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A study on the microstructural changes in hot rolling of dual-phase steels

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In this study, hot rolling behavior of a low alloy steel in the dual-phase region is studied. The effects of various process parameters such as initial temperature, soaking time, rolling speed and the cooling conditions are investigated. Then, mechanical testing and microstructural studies are performed and the effects of process parameters are studied and finally the optimum rolling program is determined based on the achieved results. The results show that rolling speed significantly alters the final microstructures and mechanical properties. Higher rolling speed results higher volume fraction of ferrite phase. In addition, the optimum dual-phase microstructure for this steel can be obtained with; an initial rolling temperature of 900 °C, after 30 min soaking time, a strain rate of 3.8 s^{-1} and cooled at the rate of 250 °C /s.

1. Introduction

Dual-Phase steels offer a combination of tensile properties such as relatively low yield strength and high tensile strength, which make them unique among high strength low alloy (HSLA) steels. They also exhibit high work hardening rates in the early stage of plastic deformation and good ductility during forming relative to strength in the deformed conditions [1–4]. The correct distribution of the two phases allows a low yielding stress, a high elongation value and a smooth flow-stress curve [5–7]. In order to produce dual phase steel, different methods can be employed such as heat treatment, hot rolling and hot forging. The utilization of thermo-mechanical processing by hot rolling near Ar_3 is an industrial method for manufacturing of dual phase steels [7–8]. In this technique, controlling the rolling parameters has a significant role on the final microstructure and mechanical properties.

Recent works have shown that the microstructure of several commercial dual-phase steels deviates substantially from a strictly ferrite-martensite combination and that the second phase is actually a complex mixture of martensite, retained austenite, and bainite [9]. In some researchers the composite like behavior of different constituents with respect to their micromechanical aspects has been studied [10]. Several studies have been conducted to determine the effect of phase morphologies on the final properties. Sun and Pugh have investigated the effect of thermo-mechanical processes on the formation of fibrous martensite [6]. Sarwar and Priestner have taken into account the influence of ferrite-martensite microstructural morphology on the tensile properties of dual-phase steels [11]. El-Sesy and El-Baradie have investigated the effect of iron carbide on the mechanical behavior of dual phase steels [12]. Fallahi has considered the role of microstructural parameters on the mechanical properties of dual-phase steels. He has shown that microstructures of 4 μm ferrite mean grain size and 35 to 40% fibrous martensite, provides optimum tensile and impact properties [13]. Deb and Chaturvedi have studied single-pass rolling at the intercritical annealing temperature and the mechanical properties of Nb-V dual-phase steel have been determined [8].

The volume fraction and composition of the micro-constituents can be altered by varying the processing parameters and steel composition which in turn it produces significant changes in mechanical behavior of the steel. Effects of different constituents have been studied by several researchers. Priestner and Sarwar have investigated the effect of thermo-mechanical processing on hardenability of austenite. They have determined the conditions for accessing the fibered martensite by rolling in the intercritical region [14]. In another work, they have investigated the effects of rolling conditions on austenite hardenability [15]. Ahmad and Priestner have studied the

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effect of rolling in the intercritical region on the tensile properties of dual phase steels [16].

Although there are several works dealing with dual-phase steels and their properties, more investigations are still necessary to understand the complex interconnections among chemical composition, rolling parameters and final microstructures. The purpose of this paper is to investigate the possible thermo-mechanical cycles resulting to a dual-phase microstructure in a low alloy steel. To do so the effects of different rolling parameters such as austenitizing temperature, austenitizing time, cooling rate and rolling speed are investigated and mechanical properties and microstructures of the final product are determined and then based on the achieved results the interconnections among rolling parameters and macrostructures are discussed.

2. Experimental procedure

The composition of the steel employed in the present study is 0.18C, 0.24Si, 1.01Mn, 0.010P, 0.007S, 0.02Cr, 0.001Mo, 0.48Ni (in wt %). The material was supplied in the form of hot-rolled plate 15 mm thick. Then, wedge shaped specimens for rolling experiments were machined out of this plate. The specimens were 36 mm in width and 80 mm in length with a 1.5 mm thickness at the front end tapered to 5.5 mm at the back end as shown in Fig. 1. All the specimens were instrumented with an embedded thermocouple located 10 mm from the thick end. To study the effect of austenitizing temperature on the austenite grain size several cylindrical specimens were austenitized at a series of temperatures in the austenite region and quenched to obtain the martensite phase in the microstructure. The specimens were sectioned and etched to reveal prior austenite grain size. The austenite grain size was determined by linear intercept method. For example, Fig. 2 shows the initial austenite grain size for a sample pre-heated at 900 °C for 30 min.

In order to assess the effects of different thermo-mechanical parameters, the hot rolling experiments were performed under different schedules. For this purpose a laboratory rolling mill with controlled rolling speed was used. The variation of temperature was measured by the thermocouples engaged in the samples. The tapered specimens were austenitized at the selected temperatures and then cooled in the air to the rolling temperature. The thin end of the wedge was fed into the roll gap first. Fig. 3 shows the different thermo-mechanical schedules used in this research. For investigating the effects of different rolling parameters four thermo-mechanical cycles were employed to assess the effect of austenitizing temperature, austenitizing time, cooling rate and rolling reduction. Then, samples were extracted from the center of a 15 mm section of the rolled samples. Different phase analysis was performed with an image-analyzing device. The mean linear intercept grain size was then determined by lineal analysis. In addition, mechanical properties of the hot rolled samples were measured by means of tensile testing.

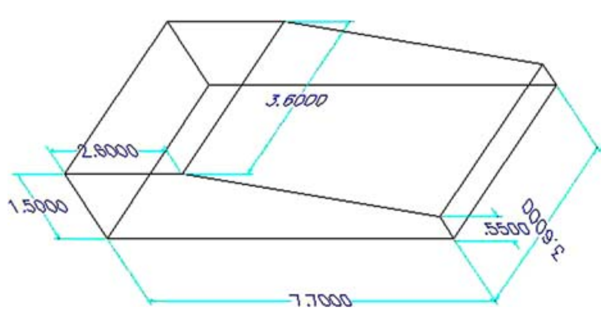


Figure 1 Wedge-shape sample used in hot rolling experiments (dimensions in cm).

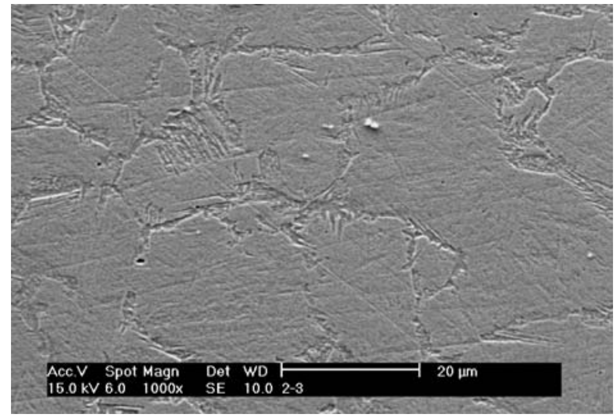


Figure 2 Initial austenite grain size for 30 min soaking time and initial temperature of 900 °C.

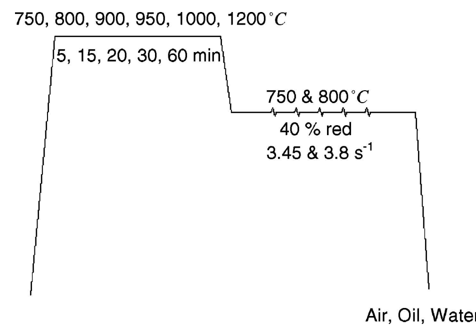


Figure 3 Thermo-mechanical schedules used in this study.

3. Results and discussion

The initial microstructure has an important role on the steel behavior during and after hot rolling. The effect of pre-heat temperature and the soaking time on the initial microstructure were taken into account. Figs. 4 and 5 show the effect of initial temperature on austenite volume fraction and grain size, respectively. It is observed at 1000 °C, the rate of austenite grain growth is increased sharply, which it may be attributed to the dissolvation of second phase such as carbides and nitrides within the matrix [16]. Based on the achieved results, hot rolling experiments

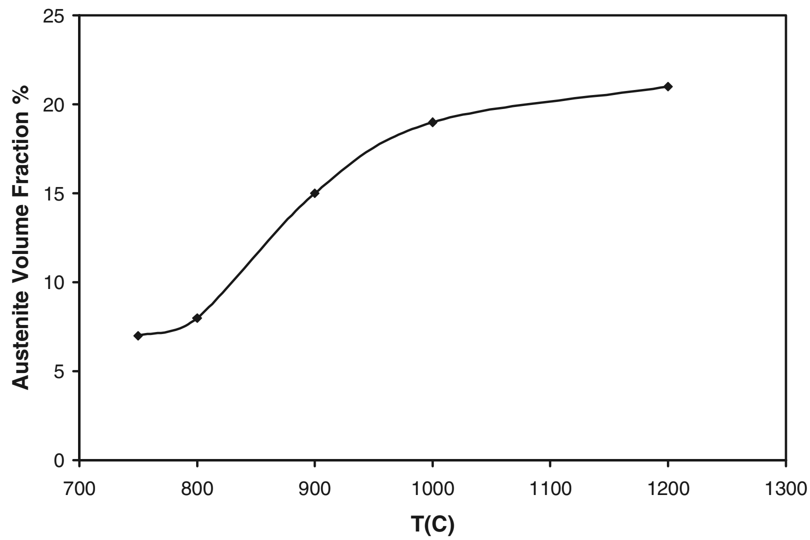


Figure 4 Effect of initial temperature on the volume fraction of austenite.

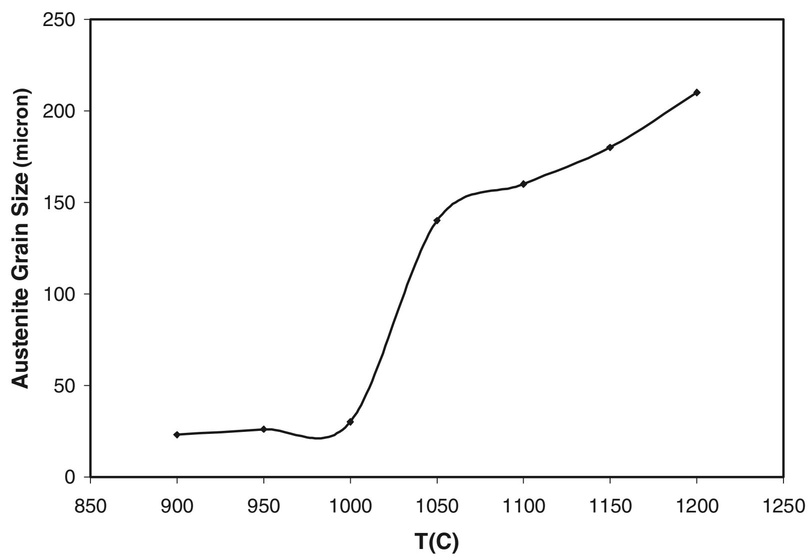
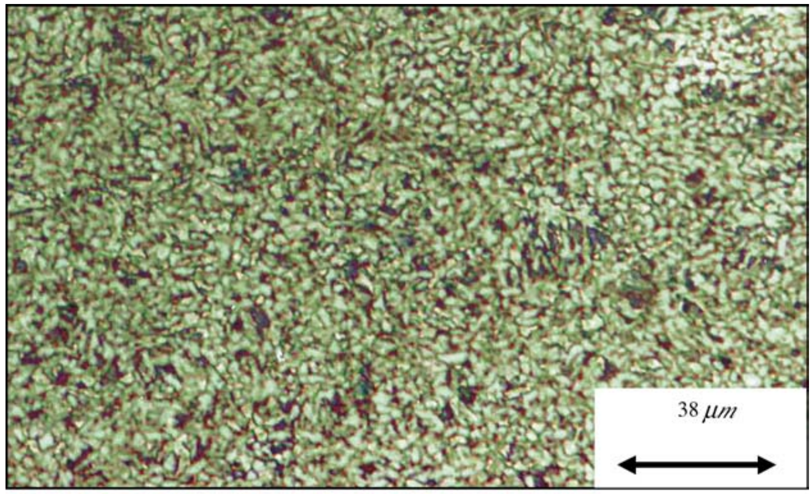


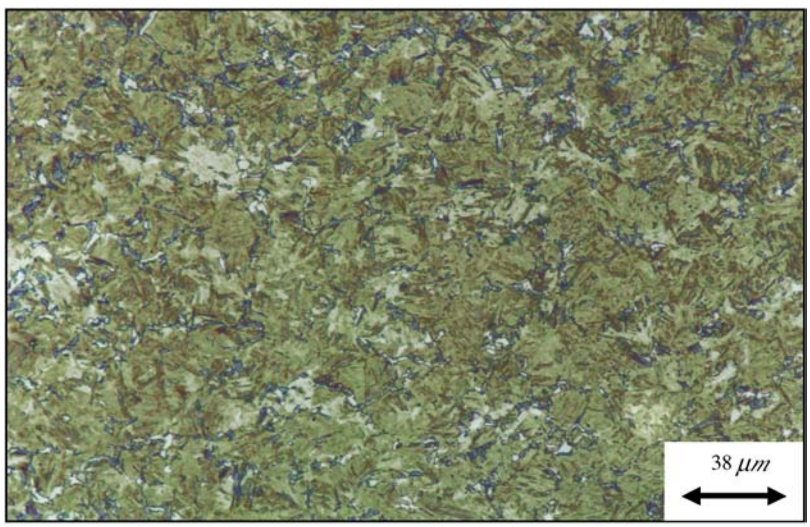
Figure 5 Effect of initial temperature on austenite grain size.

were designed and performed. For doing so, samples with an initial temperature ranging between 1200 °C to 750 °C were deformed. During each rolling experiment, 40% reduction of height was applied to the samples within three stages and then the samples were cooled in different cooling media. Microstructural studies were also carried out on the hot rolled steel and volume fraction and morphology of the phases were measured. Fig. 6 displays the sample microstructures for different initial temperatures. The results show that the volume percent of martensite phase is a function of the initial temperature. Higher martensite volume fraction is obtained for the higher initial temperatures. Fig. 7 illustrates the volume fraction of ferrite, martensite and bainite as a function of initial temperature. For temperature above 1000 °C, bainite volume fraction increases in the microstructure where at 1200 °C a considerable amount of the microstructure consists of bainite phase. Also, in several samples the martensite islands had a bainitic core as shown in this figure. This can be explained by the carbon concentration profile in the transformed area [17]. Due to the low diffusivity of carbon in austenite at lower temperatures, the carbon concentration on the austenite side of the ferrite-austenite phase boundary is higher than in the center. This leads to a difference in hardenability within the transforming austenite grain. As a result, the bainitic transformation is not always suppressed in the center of the grains during cooling of steel. This causes an inhomogeneous distribution of carbon content and provides suitable regions for bainite nucleation inside the martensite islands.

Based on previous work [18–20] the optimized dual phase microstructure is a fine polygonal ferrite matrix



(a)



(b)

Figure 6 Microstructures for different initial rolling temperatures (a) 900 °C (b) 1200 °C.

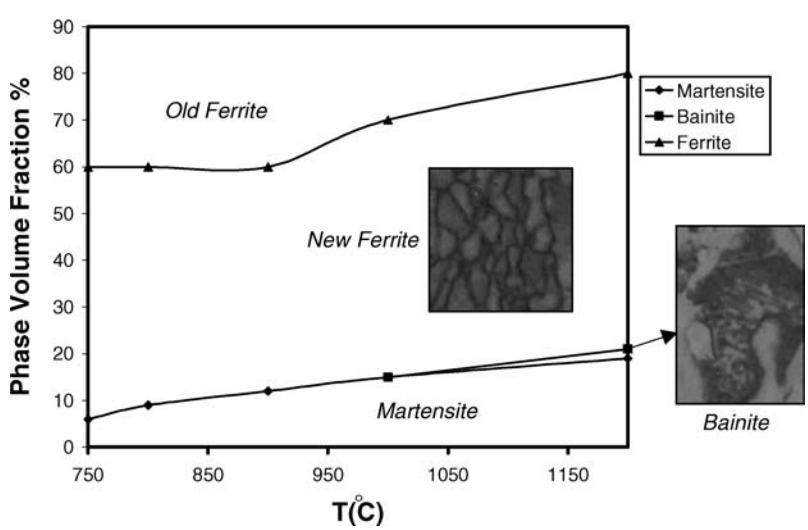


Figure 7 Effect of rolling temperature on the volume fraction of ferrite, martensite and bainite.

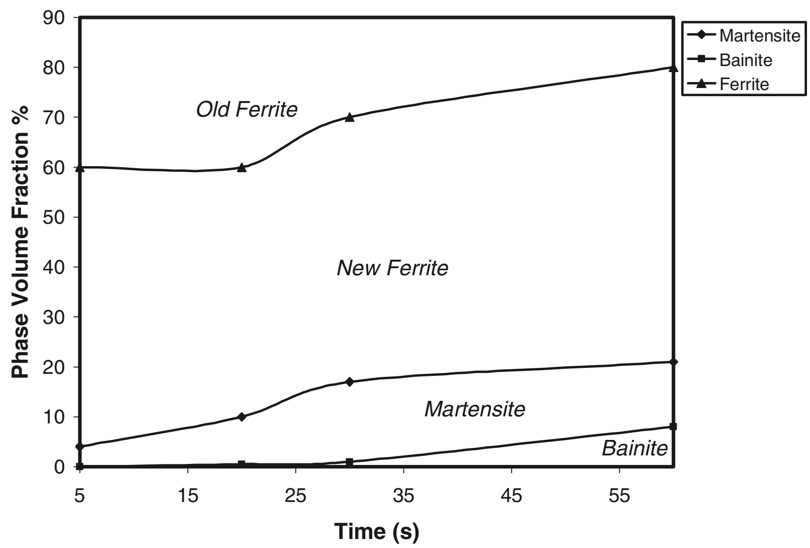


Figure 8 Effect of austenitized time on the final phase volume fractions.

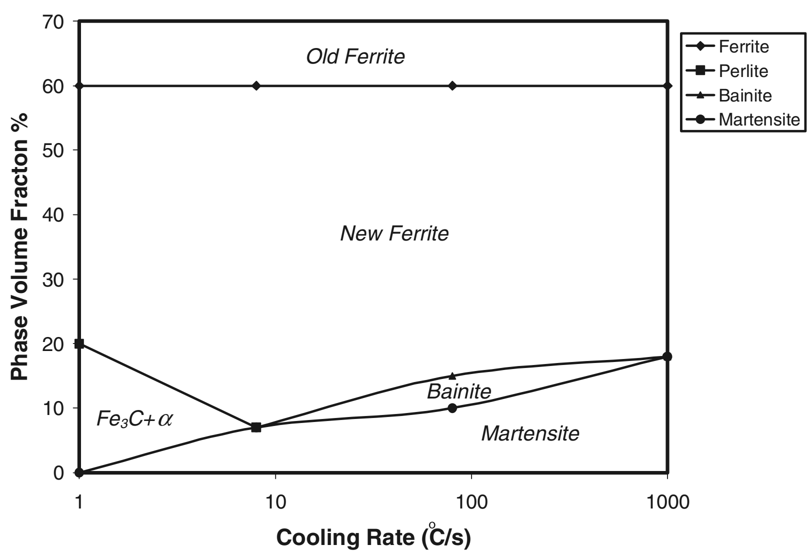


Figure 9 Effect of cooling conditions on the final phase volume fractions.

composed of about 15% fine martensite particles. The results show that this optimized dual phase microstructure is formed with an initial temperature of 900 °C. As a confirmation for these results, Santos *et al*. [21] show that using an austenitizing temperature of 900 °C produces a more homogenous ferrite microstructure after hot rolling than that with an initial temperature of 1200 °C.

Fig. 8 shows the variation of phase volume fraction with respect to austenizing time. As the austenitizing time is increased the new ferrite fraction increases. During hot rolling of dual phase steels there is a mixture of α and γ grains. Due to the difference in workability of the ferrite and austenite phases, micro-shear bands are introduced into austenite during hot deformation in the dual phase region [21]. These shear bands produce additional nucleation sites for ferrite formation during the cooling stage. Therefore, it is expected that by increasing the austenitizing time, the austenite grain size increases and so the volume fraction of new polygonal ferrite increases because of the decrease in austenite grain boundaries. Also, the volume fraction of both martensite and bainite increases. It is worth noting that similar results have been obtained by other workers [23].

Another important factor affecting the final microstructure is cooling rate on the run-out table. As it is expected higher cooling rate results higher fraction of martensite within the microstructure however the distribution of phases and their morphologies are also affected by this parameter. Fig. 9 shows the effect of cooling rate on phase volume fractions within the steel. Increasing the cooling rate results higher martensite volume fraction however, the bainite volume fraction varies in a different manner. At first it increases and then decreases to a fully ferrite-martensite microstructure. This behavior can be justified

(a)

(b)

Figure 10 Microstructures for different strain rates, (a) 3.45 s^{-1}, (b) 3.8 s^{-1}.

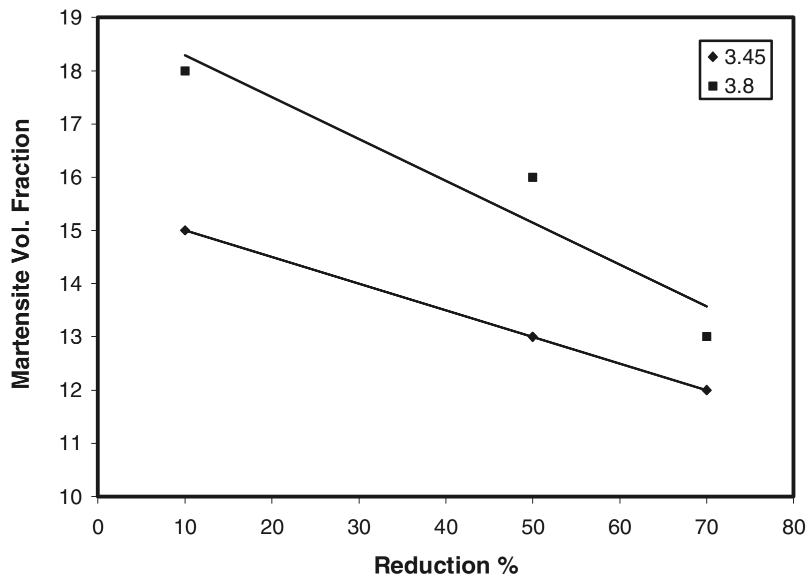
with the model, which is proposed by Garret *et al*. [24].

$$\frac{dx_f}{dt} = A_5 \exp\left(\frac{T^*(\varepsilon) - T}{B_1}\right) \times \left(\frac{r - r^*}{r}\right)^n \times (1 - x_f)^\gamma \exp\left(-\frac{G^*}{RT}\right) \quad (1)$$

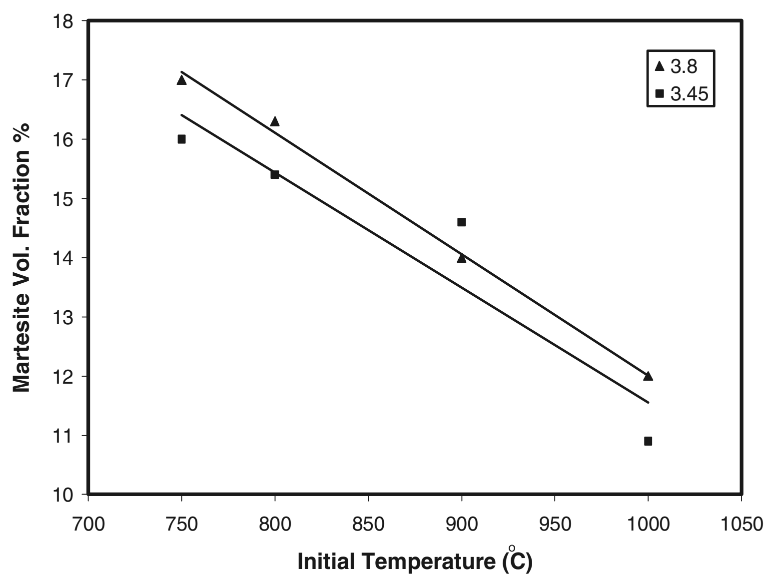
where x_f is volume fraction of bainite, G^* free energy formation of the new bainite phase, r the radius of the bainite particle and r^* is critical radius of bainite particle. The growth rate of bainite is controlled by the temperature history in the cooling steel. According to this model, for the case of high cooling rates i.e. cooling rates of 100 °C/s or more, the difference between the nose temperature T^* and the sample temperature is large enough to retard the growth of the bainite nuclei. However, for a moderate cooling rate, it is expected that a finite amount of bainite will be produced during continuous cooling due to a decrease in the critical radius of bainite particles [24].

The rolling speed is the other significant process parameter, which can remarkably affect the deformation pattern and heat transfer during rolling [25]. Therefore, it is expected that this parameter also affects the final microstructure. To examine this effect of rolling speed, rolling experiments with different rolling strain rates of 3.45 and 3.8s^{-1} were performed for the various initial temperatures. The strain rates were calculated from the following equation [23] where is roll speed (in rpm), H_0 is thickness before rolling (in mm), r is rolling reduction and R is roll radius (in mm).

$$\dot{\varepsilon} = \frac{2\pi n}{60\sqrt{r}} \sqrt{\frac{R}{H_0}} \ln\left[\frac{1}{1 - r}\right] \quad (2)$$



(a)



(b)

Figure 11 Effect of strain rate on martensite volume fraction with respect to, a) reduction, b) initial temperature.

Fig. 10 shows the microstructure of the hot rolled samples for the initial temperature of 800 °C. As it is seen the microstructure of sample hot rolled at a strain rate of 3.45 s^{-1} consists of proeutectoid ferrite grains on prior austenite grain boundaries, with a mixture of acicular ferrite and bainitic transformation products within the prior austenite grains (Fig. 10a) while the microstructure of hot rolled sample in strain rate of 3.8 s^{-1} consisted of fine grained ferrite. Fig. 11a displays the effect of strain rate on the volume fraction of martensite at different reductions and Fig. 11b shows the effect of strain rate on volume fraction of martensite at different initial temperatures. The martensite volume fraction decreases more rapidly with increasing the reduction at the strain rate of 3.8 s^{-1}. It is observed that increasing the applied strain rate leads to a decrease in martensite volume fraction at higher reductions as shown in Fig. 11a. It may be due to an increase in the nucleation rate of ferrite phase at higher strain rates. On the other hand, there is no initial temperature sensitivity of martensite volume fraction for different strain rates as illustrated in Fig. 11b where for both strain rates the slopes of martensite reduction are the same. It is worth noting that the strain rate affects several factors such as temperature drop in the roll gap, strain field and the contact time with the work-rolls. For the case of high rolling speed it is expected that the temperature drop in the samples is reduced [27] and therefore the ferrite phase is increased in the following austenite phase change on the run-out table.

It is interesting to note that increasing the strain rate also has a considerable effect on the final stress-strain behavior

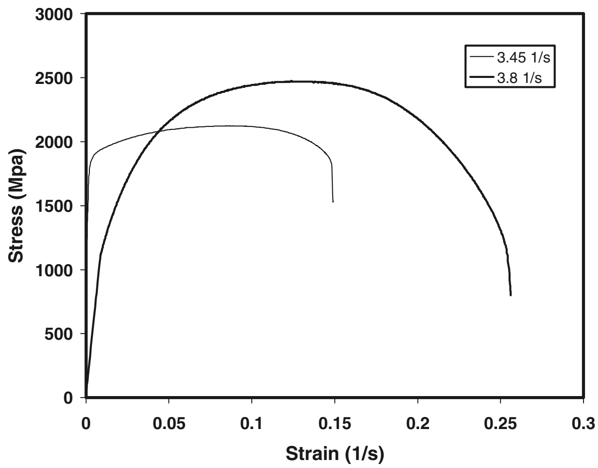


Figure 12 Effect of strain rate on stress-strain behavior of dual phase steel.

of the resulting dual-phase steel. Fig. 12 shows the effect of rolling speed on the flow behavior of the rolled samples. The total elongation and the tensile strength increase remarkably. It may be attributed to the effect of strain rate on the nucleation process of the ferrite transformation. It is known that with an increase in the strain rate, more slip planes will be activated and the rate of dislocation accumulation is increased. As a result, after deformation the suitable sites for nucleation are increased and a fine grain microstructure will be produced. Therefore, it is expected that the steel rolled at higher rolling speed has a higher tensile strength as well as higher ductility at fracture particularly for the steels having a higher volume fraction of ferrite [18].

4. Conclusions

In the present work, the behavior of a low carbon steel is determined under hot rolling conditions. The rolling experiments were carried out in the two-phase region and after rolling various cooling programs were applied and then the developed microstructures were studied. The results show that:

1. As a result of increase in initial rolling temperature the volume fraction of both bainite and martensite increase.
2. Increasing the cooling rate leads to increasing the martensite volume fraction while bainite shows a quiet different behavior first increases with increasing the cooling rate and then decreases.
3. The final microstructures and mechanical properties can be affected by the rolling speed. The rolling speed changes the morphology and the volume fraction of the present phases within the steel. Higher strain rates causes higher ferrite volume fraction with finer grain size.
4. The total ductility of dual phase steel increases with an increase in the rolling speed in the dual phase region.
5. The optimized dual-phase microstructure which consists of fine polygonal ferrite matrix composed with about 15% fine martensite particles are obtained in the initial rolling temperature of 900, soaking time of 30 min, strain rate of 3.8 s^{-1} and cooling rate of 150–250 °C /s.

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