The Effect of Titanium on the Thermomechanical Processing of a Dual Phase Steel

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Abstract
The present work studies the microalloying effect of titanium on the distribution and features of martensite of a dual-phase steel after a thermomechanical processing, and an intercritical heat treatment. The steel composition is 0.05C-1.2Mn-0.5Si-0.2Cr and titanium contents up to 0.06%. The steel was made in a laboratory and cast into small ingots, then heat treated at 1200°C to dissolve any carbides formed during solidification. After solubilisation, the steel was cooled down to 1050°C and hot rolled in a multi-pass reversible mill to get a reduction of 80%. Just at the end of hot rolling, the measured temperature was about 950°C for all the steel plates. Intercritical heat treatments were undertaken at 710, 715 y 720°C for 30 min and then water quenched. A grain refinement was observed due to the effect of titanium during the thermomechancial processing; grain size went from 25 microns for the steel without titanium to 12 microns for the 0.06%Ti steel. In addition, a diminution in the pearlite fraction from 0.12 to 0.06 was observed when titanium content increased. On the other hand, after the intercritical heat treatment the martensite fraction decreases as titanium increases for a constant temperature. By correlating the microstructure and the mechanical properties, it is assumed that titanium reduces the grain size during the thermomechanical processing, but also reduces the martensite fraction for a constant temperature during the intercritical heat treatment. The grain refinement and the presence of martensite contribute to a good combination of strength and ductility in this kind of steels, 680 MPa and 35%.

Keywords: *titanium, dual-phase steel, intercritical heat treatment.*

1. Introduction

Automotive companies are manufacturing cars, by using lighter materials such as aluminium, magnesium, polymers, etc., in order to reduce the weight car body and, consequently, to save fuel consumption. Nevertheless, the main material -still used- for this purpose is the steel. Due to their tailored properties by thermomechanical processing, dual-phase steels are required for making several parts of the car structure. That is the reason for fabricating different grades that provide high stretch flange ability and improve bendability. Commonly, low and intermediate tensile strength steels (590 to 980 MPa TS) are frequently applied in body structure that requires high energy absorption (i.e. the crumple zones – front and rear longitudinal rails and supporting structure). On the other hand, the intermediate to highest strength grades are typically used in pieces that need extremely high yield strength and adequate formability, such as passenger safety cage components limited by axial buckling or transverse bending. These components (rockers, pillars, pillar reinforcements, roof rails, and cross members) relay on high yield strength to prevent intrusion into the passenger compartment during a collision. Dual-phase steels, allow car designers to apply high yield strength steels for safety cage components that are too complex to build by using the higher strength martensite steels [1]. On this context, commercial dual-phase steels have a volume fraction of martensite ranging from 10 to 30%, its mechanical properties depend on the ferrite-martensite microstructure, martensite fraction and distribution, carbon content, and alloying elements [2]. Additional strengthening could be obtained by an increment of the martensite volume fraction; however, this is done at the expense of ductility and elongation. Therefore, an optional way to improve the strength of dual-phase steels is by adding microalloying elements such as titanium, which would form small precipitates and hinder dislocation movement in the ferrite phase to provide higher yield strength and, hence, higher yield-to-tensile- strength ratios

[1,3]. Furthermore, grain refinement of ferrite produces a positive effect on strength and ductility, the smallest grain size obtained by conventional thermomechanical processing is of ~5 microns. Nowadays, new rolling processing routes have been proposed to produce ultra-fine ferrite grain size of 1 micron, these processing routes consist of two steps: (1) a deformation treatment to produce ultrafine grain ferrite and finely dispersed cementite or pearlite and (2) a short intercritical annealing in the ferrite/austenite two-phase field followed by quenching to transform all austenite to martensite. The grain refinement in step (1) is accomplished by equal channel angular pressing process, cold rolling and cold swaging [4]. In this work, a thermomechanical processing and an intercritical heat treatment were applied.

2. Experimental Procedures

A base composition and two titanium (0.03 and 0.06%) treated Dual Phase (DP) steels were fabricated in an open induction furnace. Alloy elements were directly added to the melt and poured into metallic moulds. The cast ingots (7.5cm x 7.5cm x 7.5cm) were solubilised at 1200°C for one hour and air cooled to eliminate carbides formed during solidification. The solubilised ingots were re-heated at 1050°C, hold for two hours and thermomechanically processed in a 50 Tons reversible rolling mill. The finish temperature of the plates was 950°C with a percent reduction of 80% and then air cooled to room temperature. Steels plates of 12 cm x 20 cm with a thickness of 2 ± 0.2 cm. were obtained. In order to obtain the dual phase microstructure, which consists of ferrite + martensite, the specimens were intercritically heat treated on the ferrite + austenite region for 30 min at 710, 715 and 720 °C and quenched on water to room temperature to transform the formed austenite into martensite. Tensile specimens with a gage length of 25.4 mm were machined in accordance to the ASTM A370 standard from all the DP steels. The hardness values were measured in the Vickers scale. In order to follow the microstructural evolution, both thermomechanically and intercritically conditions of the specimens were analyzed by optical (Leinz) and SEM (Jeol JSM 6400) microscopy. Some thin foils were prepared for TEM analysis in Philips Tecnai.

3. Results and discussions

The chemical composition of the DP steels is presented on Table 1. No significant chemical variations were observed, which allowed evaluating the Dual Phase steels behaviour in terms of the titanium content. The chemical composition it is in good agreement with the ranges reported by Speich [5], who suggest a carbon content of less than 0.1%, in order to be spot welded. Manganese amounts of 1 to 1.5% to ensure sufficient hardenability so that martensite is formed upon rapid cooling. The chromium amounts are usually under 0.6%. Silicon is added to provide solid solution hardening. Small amounts of microalloying additions (≤0.1%); such as vanadium, niobium, and titanium will provide precipitation hardening and/or grain size control.

Table 1 Chemical Composition of the Dual Phase steels

Steel	%C	%Mn	%P	%S	%Si	%Cr	%Ti
DP1	0.052	1.267	0.010	0.015	0.471	0.214	**0.00**
DP2	0.051	1.280	0.010	0.016	0.452	0.216	**0.03**
DP3	0.051	1.269	0.011	0.016	0.513	0.197	**0.06**

3.1 Microstructural analysis

Since the same thermomechanical conditions were applied to the DP steels, the microstructure can be analysed before and after the intercritical heat treatment. Figure 1, shows the obtained microstructure of the DP steels after the thermomechanical treatment. As expected, the structure consists of ferrite and pearlite. From these pictures, it can be observed that the ferrite grain was refined as titanium increased. The base DP1 steel has a ferritic grain size of ~25 µm, (Fig-

1(A));the steel with 0.03%Ti DP2 has ~16 µm (Fig-1(B) and the steel with 0.06%Ti DP3 has a grain size of ~12 µm. The ferrite grain was mostly polygonal-shaped but some large and elongated grains could also be observed. The titanium effect was also notorious on the pearlite content. The volume fraction of the pearlite decreased as the titanium amount increased. Thus, the pearlite content on the 0.06%Ti DP3 steel was of 6%, while the pearlite amount of the titanium free DP1 steel was 12%. Something important to highlight, is the presence of small pearlite islands formed in the middle of the ferrite grains; see Figures 2. These pearlite islands were reduced in size as titanium was added; the base DP1 steel shown some pearlite islands of 6 µm, and the 0.06%Ti DP3 steel shown islands of 1-3 µm.

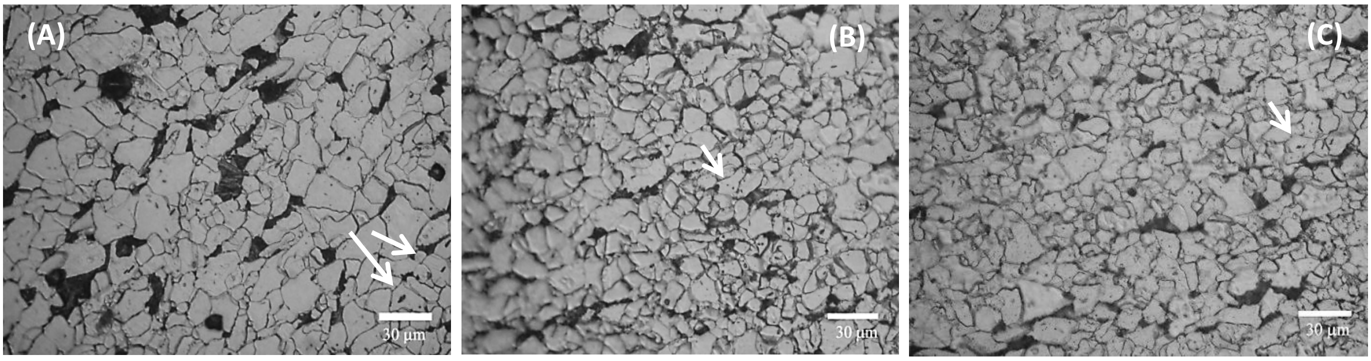

Fig. 1 Optical microscopy of the DP steels after the thermomechanical treatment: (a) base DP1 steel, (b) 0.03%Ti DP2 steel, and (c) 0.05% Ti DP3 steel.

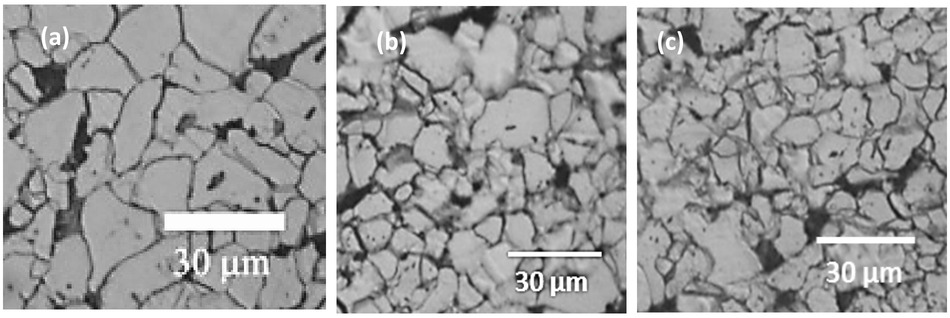

Fig. 2 Pearlite islands formed in the center of the ferrite grains, a) base DP1 steel, b) 0.03%Ti DP2 steel, and c) 0,05%Ti DP3 steel.

During the intercritical heat treatment, austenite formation occurs in two steps according to Cota et. al [6]. The first step is the pearlite dissolution followed by the ferrite to austenite transformation. Both transformations take place by nucleation and growth. In the current work, two important factors to be taken into account during the intercritical heat treatment are the *titanium amount* and the *temperature treatment*. Figure 3 shows the effect of these variables on the current DP steels. It is clearly observed from these micrographs that as the titanium amount increases the martensite volume fraction decreased; Figures 3(a) and (b) show the mictrostructure for the DP1 and DP3 steels respectively after intercritically treated at 710°C; the martensite volume fraction was of 0.28 for the DP1 (titanium free) steel and 0.07 for the DP3 (0.06%Ti) steel. Figures 3(c) and (d) show the same effect at 720°C, the martensite volume fraction was decreased from 0.33 to 0.24 for the DP1 and DP3 steels respectively. These results are in agreement with those of Charai el. at [7], who found that for dual phase steel with 0.079%C and titanium amounts from 0.00% to 0.072% the percentage of martensite was reduced as the Ti amount was increased. This effect could be explained by a less amount of carbon in solid solution upon martensitic transformation for the titanium microalloyed steel. On the other hand, as the temperature treatment increases the martensite fraction also increases. This is because more austenite is formed at higher temperatures, but also the solute partitioning influences the austenite formation. Chaturvedi and

Jena [7] have highlighted that the annealing of steel between its critical temperatures Ae_1 and Ae_3 results on the formation of ferrite and austenite, and that the solutes presents in the steel will tend to partition between these phases. Then, the amount of the austenite in the steel will be determined by the extension of partitioning which is influenced by the intercritical temperature, the higher the temperature the larger the austenite fraction. The redistribution of substitutional alloying elements is much slower than the interstitial carbon since the diffusivity of carbon is nearly 10^5 - 10^6 times larger than that for the substitutional elements. At low intercritical temperatures, the steel may approach to a partial equilibrium where the substitutional alloying elements remain unchanged while carbon reaches its equilibrium concentration. In this case, the amount of the austenite at low intercritical annealing temperatures would be equal to values corresponding to partial equilibrium; on the other hand, at higher intercritical annealing temperatures (770°C) the amount of the austenite would depart from these values since the partitioning of the substitutional solutes would tend to be greater. On these basis, Cota et. al [6] explain that the growth rate of austenite is believed to be controlled either by diffusion of carbon or by boundary diffusion of substitutional alloying elements. If the growth rate of austenite is controlled by the bulk diffusion of atoms in austenite ahead of the interface, the diffusion of carbon may play a more important role than that of the substitutional alloying elements. Diffusivity of the substitutional alloying elements in austenite is slower, as mentioned above, than that of carbon, and the substitutional alloying elements may not diffuse for long distances during the reaction.

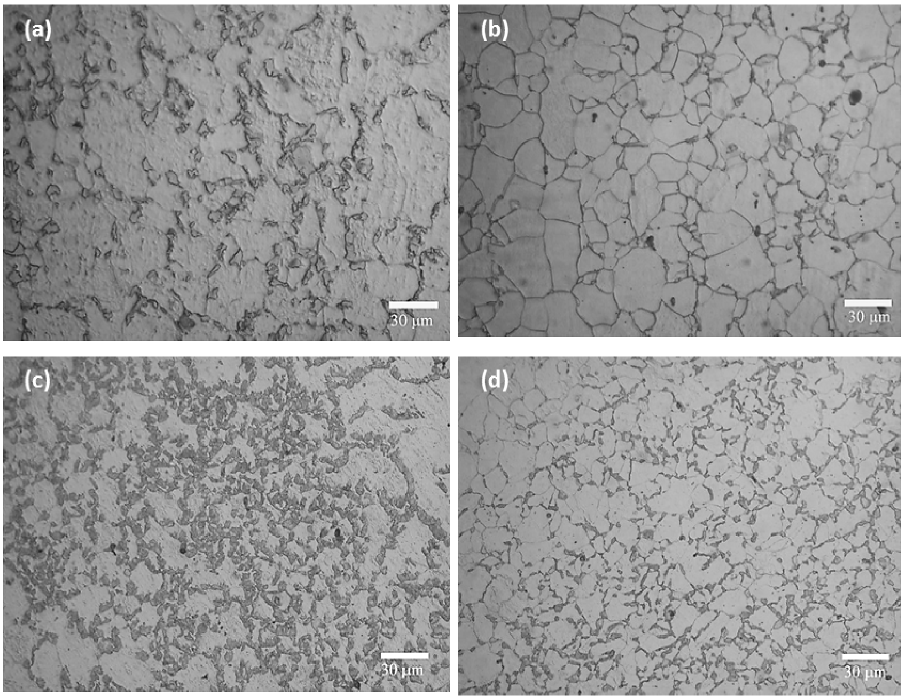

Fig. 3 Micrographs of the DP steels intercritically treated at: **710°C** - a) DP1(0.00%Ti), b) DP3 (0.05%Ti) - and at **720°C** - c) DP1 (0.00%Ti), and d) DP3 (0.05%Ti).

Figure 4 shows TEM micrographs detailing the ferrite/martensite interfase of the DP3 steel heat treated at 720°C. Note the higher density of dislocations in the ferrite phase surrounding the martensite. These are assumed to form during the austenite to martensite transformation.

3.2 Mechanical properties

Figure 5 shows the hardness results of the DP steels; an increase in hardness can be observed as the temperature of intercritical treatment increases for any titanium content. This increase in hardness is explained by the higher martensite fraction observed as the temperature increases. In addition, the higher hardness values were observed for the DP3 steel which contained the higher titanium amount (0.06%). This is due to the finer grain size obtained after the thermomechanical processing and the well distributed martensite obtained after the intercritical heat treatment.

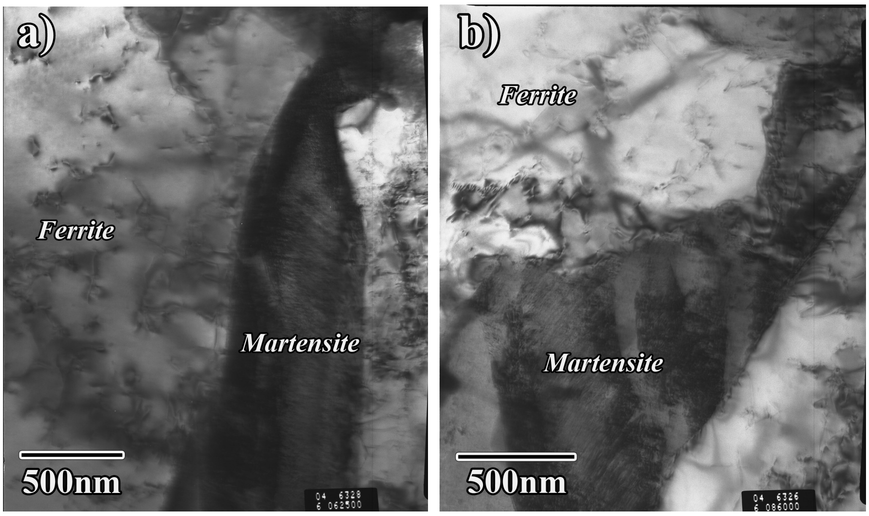

Fig. 4 TEM micrographs of the 720°C treated steel containing 0.06%Ti

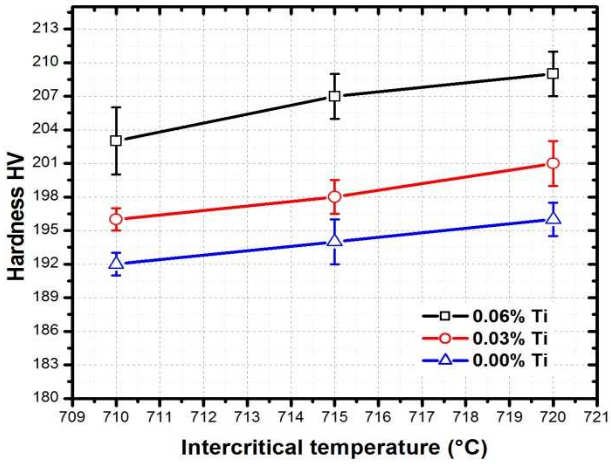

Fig. 5 Hardness (HV) results of the DP steels

Figures 6 shows the stress-strain curves for the experimental steels at two intrecritical temperatures, 710 and 720°C. As expected, tensile strength increased as the titanium amount increases, as a result of the grain refinement. For the steels heat treated at 710°C, tensile strength increased from 495 to 610 MPa for the DP1 and DP3 steels respectively; while for the steels heat treated at 720°C, tensile strength increased from 605 to 690 MPa for the DP1 and DP3 steels respectively. Again, this behavior is attributed to the grain refinement as the titanium amount increases and to the higher amounts of martensite as the temperature of the intercritical treatment increased. On the other hand, strain was reduced as the titanium increased and as the temperature of the intercritical treatment increased. The reduction of strain with the increase in temperature is due to the higher amount of brittle martensite, but the reduction of strain with the increase in titanium is more complex. Calcanogtto et. al [8] concluded that when the grain is refined, an increase of both yield strength and tensile strength and that the uniform elongation and total elongation are hardly affected. In addition, the initial strain hardening rate and the post-uniform elongation increase as the grain size decreases. They explain that the increase in the initial strain hardening rate due to grain refinement -as in the 0.03 and 0.06% titanium steels (Fig-6)- is attributed to an early dislocation interactions; the high number of dislocation sources and the back stresses exerted by martensite. On the other hand, Saikaly et. al [9] explain that the titanium carbides produce a high density per unit volume, which is in agreement with our results (see TEM micrographs of Fig. 7), mostly present in ferrite grains, and would act as obstacles to dislocation movement, raising the yield strength, which is clearly observed on the titanium DP2 and DP3 steels. Generally, these titanium carbides precipitated during the austenite to ferrite transformation due to carbon enrichment at the boundary. In addition to this, Kadkhodapour et. al [10] found that increasing the volume fraction of martensite, increase the yield and ultimate strength of the DP steels. They explain that the strains produced by the austenite to martensite transformation result in residual stresses in the surrounding ferrite. These internal stresses are assumed to facilitate plastic flow and, hence, reduce the elastic limit. Furthermore, the change in volume induces plastic deformation of adjacent ferrite grains and, therefore, creates a high density of unpinned dislocations in the vicinity of martensite, these dislocations are assumed to be (at least partly) mobile during the early stages of deformation and contribute to work hardening, this effect it is more clearly observed on the base DP1 steel. The heterogeneous distribution of dislocations is supposed to control continuous yielding in dual phase steels. It is assumed that the deformation starts in ferrite areas with low dislocation densities and spreads with increasing plastic strain into regions with higher dislocation densities [9].

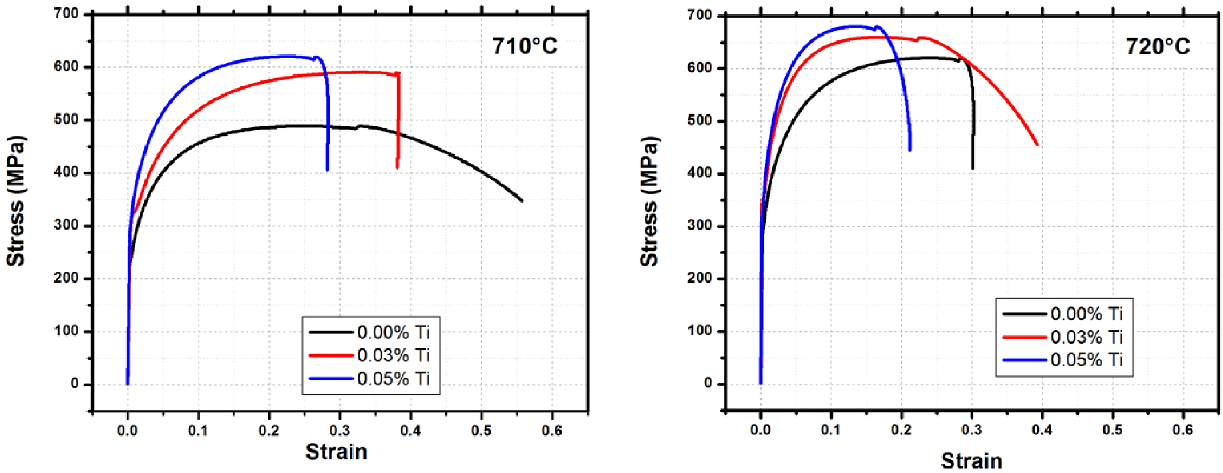

Fig. 6 Stress - strain curves for the DP steels

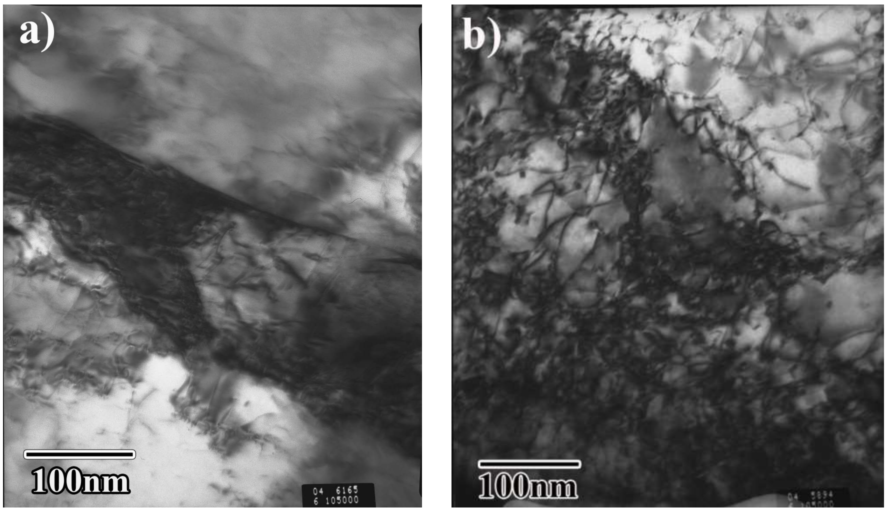

Fig.7 TEM micrographs showing the difference in dislocation density for the DP1 steel (a) and for the DP3 steel (b).

4. Conclusions

- After thermomechanical processing, titanium refined the ferritic grain size and diminished the pearlite fraction. The refinement is due to the pinning effect and the pearlite diminution is due to carbon consumption for the TiC(N) formation during the thermomechanical processing.
- After the intercritical heat treatment, the martensite fraction decreased as the titanium amount increased for a specific temperature, since Ti shifts the Ac1 temperature.
- The tensile strength was increased as the titanium increased due to a grain refinement effect, and ductility decreased due to the increase in the fraction of martensite.

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