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Research Article

The Influence of Thermomechanical Processing Conditions on the Evolution of Microstructure and Crystallographic Textures and the Mechanical Properties of Deformed Mild Steels in the Intercritical Region

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Rolling temperature and rolling reduction intensively influence the formation of Luder lines and fluting marks in mild steels. They govern these effects through control of strain aging. In order to enhance the strain aging resistance and the consequent reduction of yield point elongation and fluting intensity, warm rolling without using the skin pass process is applied. The development of microstructure and crystallographic textures during deformation process and the determination of fluting intensity and mechanical properties consisting of tensile and formability properties in terms of different thermomechanical conditions (RT and RR %) were investigated in this study. These properties are determined through the use of bending, tensile tests, optical microscope, and EBSD analysis.

1. Introduction

The mild steel known for being very strong, has been used as the structural components in the part of building construction like gutters for water drainage, pipes, and channels. High formability is required to form these components, but the solute carbon and nitrogen, as the interstitial atoms in low-carbon steel, play a significant role in formability deterioration. The segregation of interstitial atoms around the dislocation and formation of the Cottrell atmosphere lead to blockage of dislocations motion. This phenomenon appears as wrinkled lines (fluting lines) in bended steels [1, 2].

According to Cottrell and Bilby, strain aging and the subsequent phenomenon, that is, yield point elongation, could be controlled by the concentration of the interstitial solute atoms and of the mobile dislocation density. Based on previous investigations, the kinetics of the strain aging is modified and slowed in low-carbon steel by adding some alloying elements (Nb, V, and Ti), with the formation of the Ti, V, and Nb (C and N) precipitates. In addition, the introduction of a higher amount of mobile dislocations through temper rolling can remove the discontinuous yielding. However, the last action is often not considered as an invariable solution for eliminating the yield point elongation in mild steels because after aging, the interstitial atoms pine the dislocations and form the Cottrell atmosphere [3, 4].

Numerous studies were carried out on the hot rolling of the microalloyed steels to produce steel with high mechanical performances, that is, a good strength-toughness combination obtained by precipitation strengthening of (Nb, V) (C, N) precipitates and by removing C, N from the matrix [5–8]. In recent years, however, the thermomechanical process became known as being effective for obtaining high steel strength and toughness, and the addition of the alloying elements to enhance mechanical properties was not strictly needed. In this processing method, refined ferrite grains can be formed

Table 1: Elemental composition of mild Steel (wt.%).

C	Mn	Si	P	S	Cu	Al	Nb	V	Ti	B	N
0.034	0.103	0.008	0.0064	0.0064	0.197	0.045	0.000	0.002	0.0009	0.0002	0.0067

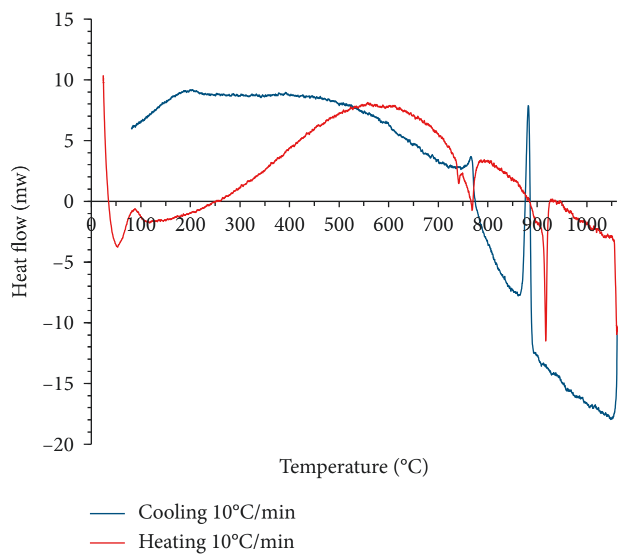

Figure 1: DSC curves of mild steel cooled and heated at 10°C/min.

Figure 2: Fluting lines and segments observed on bended sample.

through dynamic recrystallization by controlling some key parameters (T, Rolling reduction) during the forming process [9, 10].

In our work, the mild steel was rolled in the intercritical region ($\alpha + \gamma$) to avoid hot rolling and to eliminate the cold rolling and annealing processes in order to minimize the fluting phenomenon. Furthermore, the microstructures of the steels rolled at different thermal levels were characterized through optical microscope analysis and EBSD analysis, while mechanical characterization was performed by means of tensile test in order to point out the optimum thermo-mechanical process condition (T, rolling reduction %) which results in appearance of few (or absence) of the fluting lines and the best formability, which are the aim of this study.

2. Experimental Procedure

The chemical composition of tested steel is listed in Table 1. The strip samples with dimensions $250 \times 30 \times 2.5$ mm were warm rolled in the lab using the roll machine within the region temperature of Ar_1 and Ar_3.

Differential scanning calorimetry was conducted to determine the intercritical region range of the steel. This test was performed by reheating the samples to 1060°C at a heating rate of 10°C/min and then cooling them to room temperature at the same rate. The achieved curve from the DSC test is shown in Figure 1. The intercritical region temperature is between two peaks occurring at $T = 782$°C–883°C during the cooling step and between $T = 768$°C and 917°C in the heating step. In order to roll the samples in the intercritical region, the strips were reheated to 1000°C for 10 minutes to fully austenitize the microstructure, and then they were kept in a furnace for 15 minutes at the selected rolling temperatures. The samples were rolled at two different rolling reductions, 30% and 60%, with two and four rolling passes, respectively. In each pass, the specimens were reheated for 2 minutes at the set rolling temperature before rolling. After finishing the rolling process, the samples were air cooled to room temperature. Tensile specimens with a gauge length of 50 mm and a width of 25 mm were prepared from rolled strips. The tensile test was performed at room temperature at a cross head displacement rate of 2 mm/min. The Yield Point Elongation (YPE) was determined from the tensile tests. YPE was measured according to the International standards of UNI EN ISO 6892-1. Furthermore, the fluting intensity of samples was determined by way of the bending test.

The rolled strips were bent around the cylinder of diameter 50 mm. The fluting intensity is defined as the average length of the fluting segments that form on the bent sheet, as shown in Figure 2. The microstructures of the rolled strips were analyzed using an optical microscope after the sample had been etched using 2% Nital solution for 10 seconds.

The crystallographic textures were analyzed through electron back scattered diffraction (EBSD). The deformed samples, after being polished with a colloidal Silica suspension, were investigated using EBSD operating at an acceleration voltage of 20 Kev and a magnification of 500x.

3. Experimental Results

3.1. Microstructure and Crystallographic Texture. The effects of the initial rolling temperature and the rolling reduction on the microstructure are shown in Figure 3, and the grain size of the samples is reported in Table 2. At the lowest temperature (790°C), the elongated grains consisted of shear bands which were the results of induced dislocations. At higher deformation temperature, these bands were rearranged within some grains and they subdivided the grains into fine grains; therefore inhomogeneous microstructure featuring a mixture of subgrains as the fine grains and

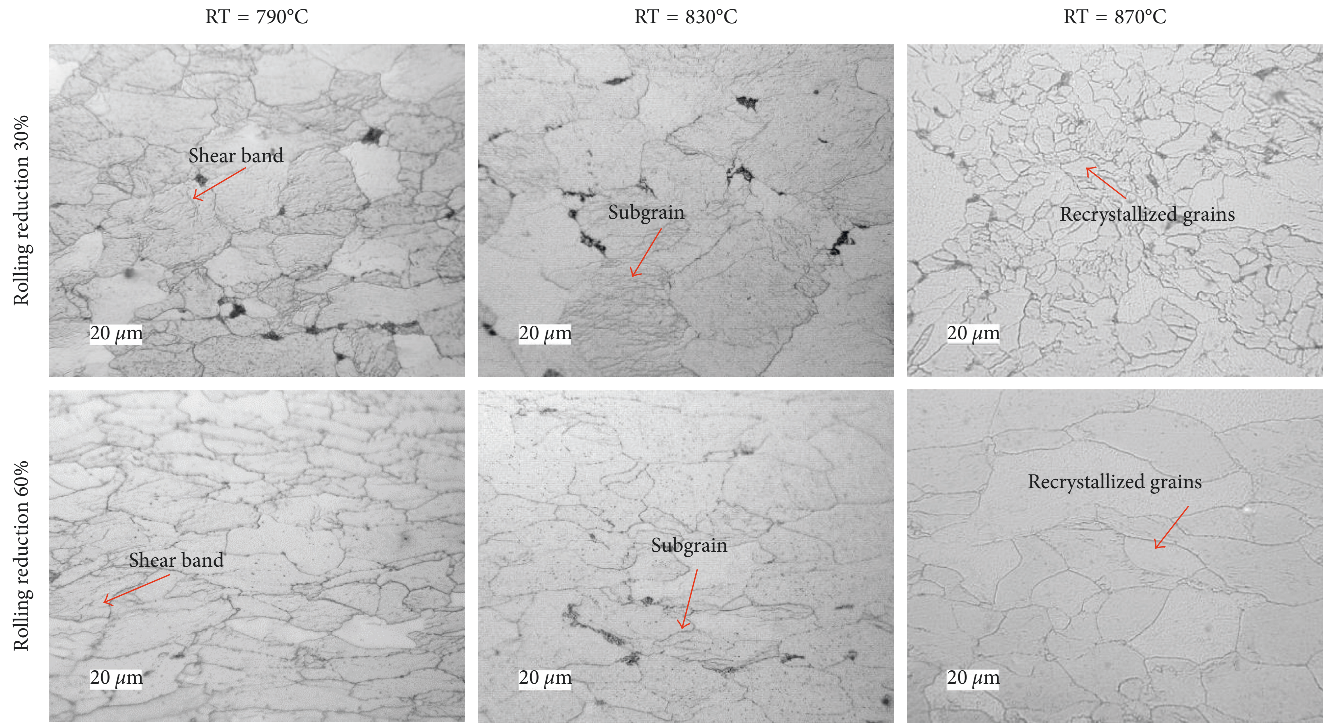

Figure 3: The microstructure of rolled mild steel affected by rolling temperatures of 790, 830, 870°C, and rolling reduction of 30% and 60%.

Table 2: Mean equivalent diameter (D_0) of ferrite grains as a function of the rolling temperature and rolling reduction %.

Steel	% rolling reduction	Ferrite grain size (μm) (790°C)	Ferrite grain size (μm) (830°C)	Ferrite grain size (μm) (870°C)
Mild steel	30	27.15	38.35	7.9
	60	15.9	24.6	25.35

deformed grains as the large grains appeared. At a rolling temperature of 870°C, the refined structure was obtained from the growth of subgrains and revealed the recrystallized α grains.

The ferrite grain size decreased as the rolling reduction increased to 60%, and the grains elongated along the rolling direction at lower rolling temperatures. The grain growth was obviously observed as the rolling temperature increased. Although deformation increased, the high reheating interpass temperature resulted in the easy mobility of the high angle grain boundaries of the recrystallized grains, and the grain growth was rapid according to the Arrhenius relationship.

The crystallographic texture is featured in Figure 4. It demonstrates the influence of the rolling reductions and the rolling temperatures on the texture of the samples. The ODF (orientation distribution function) maps show the weak component {100} <001> with an intensity of 5 as the number of random occurrence times and the strong component of {111} <011> with an intensity of 7 as the number of random occurrence times in $\Phi_2 = 45°$. The texture component of {111} <011> remained with a lower intensity of 6 when the rolling temperature rose to 830°C. In contrast to steels deformed at lower temperatures, different textures including weak {001} <110>, weak {111} <011>, {110} <001>, and weak {110} <110> with an intensity of 5 as the number of times random occurrence are distinguished when RT = 870°C. Increasing the rolling reduction from 30% to 60% revealed a similar component with higher intensity. The texture component of {111} <011> with intensity of 8 and the component of {100} <001> with intensity of 6 are observed when RT = 790°C. The same {111} <011> with lower intensity of 6 revealed when rolling temperature rose to $T = 830°$C. The use of rolling reduction = 60% and rolling $T = 870°$C form {111} <011>, {110} <001>, and {001} <110>, which are intensified in comparison to steel deformed with a rolling reduction of 30% and with an intensity of 8, 7, and 6 respectively.

The histograms of grain boundary misorientation degrees versus the percentage of their numbers in different rolling temperatures and rolling reductions are depicted in Figure 5. The percentage of the low angle grain boundaries $\Theta < 8°$ decreases when the rolling reduction increases in the steel strips rolled at RT = 790°C and RT = 830°C. The high angle grain boundaries increase as the rolling reduction increased from 30% to 60% in the presented rolling temperatures. The most number of HAGBs are observed in the steels deformed at RR = 30% as the rolling temperature rose to 870°C. Moreover, two distinctive peaks of HAGB numbers can be seen in the ranges of 28–35° and 57–62° when the steels were deformed at RR = 60%.

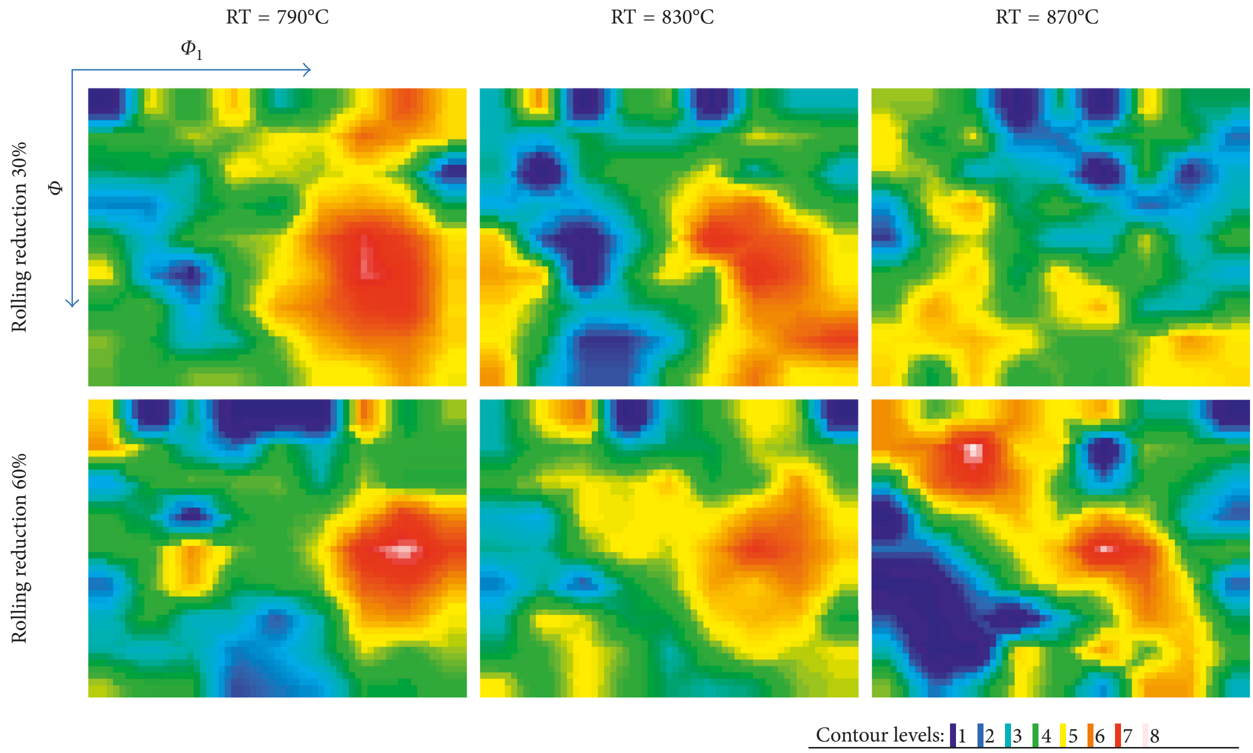

FIGURE 4: Orientation distribution function of warm rolled steels at different thermomechanical conditions at $\Phi_2 = 45^\circ$.

3.2. Tensile Properties. The correlation between the yield point elongation % and the fluting intensity is presented in Table 3. It can be observed that the yield point phenomenon is obviously linked to the thermomechanical process. Continuous yielding took place in the steels subjected to a rolling reduction of 60%, while the yield point phenomenon (discontinuous yielding) occurred in the rolled steels with a rolling reduction of 30%. In the case of steels rolled in the lower rolling reduction value, the yield point elongation also depended significantly on the rolling temperature. Increasing the rolling temperature from 780°C to 870°C decreased the yield point elongation abruptly. In addition, the fluting intensity was influenced by the thermomechanical conditions. Steels rolled at $T = 790^\circ$C with a rolling reduction of 30% gave the highest fluting intensity value, which decreased as the rolling temperature increased. The surface of the steels rolled with the rolling reduction of 60% was smooth and did not reveal intense fluting marks.

The yield strength of the samples was influenced by the thermomechanical parameters employed in this work. Figure 6(a) shows the yield strength in terms of the rolling temperature for steel sheets rolled with two different rolling reduction percentages. As the initial rolling temperature was increased from 790°C to 830°C, the yield strength decreased from 397 to 362 MPa, and it decreased from 362 MPa to 330 MPa as the rolling temperature rose from 830°C to 870°C.

The amount of imposed strain affects the yield strength of samples as well. The sheets subjected to the rolling reduction of 60% had a higher yield strength compared with the steels deformed by the rolling reduction of 30%. As depicted in Figure 6(b), the tensile strength has the same trend as a function of the rolling temperature. It decreases monolithically as the rolling temperature increases. The ultimate tensile strength is also affected by the amount of strain. It rises when the dislocation density increases by way of higher amount of rolling reduction.

The trend of the total elongation variation in different levels of the imposed strain is represented in Figure 6(c). Steels rolled at $T = 870^\circ$C with a rolling reduction of 30% shows the highest formability with a large total elongation value of 22.9%.

4. Discussion

4.1. Microstructure and Crystallographic Texture. Concerning the effect of the rolling temperature and the rolling reduction, the optical microstructure results show that the shear bands appeared sharply when the steel strip was deformed at the lowest rolling temperature. An increase in the rolling temperature led to a recovery phenomenon that was accompanied by annihilation of the shear bands. The formation of subgrains which subdivided some grains deformed at a rolling temperature of 830°C occurred after the recovery phenomenon [12–14]. After rolling the strip at 870°C, the recrystallized grains appeared due to the growth of subgrains inside the original grains or due to the growth of the subgrains located at the grain boundaries [15]. The softening mechanisms involving dynamic recovery and recrystallization (nucleation and grain growth of new grains) are not delayed in this type of steel because micro alloying elements (Nb, V, and Ti) are not present, so their precipitates do not interfere with the mobility of the grain

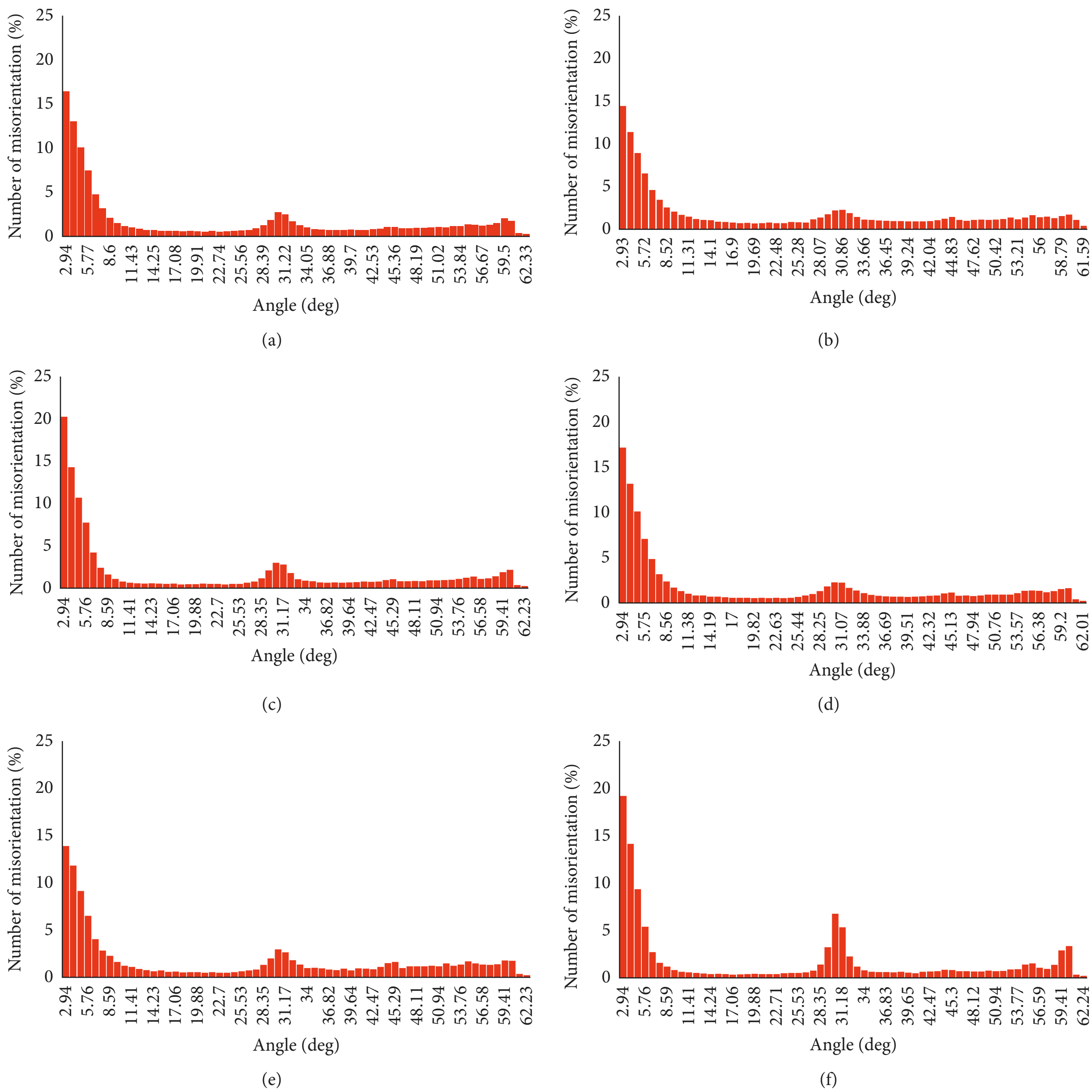

Figure 5: Misorientation distribution in warm rolled steels. (a) RT = 790°C, RR = 30%, (b) RT = 790°C, RR = 60%, (c) RT = 830°C, RR = 30%, (d) RT = 830°C, RR = 60%, (e) RT = 870°C, RR = 30%, and (f) RT = 870°C, RR = 60%.

Table 3: Effect of the rolling temperature and the rolling reduction on yield point elongation and fluting intensity in mild steel.

Rolling temperature of mild steel (°C)	YPE% (30% rolling reduction)	Fluting intensity (mm) (30% rolling reduction)	YPE% (60% rolling reduction)	Fluting intensity (mm) (60% rolling reduction)
790	2 ± 0.34	4.1 ± 1.8	~0	~0
830	0.9 ± 0.27	2.3 ± 0.3	~0	~0
870	0.42 ± 0.1	1.7 ± 0.1	~0	~0

boundaries [16]. The growth of recrystallized grains in the microstructure of strips formed at a rolling temperature of 870°C and with a 60% rolling reduction can be attributed to the mobility of the high angle grain boundaries of the recrystallized grains. Grain growth is rapid because of the grain boundaries migration, and according to the Arrhenius relation, it is the thermally activated process. [17].

In ODF maps representing the steels rolled at $T = 830$°C, preservation of the structure component of {111} <011> depicts the recovery phenomenon, which occurred when the

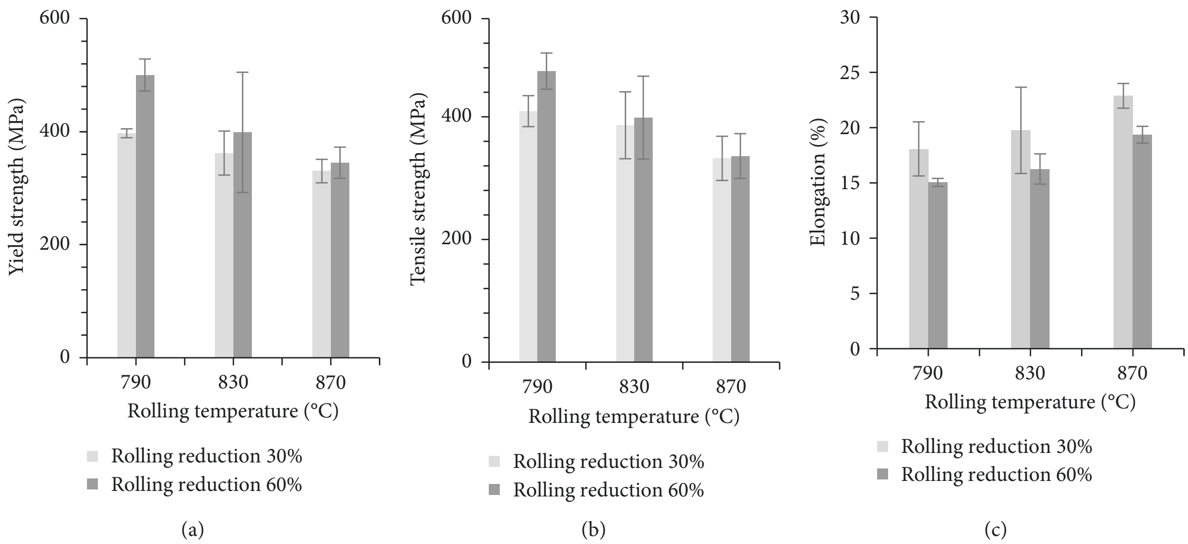

Figure 6: (a) The trend of yield strength values. (b) The trend of tensile strength values. (c) The trend of elongation values for warm rolled steel as function of rolling temperature and rolling reduction.

temperature was increased from 790°C to 830°C. Moreover, the presented softening phenomenon creates weaker components compared with the steels deformed at $T = 790$°C.

Induction of the dislocations through rolling and the use of a rolling temperature near the recrystallization temperature form different textures including weak {001} <110>, weak {111} <011>, weak {110} <001>, and weak {110} <001> and {110} <110>. This effect can be due to dynamic recrystallization in which the diverse texture components with low intensity appeared.

Increasing the dislocation densities by applying more rolling reduction and a high reheating temperature in the interpass process causes the induction of high stored energy to form the intense textures of {110} <001> and {001} <110>. As the rolling temperature is high, the recrystallized grains grow and feature the new texture components intensely. The existence of a strong {111} <011> texture resulted in deformed steel sheets with a high normal anisotropy value. This property is desirable for applications in which high draw ability is required [11, 18, 19, 26].

The formation of a large number of high angle grain boundaries at the highest rolling temperature and a rolling reduction of 30% indicates the occurrence of the recrystallization phenomenon, which is consistent with the equiaxed and refined grains observed in Figure 3. Observation of the peaks of boundary misorientation degrees in the ranges of 28–35° and 57–62° shows the full recrystallization phenomenon, which depends on grain boundary mobility and the driving force induced by the use of the high rolling temperature and the high rolling reduction [20, 21].

4.2. Tensile Properties. The highest value of YPE% related to the samples rolled with the lowest rolling temperature and the lower level of rolling reduction indicates that a low reheating temperature is not sufficient to reduce the dislocation density drastically, so the large amount of mobile dislocations was arrested by the solute atoms of N and C. In contrast to the steels deformed in a previous thermomechanical condition, the lowest value of YPE% in steels rolled at the highest rolling temperature can be attributed to the recrystallization phenomenon. Due to the softening mechanism, less solute atoms can segregate around the remaining dislocations, and less interaction happens between the dislocations and the solute atoms to form a Cottrell atmosphere (pipe diffusion) [9].

It is observed that the smooth yielding behavior is revealed in the rolled steels subjected to the higher level of rolling reduction. As the content of interstitial atoms (C, N) remained constant during the rolling process, and the same amount of atoms were diffused to the larger number of dislocations; consequently less dislocations were immobilized with the interstitial atoms. Moreover, the entrapped dislocations in the Cottrell atmosphere could be released by the generated dislocations.

A higher yield strength for the steel sheets rolled at $T = 790$°C can be due to the fact that the dislocations formed during plastic defamation at this temperature did not have sufficient internal energy to move and subsequently to annihilate the other dislocation with the opposite sign. Thus, the dislocation density imposed at this rolling temperature was not reduced in the same manner as the dislocation generated at $T = 830$°C, 870°C in which recovery and recrystallization had occurred [22, 23].

The use of warm rolling led to the formation of strips with a low total elongation % value. This result can be attributed to the formation of the oxide scale with low plastic deformation reducing the surface elongation of the strips [24, 25].

5. Conclusion

(1) The results show the best mechanical properties of mild steel obtained by controlling the thermomechanical parameters (rolling temperature and

rolling reduction) in the intercritical region phase ($\alpha + \gamma$). Control of the thermomechanical parameters leads to desirable mechanical properties such as low yield point elongation.

(2) In this work, the highest elongation % values as the formability property and the lowest yield point elongation and fluting intensity, which are the desired results for our study, were obtained for the strip that was warm rolled at $T = 870^{\circ}$C with a 30% rolling reduction.

(3) The high yield strength and tensile strength values in low temperature rolled strips with a rolling reduction of 30% and 60% are due to the formation of high dislocations.

(4) The improvement in the formability property and the lower yield point elongation and fluting intensity in steel deformed at $T = 870^{\circ}$C in a rolling reduction of 30% is the result of recrystallized grains.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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