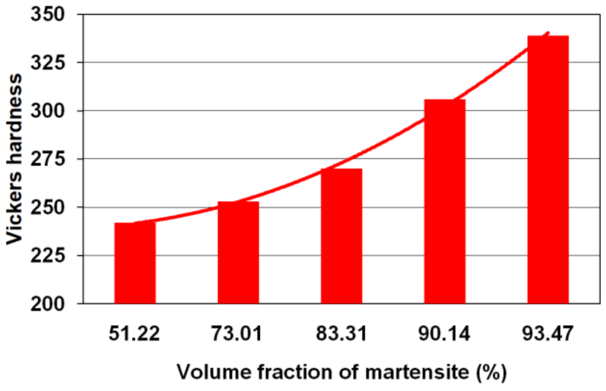


**Figure 5.** *Variation of Vickers hardness with the volume fraction of martensite*

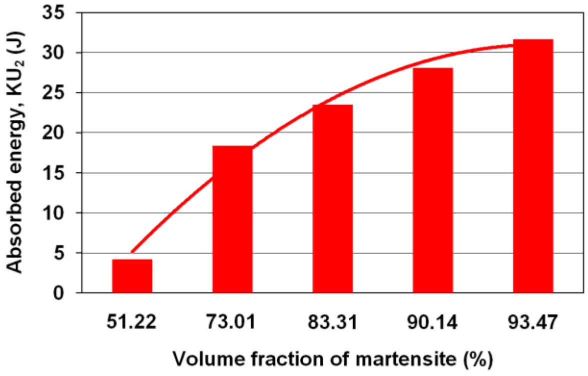
From the above data, it follows that the increase in the volume fraction of martensite in the structure ($V_M$) with the rise of the quenching temperature ($T_Q$), determined an increase in the Vickers hardness (HV5), the strength characteristics ($R_m$) of the dual-phase steel; thus, the hardness increased from 242 HV5 ($R_m$ = 755 MPa) for $V_M$ = 51.22% ($T_Q$ = 770 ˚C), to 270 HV5 ($R_m$ = 845 MPa) for $V_M$ = 83.31% ($T_Q$ = 810 ˚C), then at 339 HV5 ($R_m$ = 1064 MPa) for $V_M$ = 93.47% ($T_Q$ = 850 ˚C).

As shown above (§ 1), dual-phase steels have a high deformability combined with a very good strain hardenability and therefore, they are used in the automotive industry to achieve, by applying cold plastic deformation technologies (deep drawing, stamping, etc.), of some vehicle components (especially, car body elements). However, some car manufacturers have encountered difficulties in using these steels, especially those with high mechanical strength (up to 1200 MPa), due to the increased frequency of the appearance of cracks during processing. As a consequence, an understanding of the behavior of these materials under impact stresses, of the effect of the structure (of the volume fraction of martensite) on the crack resistance is necessary, [12-14]. Therefore, to establish the influence of the volume fraction of martensite ($V_M$) on the behavior of $DP_{Mn\text{-}Cr}$ steel under certain impact stress conditions, i.e. to highlight its property to avoid initiation or stop the propagation of a crack, standard *Charpy* specimens with **U** and **V** notch, made in accordance with the indications in the EN ISO 148-1:2017 standard and then heat treated, were subjected to impact tests. The specimens were grouped into batches of ten pieces for each variant of intercritical quenching described in the "Materials and Methods" chapter. The tests were carried out at room temperature (about 22 ˚C), on a pendulum hammer type "Impact 300" - Cesare GALDABINI Sp A, Italy (with the nominal initial potential energy of 300 J and the radius of the striking edge of 2 mm); the absorbed energy to break ($KU_2$ and $KV_2$) was determined, the results obtained being reproduced in Table 4 and Figure 6.

**Table 4.** *Absorbed energy to break specimens with **U** and **V** notch.*

| $V_M$, % ($T_Q$) | 51,22 (770 ˚C) | 73,01 (790 ˚C) | 83,31 (810 ˚C) | 90,14 (830 ˚C) | 93,47 (850 ˚C) |
|---|---|---|---|---|---|
| $KU_2$, J | 4,20 | 18,40 | 23,50 | 28,10 | 31,67 |
| $KV_2$, J | 6,70 | 20,85 | 27,73 | 33,60 | 37,65 |

Increasing the volume fraction of martensite ($V_M$) in the structures of the dual-phase steel studied (due to raising the intercritical quenching temperature, $T_Q$, from 770 to 850 ˚C), caused an increase in the absorbed energy to break Charpy specimens with **U** and **V** notch ($KU_2$ and $KV_2$); thus, $KU_2$ and $KV_2$ increased from 4.20 J and 6.70 J for $V_M$ = 51.22% ($T_Q$ = 770 ˚C), to 31.67 J and 37.65 J for $V_M$ = 93.47% ($T_Q$ = 850 ˚C).



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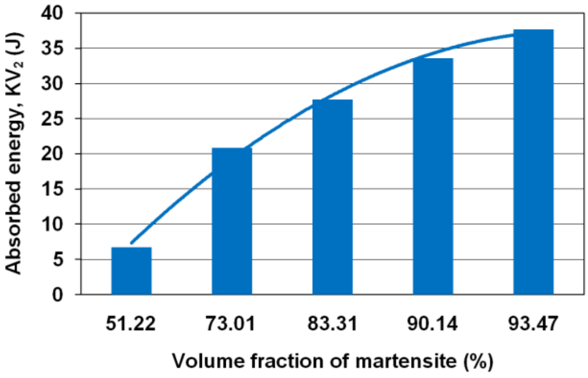

(**b**)

**Figure 5.** *Variation of energy absorbed to break with the volume fraction of martensite (**a**) Charpy specimens with U-notch; (**b**) Charpy specimens with V-notch*

From the data presented, it can be seen that an increase in the volume fraction of martensite in the structure ($V_M$) from 51.22% to 73.01%, generated an important jump in the values of absorbed energy at break from 4.20 J to 18, 40 J, for determinations made on Charpy specimens with **U** notch and from 6.70 J to 20.85 % for those with a **V** notch; for values of the volume fraction of martensite ($V_M$) greater than 73.01%, values obtained by intercritical quenching from temperatures located between 810 and 850 ˚C, the variation of absorbed energy at break is less. The increase in absorbed energy at the break of the Charpy specimens with the increase in the volume fraction of martensite ($V_M$) in the structure of the $DP_{Mn-Cr}$ steel indicates an improvement in the ability of this material to avoid the initiation of a crack (the results obtained for the specimens with **U**-notch) as well as to stop the propagation of an initiated crack (the results obtained for specimens with **V**-notch).

Analyzing the above data from (Tables 6.3 ÷ 6.4.), it is found that when the volume fraction of martensite ($V_M$) increases to values greater than 75%, there is a sharp increase in the absorbed energy at break of the Charpy specimens ($KU_2$ and $KV_2$); it is possible that this manifestation of the dual-phase steel studied is also influenced by the carbon content of the martensite ($C_M$). It is known from the specialized literature, [8, 12-14, 16-19, 22-24], that the variation of the volume fraction of martensite ($V_M$) has two contradictory effects on the mechanical characteristics (in particular those of strength): on the one hand, the strength properties of the steel increase with the increase of the volume fraction of martensite, and on the other hand, the carbon content of the martensite decreases, and therefore its strength decreases, with the increase of the volume fraction of martensite, improving the ductility and tenacity.

## 4. Conclusions

Raising the quenching temperature in the intercritical range (between 770 and 850 ˚C), determined an increase in the volume fraction of martensite ($V_M$), which generated an increase in the Vickers hardness (therefore, in the strength characteristics of the steel).

The increase in the volume fraction of martensite ($V_M$) in the dual-phase steel structure (especially at values higher than 75%) determined an increase in the absorbed energy to break the Charpy specimens ($KU_2$ and $KV_2$), a fact that indicates an improvement in the ability of this material to avoid initiation of a crack (results obtained for specimens with **U**-notch) as well as to stop the propagation of an initiated crack (results obtained for specimens with **V**-notch)..

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