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Microstructures and mechanical properties of duplex low carbon steel

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Abstract. The microstructures behavior of duplex cold-rolled low carbon steel for automotive applications has been investigated. Intercritical annealing treatment is commonly used to develop a duplex low carbon steel containing ferrite and martensite. To get a duplex phase ferrite and martensite, the specimens were heated at inter-critical annealing temperature of 775°C - 825°C, for heating time up to 20 minutes, followed by water-quenched. The hardness of specimens was studied. The optical microscopy was used to analyze the microstructures. The optimal annealing conditions (martensite volume fraction approaching 20%) at 775°C with a heating time of 10 minutes was achieved. The highest hardness value was obtained in cold-rolled specimens of 41% in size reduction for intercritical annealing temperature of 825°C. In this condition, the hardness value was 373 HVN. The correlation between intercritical annealing temperature and time can be expressed in the transformation kinetics as $f\gamma/fe = 1-\exp(-Kt^n)$ wherein K and n are grain growth rate constant and Avrami's exponent, respectively. From experiment, the value of K = 0.15 and n = 0.461. Using the relationship between temperatures and heating time, activation energy (Q) can be calculated that is 267 kJ/mol.

1. Introduction

The high demand for materials of automotive industry with enhanced mechanical properties has brought to the development of wide variety of duplex phase steels. The structure of duplex phase steel consists of ferritic matrix and clusters of martensite. Martensite contribute to strength of base material and ferritic provide good ductility [1]. Dual phase steel is appropriate material for automotive industry because this material has good mixture of high strength with elongation [2]. The request for more light and fuel efficient vehicles has caught attention beside the fact that the duplex phase steel has a good tensile strength which is similar to plain carbon steels, and excellent ductility [3]. The ferrite phase offers the ductility while martensite provides strength. The properties of duplex phase steel such as low yield strength, continuous yielding behavior, and highly uniform total elongation are also as detrimental properties [4]. Beside the ferrite grain size [6], martensite volume fraction and its morphology affect the mechanical properties of duplex phase steels [5]. Alaneme [7] noted that a good combination of strength and ductility can be achieved by intercritical heat treatment to transform low carbon steels to duplex microstructures of ferrite and martensite on the right level. Increasing in heating time at low temperature decreases the microstructural strapping in cold-rolled dual phase steel, while in the intercritical range, the formation of ferrite was observed more by quenching. The present

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work examines the microstructural changes in cold-rolled low carbon steel during intercritical annealing with a focus on the formation of duplex ferrite-martensite phase.

2. Experimental procedure

The material for the study is a hot-rolled low carbon steel plate with 100x75x3.40 mm in dimension. The element composition is as follows: C (0.155); Si (0.18); Mn (1.05); P (0.056); S (0.0065); Cr (0.011); Ni (0.008); Mo (0.0025); V (0.0036); Nb (0.0019); Ti (0.0012); W (0.0041), in wt%. The plates were initially subjected to intercritical annealing and quenching [8-9]. The plates with initial diameter of 3.40 mm were cold-rolled to approximately 41% after intercritical treatment was performed. Before intercritical treatment, the lower critical temperature (A_1) and the upper critical temperature (A_3) for the test material were determined following empirical relations in accordance with Andrews [10]. The plates were heated at intercritical temperatures of 775°C, 800°C, and 825°C for 10, 15 and 20 minutes, respectively, followed by water quenching. After quenching, the samples were tempered at 200°C for 20 minutes and then cooled in the air. A micro Vickers hardness was used to obtain the hardnes value of cold-rolled steel. The microstructures of samples were evaluated by optical microscopy. Martensite volume fraction was calculated based on ASTM E562-83 standard.

3. Result and discussion

Figure 1 shows the microstructure of cold-rolled plate before and after quenching. The cold-rolled plate before quenching was consisted of ferrite and pearlite phases (figure 1 (a)). Volume fraction of the phase was obtained by using point counting calculations.

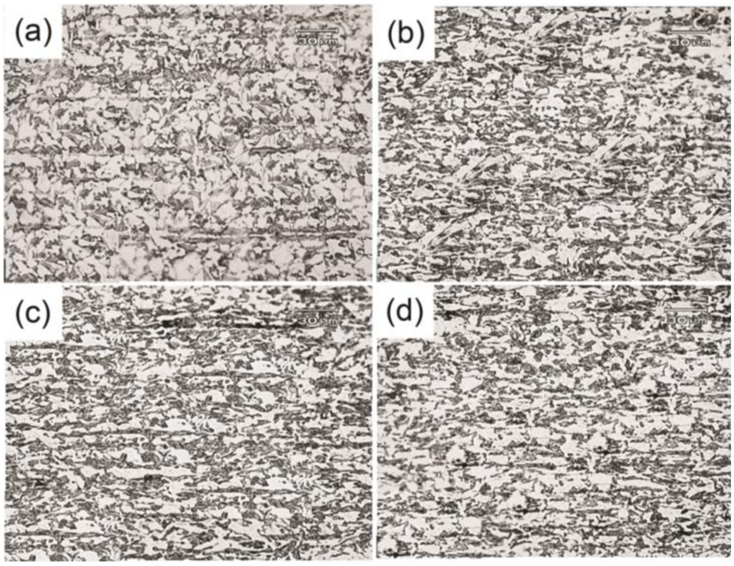

Figure 1. Microstructure of cold-rolled plate (a) before and after heat treatment at 775 °C for (b) 10, (c) 15 and (d) 20 minutes, water-quenched, 41% cold-rolled.

Volume fraction of ferrite and pearlite were 79.7% and 20.3%, respectively. After quenching, ferrite, pearlite and martensite phase were formed which can be shown in figure 1(b-d). Martensite volume fractions for heating time of 10, 15 and 20 minutes were 26.5%, 29.2% and 31.8%, respectively. The effect of intercritical temperature on martensite volume fraction at several heating time are shown in figure 2. Intercritical temperature has significant effect on increasing the hardenability compared to that of heating time. Martensite volume fraction will significantly increases with increasing temperature. When the hot-rolled plates were heated at intercritical annealing point, austenite start to nucleate and grow [11]. Austenite is unstable phase and it will be transformed during cooling.

Eutectoid transformation from austenite to ferrite, cementite and pearlite is begun in the A_1 temperature.

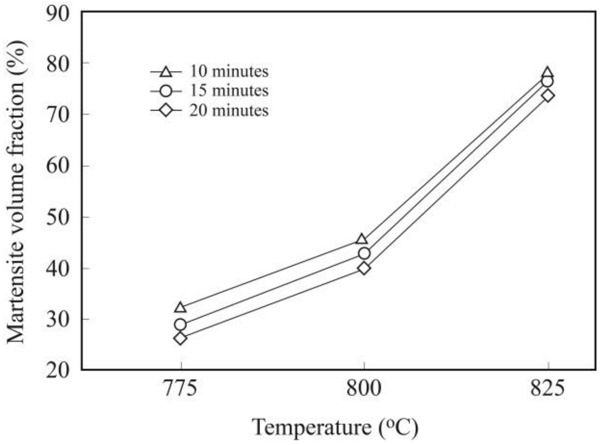

Figure 2. Effect of temperature on martensite volume fraction of specimens heated at various holding time.

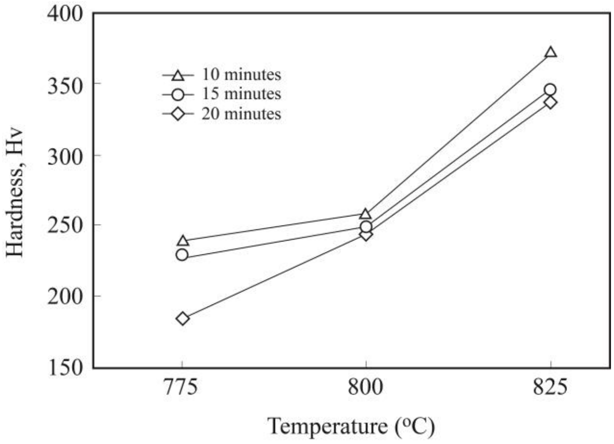

Figure 3. Effect of temperatures on hardness at various heating time.

When the temperature is raised above the A_1, carbon atom easily dissolved into austenite [12]. Therefore, increasing heating temperature increase the volume fraction of austenite after rapid cooling. Increasing in holding time will promote the formation of austenite. The heating time affected to the phase formation, because the holding time provides an opportunity for atoms to diffuse thus homogeneously into austenite [11]. Austenite is an unstable phase and it can be transformed easily into another phase during cooling process.

Figure 3 shows the hardness value of specimens. The hardness of hot-rolled plate before heat treatment was 135.6 HVN. Heating was carried out on the ferrite-austenite region. Increase in the volume fraction of martensite caused increase in hardness. The difference in phase formations; ferrite-pearlite and ferrite-martensite, respectively, was caused by the difference of cooling rate between specimens before and after heat treatment. Ferrite and pearlite were appeared in low carbon steel. Carbon content determined hardness of the cold-rolled plate which is affected by ferrite and pearlite appearance. After quenching, the final structure was ferrite and martensite containing saturated carbon atoms. The formation of martensite can cause on rising in hardness value. The increased cooling rate will be accompanied by an increase in heating temperature so that martensite can be easily formed. Increase in the number of martensites will be followed by an increase in the value of violence. Increase in martensite volume fraction cause the increasing of hardness value [13]. The strengthening mechanism of duplex-phase steel is caused by martensite structure as a strong constituent in the soft ferrite matrix. High tensile strength is generated by dislocation density, also has an influence to the strengthening mechanism in a high rate of work hardening duplex phase steel. The presence of high density of dislocation can be obstacle for the movement of the other dislocations.

Formation kinetics of austenite-martensite transformation during the heat treatment point of view intercritical annealing has long been examined. The transformation kinetics of austenite in duplex phase steel is controlled by diffusion growth. The transformation of austenite during intercritical annealing can be calculated using Johnson-Mehl-Avrami-Kolomogrov (JMAK) equation [14].
By modifying the JMAK equation, the grain growth rate constant (K) and the Avrami exponent (n) can be determined. K and n value is obtained from the slope and intercept which is resulted from linear equation relationship between ln [ln (1/(1-f_γ/fe)] versus ln t, as can be shown in figure 4. From figure 4, the n and K can be obtained, as listed in Table 1.

Table 1. n and K value at 775°C, 800°C and 825°C

Temp. (°C)	Equilibrium Austenite volume fraction (f_e)	Avrami's exponent (n)	Rate constant (K)
775	0,2808	0,461	0,15
800	0,4265	0,598	0,41
825	0,7692	0,281	0,52

Rate constant (K) is a value that depends on the temperature and velocity related with grain growth and frequency of nucleation. The value of K will increase if temperature of intercritical annealing is high. [15]. The Avrami exponent (n) depends on the nucleation and growth processes. The grain nucleation rate has a significant effect on the value of n [14]. From the data of grain growth rate constant (K), the value of activation energy (Q) and constant (A) can be calculated [15]. Figure 5 shows the value of activation energy (Q) and constant (A) were obtained from the slope and intercept resulting from linear equation between ln K and 1/T. From this correlation, activation energy (Q) and constant (A) will be 267kJ/mol and 2.97 x 1012, respectively.

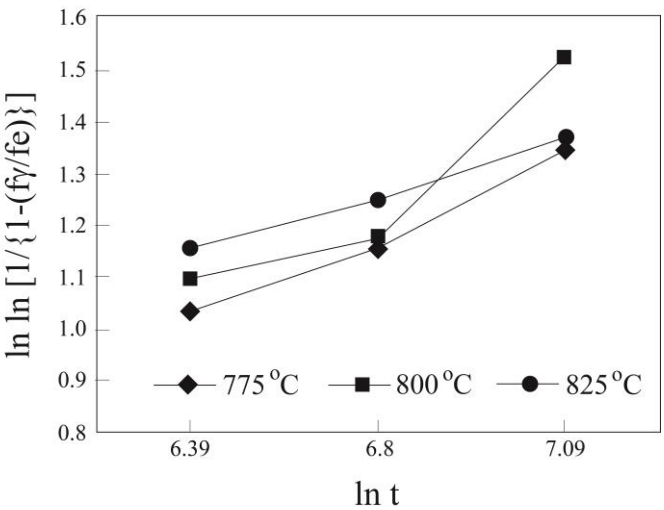

Figure 4. The relationship between ln [ln (1 / (1 - fɤ/fe)] and ln t from experiment.

4. Conclusion

After the the chemical composition of the investigated steel allows to manufacture the products with the ferritic–martensitic structure by under hardening from the austenite and ferrite area. The coexistence of harder (martensite) and softer (ferrite) phase in the microstructure of duplex phase steel produce an excellent combination between strength and ductility. The promising hardness was obtained when treatment was performed at 825°C in comparison to 800°C and 777°C. The optimum value was 373 HVN with 78% of martensite. At the optimum point (at volume fraction of martensite approaching 20%), the value of hardness was 184 HVN. Rate constant will increase with increasing heating temperature. In this work, activation energy (Q) of specimen was 267 kJ/mol.

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