Aspects regarding the plasticity of the steel subjected to non-conventional treatment

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Abstract. Plasticity is an important property to determine the capability of the steel to support plastic deformations, to obtain important pieces for industry. It is important to know the optimal cooling regime for this material because the steel have been rolling at high temperature or, the steel have been heated at high temperature after lamination process. It was considered a steel grade with a low carbon content, which can be find often in machine industry and in metallurgical operations. Three different mediums for directing of the cooling process have been considered and the properties of the steel have been modified. This study tried to determine a way to improve the properties of this kind of steel to obtain a higher durability corresponding to the exploitation conditions.

1 Introduction

The plasticity of the steel depends on its deformability. According to the literature, the deformability of the metallic materials characterizes their ability to be deformed permanently without breaking the inner linkages. Deformable metals and alloys are elasto-plastic-viscous bodies. Temperature is a factor that determines the physico-chemical state of the alloys. With increasing temperature, the speed of the modifying of the properties through deformation increases and the possibility to appear micro-cracks in the deformation decreases.

Studying Hanning’s and Boulger's deformability variations depending by temperature, it can be seen that the temperature of deformability around (250-300) °C is due to the formation of precipitates that favor the fragility of “the tempering to blue”. The sudden increasing in deformability between 600°C and 800 °C is due to inter-crystalline displacements and re-crystallization of steel. At the same time, the deformability of the steels depends on the carbon content [1, 2].

In the case of the steels with 0.1% C, 0.48% Mn, 0.24% Si, the micro-structural parameters which determine the mechanical properties of the steels are the sizes and the shapes of pearlitic (P) and ferritic (F) grains which form its microstructure. Ferrite has a low mechanical strength but it has good plasticity properties. Cementite (Cem) in steels has a good hardness but it is fragile [3, 4]. Cementite can cause cracks. Therefore, with the increasing of the carbon content, the hardness and the strength of the steels increase and the plasticity properties decrease [3, 5, 6-8].
The steels with low carbon content have high plasticity properties below 550°C and the thermal stresses will not lead to the formation of cracks [1]. Damage in the case of materials represents the progressive or sudden deterioration of their mechanical strength which conducts to dangerous effects for products [1-4]. It is important to know how it is possible to improve the properties of the steels [3].

The paper focuses on directed fast cooled steels strips for automotive application after hot laminated process [3].

### 2. Technology of rolling of large thickness sheets before non-conventional treatment

In order to collect the samples, it was considered a scheme of hot rolling of steel sheet. The samples had the following dimensions: 10 x 150 x 200 mm and came from a slab with the dimensions: 150 x 1500 x 2500 mm, in the case of a thick sheet rolling consisting of one system type quarto (two pairs of rolls - four Rollers Cylinders), with a sheet length maximum of 3000 mm and a vertical rolling system, placed in front of the first system. The hot rolling scheme is shown in Table 1 [1].

The mill from Mittal Steel Galati [1] consists of a reverse Roll Mill type "Quarto" and the equipment for straightening, cutting and marking of finished products.

### Table 1. Hot rolling scheme of the steel [1]

| Nb. of passes | Type of rolling/ Fasses/crossing | Thick ness [mm] | Width [mm] | Length [mm] | Absolute reduction ratio [mm] | Relative reduction ratio [%] | Reduction ratio coefficient | Obs. |
|---------------|----------------------------------|-----------------|------------|-------------|-------------------------------|----------------------------|-----------------------------|------|
| 0             | -                                | 150             | 1500       | 2500        | -                             | -                           | -                           | -    |
| 1             | Pressing/Forge rolling            | 150             | 1450       | 2600        | -                             | -                           | -                           | Rotation 90° |
| 2             | Rolling on width                  | 185             | 2600       | 1750        | 23                            | 16.9                        | 1.20                        | -    |
| 3             | Rolling on width                  | 105             | 2070       | 2090        | 20                            | 16                          | 1.19                        | -    |
| 4             | Pressing/repressing/Forge rolling | 105             | 2050       | 2620        | -                             | -                           | -                           | Rotation 90° |
| 5             | Pressing/Forge rolling            | 105             | 2050       | 2650        | -                             | -                           | -                           | -    |
| 6             | Rolling on length / flatting      | 85              | 2050       | 3250        | 20                            | 19                          | 1.24                        | -    |
| 7             | Rolling on length / flatting      | 65              | 2050       | 4200        | 20                            | 23.5                        | 1.30                        | -    |
| 8             | Rolling on length / flatting      | 45              | 2050       | 6100        | 20                            | 30.8                        | 1.44                        | -    |
| 9             | Rolling on length / flatting      | 30              | 2050       | 9200        | 15                            | 33.5                        | 1.50                        | -    |
| 10            | Rolling on length / flatting      | 20              | 2050       | 13700       | 10                            | 33.3                        | 1.50                        | -    |
| 11            | Rolling on length / flatting      | 14              | 2050       | 19600       | 6                             | 30                          | 1.43                        | -    |
| 12            | Rolling on length                | 11              | 2050       | 25000       | 3                             | 21.4                        | 1.27                        | -    |
| 13            | Rolling on length                | 10              | 2050       | 27500       | 1                             | 9.1                         | 1.10                        | -    |

After the technology to obtain Hot-Rolled Sheet’s Steel corresponding to the scheme presented in the table 1, the samples have been debited. The samples supported non-conventional treatments, watching the conduction of the cooling, modifying the speed of cooling after the heating of the steel samples.
The chemical composition of the steel was presented in Table 2.

| Element | C  | Mn  | Si  | Al  | P   | S   | Cu  | Mo  |
|---------|----|-----|-----|-----|-----|-----|-----|-----|
| Content [%] | 0.14 | 1.51 | 0.31 | 0.041 | 0.01 | 0.01 | 0.18 | 0.009 |

3. Experimental procedure

After rolling process, according to EN 10025-2:2004, 24 experiments have been carried out – considering three groups of samples and each group supported three types of non-conventional treatments, taking in consideration four values of the initial temperatures.

There were considered three groups of samples of the steel grade and each group had eight samples. The Chemical composition of the steel has been presented in table 2 [1].

The samples were heating at the different temperatures: T1 = 850°C (for the first batch of samples), T2 = 900°C (for the second batch of samples), T3 = 950°C (for the third batch of samples) and T4 = 1000°C (for the last batch of samples). Three cooling regimes [1, 3] have been used: (1) cooling regime in normal conditions; (2) cooling regime in metallic box; (3) cooling in air flow (using a jet of cold air). If the cooling mediums differ, the speeds of the cooling differ too.

Traction tests at the room temperature were carried out according to ASTM: E8M-11 standard [1, 9, 10], while those related to elevated temperatures were carried out according to ASTM: E21-09 [1, 3, 11]. Charpy impact tests for resilience determination were carried out according to ASTM: E23-07ae1 standard [12].

The preparation of metallographic specimens was conducted according to ASTM E3-11 standard [13]. All of mentioned standards can be found in Annual Book of ASTM Standards (2012) [1].

4. Results and discussion

In table 3, the cooling speed values for each different cooling conditions and the evolution of some mechanical properties of the steel [1], obtained after the experimental scheme, have been presented.

| Cooling Conditions | Initial temperature [°C] | Z [%] | KV<sub>20</sub> (-20°C) | Cooling Speed values (VR) - Average [°C/min] | KV<sub>20</sub> (20°C) | A5 [%] | Rm [N/mm<sup>2</sup>] | σ<sub>c</sub> (RC) [N/mm<sup>2</sup>] |
|-------------------|--------------------------|-------|--------------------------|---------------------------------------------|--------------------------|-------|---------------------|---------------------|
| (1)               | 1000                     | 78    | 73                       | 5.03                                        | 93.5                     | 35    | 549                 | 385                 |
| (1)               | 950                      | 78.1  | 83                       | 6.20                                        | 91                       | 34.2  | 547                 | 386.5               |
| (1)               | 900                      | 73.7  | 80                       | 6.82                                        | 87.5                     | 43    | 551                 | 396                 |
| (1)               | 850                      | 77    | 61                       | 7.35                                        | 81                       | 32.5  | 562                 | 406                 |
| (2)               | 1000                     | 77.8  | 76                       | 3.69                                        | 94.5                     | 35.3  | 558                 | 377                 |
| (2)               | 950                      | 77.5  | 69                       | 3.88                                        | 85.5                     | 34    | 548                 | 396                 |
| (2)               | 900                      | 77.8  | 65                       | 4.15                                        | 88                       | 36.8  | 534                 | 392                 |
| (2)               | 850                      | 78.5  | 75                       | 4.61                                        | 89                       | 35.8  | 562                 | 393                 |
| (3)               | 1000                     | 76.8  | 56.5                     | 19.62                                       | 98                       | 33.8  | 542                 | 367                 |
| (3)               | 950                      | 76.6  | 66                       | 20.21                                       | 96                       | 34.8  | 549                 | 440                 |
| (3)               | 900                      | 72.6  | 85                       | 20.95                                       | 98                       | 33.8  | 555                 | 390                 |
| (3)               | 850                      | 77.8  | 77                       | 21.84                                       | 90                       | 33.2  | 551                 | 391                 |

Cooling Speed value (VR) – Average [°C/min] was calculated with the following relation:
\[ V_r = \frac{t - t_0}{\Delta t}, \quad [\text{°C/min.}] \]  

Where:
- \( t \) = the initial temperature corresponding to each cooling regime, [°C];
- \( t_0 \) = the final temperature which was approximate to 20 °C;
- \( \Delta t \) = the cooling duration, [min.].

In some cases, the difference between the initial temperature and the final one dues that the behavior of the evolution of the cooling speed values was special, unexpected.

In figures 1 to 4 have been presented the evolutions of the mechanical properties depending on the cooling speed from the initial temperature, in case of the cooling in normal conditions (1), corresponding to the steel analyzed.

Figure 1. Resilience determined at (-20)°C depending on the cooling speed \((V_R)\) in the case of the cooling regime (1)-normal conditions

Figure 2. Resilience determined at 20°C depending on the cooling speed \((V_R)\) in the case of the cooling regime (1)-normal conditions

Figure 3. The elongation at break \((A_S)\) depending on the speed of cooling \((V_R)\), corresponding to cooling regime (1)

Figure 4. The flowing limit \((RC)\) level depending on the speed of cooling \((V_R)\) in normal conditions (1)
In figures 5-8 were represented the evolution of the mechanical properties versus the cooling speed from the initial temperature, in case of the cooling in metallic recipient (2).

![Figure 5](image1.png)  
**Figure 5.** Resilience values determined at (-20) °C depending on the cooling speed (VR) in the case of the cooling regime (2) – in metallic box

![Figure 6](image2.png)  
**Figure 6.** Resilience values determined at +20 °C depending on the cooling speed (VR) in the case of the cooling regime (2) - in metallic box

![Figure 7](image3.png)  
**Figure 7.** The elongation values (A5) depending on the speed of cooling (VR), in case of the cooling regime (2), in metallic box

![Figure 8](image4.png)  
**Figure 8.** The flowing limit (RC) level depending on the speed of cooling (VR), in case of metallic box (2)

It is noticed that when the samples are cooling in a metal box from an initial temperature of 1000 °C, a good resilience is achieved at ambient temperature (+ 20 °C).

In figures 9-12 were represented the evolution of the mechanical properties depending on the cooling speed from the initial temperature, in case of the cooling in jet of air (3), corresponding to the steel analyzed.
The temperature of the rolling of steel influences the characteristics of the steel. If it is applied a heating after rolling and it is studied the influence of the speed of cooling on some characteristics of that steel, it can be obtained a changes of the properties, implicit changes of the plasticity evolution.

It is noticed that a higher degree of thinning \( Z \) than in the case of the cooling in cold jet of air, have been obtained.

The flowing limit - the highest value - was obtained in the case of jet air-cooling from 950 ° C. In all cases, high flow limits were recorded at the cooling in jet of air from the temperatures of 950 ° C, 900 ° C
After non-conventional heating process and cooling in different mediums, the steel flowing limits have exceeded the values of the same steel after rolling ($\sigma_c = 360 \text{ daN/mm}^2$).

High resilience values determined at $+20 \degree \text{C}$ were obtained by cooling in an air jet. It can be said that a rapid cooling from high temperatures produces better resilience of the material analyzed, instead, in this case (cooling in the air jet), the elongation ($A_5$) at breakage decreases. The plasticity properties decrease in this case.

The lowest resilience value determined at negative temperatures ($-20 \degree \text{C}$) was recorded for air-jet cooling from $1000 \degree \text{C}$. The resilience represents the tenacity of the steel. A good tenacity represents a good plasticity of the steel.

Tenacity is the ability of a material to absorb energy and to have plastic deformation before it breaks; the amount of energy absorbed during both deformation and fracture is a measure of the tenacity of the material.

The size of the deformation preceding the tear is a measure of ductility, and the force required to break is a measure of mechanical strength.

Figure 13 presents micro-structural aspects after non-conventional treatments. Microstructure in strings is appropriate to the structure of Hot-rolled steel/

![Figure 13](image)

Figure 13. a) Cooling in jet of air; $T_i = 900 \degree \text{C}$, Nital Attack 2%, x100; b) Cooling in normal conditions; $T_i = 900 \degree \text{C}$, Nital Attack 2%, x100; c) Cooling in metallic box; $T_i = 900 \degree \text{C}$, Nital Attack 2%, x100.

A fine structure of the hot-rolled steel is observed in the case of the cooling in metallic recipient (box) and in the case of the cooling in jet of air. The basic structure is compound by Ferrite (F) and lamellae of Pearlite (P). The ratio is 25/75 % (P/F) and corresponds to figure 13c. The ratio 40/60 % (P/F) corresponds to the microstructure of figure 13b. The ratio 35/65 % (P/F) corresponds to the microstructure of figure 13a. The micro-structures in strings are specific to laminated structures. Manganese (Mn) content more than 2.75% determines the increasing of the tenacity and plasticity of the steel, comparing to the simple casted steel.

5. Conclusions

The experimental program shown that the plasticity characteristics differ appreciably according to process parameters as the cooling speed (VR) during non-conventional treatments and it is in accordance with non-conventional treatment applied. It was shown that the cooling conditions can modify the
mechanical characteristics of the steel with a low content in Carbon. For example, the highest resilience 
had been obtained in the case of the cooling in jet of air comparing with the normal conditions of cooling.

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