Mechanical properties improvement in an advanced automotive steel

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Abstract. Due to the increase in environmental and safety regulations that have been applied worldwide, the automotive industry has seen the need to develop steel alloys whose mechanical properties perform, not only reliably, but at a low cost. This is why the study of the third – generation steel has taken a defining position in the industry; due to the high mechanical properties, it offers and the advantages that will be reflected in the production of vehicles. In this sense, this study proposes an alternative to traditional materials, which not only reduces costs but also meets the characteristics required by the market based on two different processing routes: 1) hot – rolling + water quenching (HR + WQ), and 2) hot – rolling + water quenching + sub-zero treatment (HR + WQ + ST).

1. Introduction

The current requirements of the automotive industry focus on increasing the safety of passengers and the resistance of the structures used, in addition to generating a reduction in the weight of vehicles, which allows low fuel consumption and a decrease in emissions of carbon dioxide. That is why, to fulfill these qualities, materials whose properties are outstanding are required [1].

For the specific case of steels, high strength steels began to demonstrate properties compatible with the purpose, standing out over medium carbon steels due to their combination of strength and elongation, among which are dual phase steels (DP) and deformation-induced steels (TRIP), which are characterized by having a ferritic matrix with bainite and austenite in their microstructure, resulting in high strength and good formability. With advances in the area, the second generation of high-strength steel emerged, which includes twinning-induced plasticity (TWIP), which has a microstructure composed, for the most part, of austenite. For the third generation of advanced steels, a combination of locally partitioned nanostructure was developed, from which quenching & partitioning steels (Q&P) and medium manganese steels (MMnS), have been the ones that more closely match the needs of the industry [1-4].
Control of the chemical composition has been crucial for the development of third-generation steels, since utilizing this the resulting microstructure can be controlled, as well as the final mechanical properties, reaching an ideal balance between resistance and elongation [5]. The present work, aware of the importance of the composition, has focused on the design of the alloy, emphasizing severe deformation processes such as hot rolling, as well as the thermal treatment of the resulting plates, allowing to find the ideal balance between resistance and elongation, which is explained based on the resulting microstructure.

2. Experimental Procedure

The manufacture of the steel under study was carried out from the melting of 1010 steel and the addition of ferroalloys such as FeMn, FeSi, FeCr, FeTi and FeB in such a way that the final chemical composition of the steel is presented in Table 1. The induction furnace used for this purpose can operate in a controlled atmosphere or under vacuum with a power source that has a maximum power of 30 KW. The fusion process consisted of placing the raw materials for the fusion inside a recrystallized alumina crucible and a graphite inductor. It started with the evacuation of the induction furnace, reaching an internal pressure of 1X10^{-3} atmospheres and immediately argon was injected into the furnace chamber until reaching an internal pressure of 6.0×10^{-1} atmospheres. Once the steel was in a liquid state, the power of the induction furnace was decreased to a value of 12 KW. This was carried out to float the slag, and if necessary, vacuum degassing could be carried out to remove gases dissolved in the liquid metal. Finally, the liquid steel, inside the induction furnace chamber, was cast into a copper metal mold to obtain the ingot with dimensions of 0.20×0.10×0.5 m.

Table 1. Chemical composition of the steel under study.

| Element | C   | Mn  | Si  | Cr  | Ti  | B   | Fe     |
|---------|-----|-----|-----|-----|-----|-----|--------|
| wt. %   | 0.30| 2.3 | 0.22| 0.43| 0.13| 0.005| Bal.   |

Already in the casting condition, the steel plates were machined to undergo a unidirectional hot rolling process monitoring the temperature through a cromel/alumel thermocouple inserted in the center of the piece with a heating speed of 4 °C/s, the soaking time was 100 minutes, proceeding to carry out the first hot deformation once the temperature of 1373 K (1100 °C) had been reached. It should be mentioned that between each rolling step, the ingot was introduced back into the furnace to reach the temperature of 1373 K (1100 °C) for 10 minutes, the final rolling temperature was 1143 K (870 °C).

The rolling process was carried out on a Fenn 5-MILL, reversible rolling mill until a reduction percentage of 98.2% was achieved. After having reached the optimal thickness of the plate, it was immediately quenched in water at a cooling rate of 85 °C / s. Thus, two processing routes after hot – rolling were performed: 1) water quenching (HR + WQ), and 2) water quenching plus a sub – zero treatment (HR + WQ+ ST).
The resulting microstructure was analyzed in a Jeol Field Emission 7600F scanning electron microscope, coupled with a microanalysis detector. The tensile (ASTM E-8) test was performed on an Instron 1125 (10 ton) machine with a strain rate of $5 \times 10^{-3}\text{s}^{-1}$.

3. Results and Discussion

Table 2 shows the mechanical properties obtained for the HR + WQ and HR + WQ + ST conditions. Recent research has been carried out around to different 3rd generation AHSS steels. For the chemical composition of $\text{Fe} - 0.485\text{C} - 1.195\text{Mn} - 1.185\text{Si} - 0.98\text{Ni} - 0.21\text{Nb}$, 2160 MPa of UTS and 9% elongation were obtained (under a quenching, partitioning and tempering treatment) [5]. For Q&P steel ($\text{Fe} - 1.36\text{C} - 3.3\text{Si} - 2.6\text{Mn}$) 980 MPa and almost 25% of total elongation were reported [6]. Ding, et. al [7] report an elongation of 30% and UTS of 1300MPa in a MMnS steel. Regarding the results obtained for hot-rolled high-strength steels, interesting results were reported for a medium manganese TRIP steel ($\text{UTS} = 1130 \text{MPa and elongation} = 22\%$) [8], and Zhang et.al [9] developed a DP steel with a chemical composition of Fe--0.20C--5Mn--4Al in which they report 1408 MPa of UTS and 12 % elongation. Another dual-phase steel (Fe--0.15C--5Mn--3Al) shows results of 1199 MPa of UTS and 14.8 % of elongation [10]. In this work, the HR + WQ condition shows 1866 MPa of UTS and 18 % elongation, and the HR + WQ + ST condition showed 1744 MPa of UTS and 30%.

**Table 2. Mechanical properties for HR + WQ and HR + WQ + ST conditions.**

| Condition   | YS (MPa) | UTS (MPa) | Elongation to failure (%) | n  |
|-------------|----------|-----------|---------------------------|----|
| HR + WQ     | 1209.9   | 1866      | 18                        | 0.20 |
| HR + WQ + ST| 670.0    | 1744      | 30                        | 0.73 |

The improvement is made due to the controlled procedure, which determines a large amount of martensite in both samples. Figure 1a shows the microstructure of the HR + WQ condition, where a banded structure is observed caused by severe deformation of hot rolling. In addition to the above, the HR + WQ + ST condition (Figure 1b), presents a grain refinement due to the subzero treatment, which allows obtaining different mechanical properties cooperating to the HR + WQ condition.
On the other hand, the study of the mechanical behavior of hardening is carried out through the hardening coefficient calculated through the Hollomon equation, based on the true stress-strain curve. The values of n for each part are shown in Figure 3.

The difference between yield stress and ultimate tensile stress values showed in Figure 2, reveals a large amount of deformation, mainly for HR + WQ+ST steel. This implies that the strain hardening is very large, which is related to the reported coefficient value n. The influence of martensite greatly affects the value of n, in the case of this steels. Thus, the hardening mechanisms are described based on three stages: plastic deformation of the soft phase, plastic deformation of both phases and rupture of the harder phase. The second stage determines the hardening results for the presented steels, due to the phenomenon of multiplication and accumulation of dislocations in addition to the dynamic recovery present in the mentioned plastic deformation interval [2]. When worked hot, the morphology of the resulting
microstructure shows a characteristic banding; concerning this, it has been mentioned [11] that plasticity due to martensite is favored when its structure is banded and not in the form of islands. Thus, the microstructure is relatively homogeneous, with areas of low and high manganese content, making it normal for this to be visible in some parts of the sample. The above does not represent a disadvantage in mechanical properties.

As for the hardening coefficient, in the HR + WQ condition obtain a lower value (n = 0.20) was obtained for the test piece whit less elongation, the highest value corresponds to the HR + WQ+ST condition (n = 0.73), which corresponds to the specimen with the highest elongation value.

This suggests that material with this behavior is suitable for the manufacture of components (type B pillars, suspension, chassis, bumpers and powertrain) that involve high energy absorption without the formation of fragments or projectiles. Therefore, the mechanical properties of HR + WQ and HR + WQ+ST steels position them as attractive materials in the manufacture of the aforementioned components, due to the current formability requirements since automobile manufacturers together with their suppliers are betting on the development of ultra-light and resistant materials, to reduce fuel consumption and greenhouse gases.

4. Conclusions
The developed steel (Fe–0.30C–2.3Mn–0.22Si–0.43Cr–0.13Ti–0.005B) presents a good balance between resistance and elongation. Due to the combination of the thermomechanical process and heat treatments, a banded martensitic microstructure was obtained with the presence of dispersed carbides. This allows to obtain an improvement in the mechanical properties. This exhibits these steels as a suitable option for the manufacture of automotive components, due to their good formability. Thus, based on the results currently reported, the HR + WQ + ST condition is a suitable candidate material to meet the current requirements of the automotive industry focused on increasing safety, reducing weight and polluting gas emissions.

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