Journal of Engineering and Applied Sciences 10 (7): 190-196, 2015
ISSN: 1816-949X

A Study on Phase Transformation of Hot Rolled Dual Phase Steel using Deformation Dilatometer

Sakhob Khumkoa and Ronnachai Jadudom
School of Metallurgical Engineering, Institute of Engineering,
Suranaree University of Technology, Muang, Nakhon Ratchasima 30000, Thailand

Abstract: This research studied the effects of hot rolling parameters on dual phase steel as a hot rolled product. Objective of the research was to determine the influence of different hot roll parameters that affect the microstructure of the rolled steel when it was tested in the conditions similar to hot rolling. These parameters consisted of deformation degree, deformation temperature, holding temperature and holding time at a constant temperature after the test specimen is deformed. These tested parameters affect the morphology and volume fraction of soft ferrite matrix of dual phase steel. The type of morphology and volume fraction of ferrite will lead to different properties of hot rolled dual phase steel. This research used a carbon steel containing manganese-niobium as master specimens. Rolling simulation was conducted with the aid of a deformation dilatometer. Experimental procedure consisted of a development of continuous cooling transformation diagrams of tested steel, investigation of hot rolling parameter on ferrite formation and modeling of ferrite formation. By considering the continuous cooling transformation diagram, the ferrite formation temperature of tested steel is in the range of 650-700°C. The hot rolling simulation at a temperature between 650 and 690°C showed that increasing of deformation degree increased volume fraction of ferrite. This was due to the increasing deformation degree which affected the increasing nucleation site of ferrite and also affected grain refinement of ferrite. Holding temperature and holding time of specimens after deformation significantly influenced the ferrite formation. The test series showed that lower holding temperature and longer of holding time resulted in increasing volume fraction of ferrite. Comparative results obtained from hot rolling simulation using deformation dilatometer and the calculated results using a mathematical model showed similar trends of hot rolling parameter influences on ferrite formation and also shared comparable values. This research therefore introduced a construction of a processing map which presented the relationships among hot rolling parameters and ferrite formation. This processing map could be used for controlling a hot rolling process to obtain a desirable hot rolled dual phase steel.

Key words: Dual phase steel, phase transformation, hot rolling of steel, deformation dilatometer, ferrite

INTRODUCTION

Dual Phase (DP) steel is a popular material in automobile industry and in many instances is being used to replace more traditional HSLA steel. It is not only lighter in weight than traditional steel but also has a greater ability to absorb crash energy and resist fatigue. It exhibits some desirable mechanical properties such as continuous yielding, low yield strength, high initial work-hardening rate, high tensile strength, good ductility and good formability. The microstructure of DP steel consists of hard martensite island 5-30% embedding in soft ferrite matrix (Niakan and Najafizadeh, 2010; Wang *et al*., 2010). Ferrite fractions effect on formability of DP steel. Normally, the chemical composition of DP steel compose of 0.06-0.15% C, 1.5-2.5% Mn and 0.2-0.5% Si. Carbon enhance strengthen martensite and austenite stabilizer. Manganese enhances austenite stabilizing and solid solution strengthening of ferrite. Silicon promotes ferritic transformation (Kuziak *et al*., 2008). Niakan and Najafizadeh (2010) showed that niobium retard the formation of bainite and increase yield strength. Therefore, niobium is added in DP for those purposes. Suwanpinij *et al*. (2010) has proposed the rate law of transformation model of hot rolled dual phase steel. This model is a derivative differential equation and is applied to predict the phase transformation. In this study, we focus on the phase transformation of ferrite. The mathematics model of ferrite transformation will be expressed to clarify the ferrite formation. In addition, effects of deformation temperature, holding time and degree of deformation on phase transformation will be expressed.

Corresponding Author: Sakhob Khumkoa, School of Metallurgical Engineering, Institute of Engineering,
Suranaree University of Technology, Muang, Nakhon Ratchasima 30000, Thailand

MATERIALS AND METHODS

Materials and equipment: The chemical composition of test steel in this study consist of 0.082% C, 1.48% Mn, 0.28% Si, 0.017% P, 0.001% S and 0.054% Nb. Steel slab with dimension of 10×10×30 cm^3 is taken as received sample. The microstructure of slab steel is coarse structure. The steel slab steel was heated up to 1200°C and kept at this temperature for 2 h in order to homogenize the microstructure of the steel slab. The main equipment used for study the phase transformation, in this study, is a deformation dilatometer (Model DIL 805 A/D) shown in Fig. 1. This machine is used to simulate hot deformation of steel.

CCT diagram: Continuous Cooling Transformation (CCT) diagram reveals phase transformation of steel with temperature and time under continuous cooling situation. To develop the CCT diagram, the test steel was investigated the temperature of ferrite formation. The homogenized steel slab is machined to a rod shape with 5 mm in diameter and 10 mm long. The sample was installed into dilatometer and was heated up to 950°C with heating rate of 10°C sec^{-1}. At that temperature the specimen was held for 30 sec^{-1} and then was cooled with different cooling rate to room temperature. Cooling rate was controlled with 0.8, 4, 6, 8, 10, 40, 100, 200 and 1000°C sec^{-1}. Heating and cooling cycle is shown in Fig. 2. The experiment procedure was controlled by interactive computer program. Microstructure of sample from cooling test were investigated. Recorded data were analyzed to create the CCT diagram of the test steel.

Test parameters: In this study, the effects of degree of deformation, holding temperature and holding time on the formation of ferrite are taken into consideration. Ferrite grain was refined by the effect of deformation below non-recrystallization temperature and higher T_{ac3} temperature. These temperatures depend on chemical composition of steel. The non-recrystallization and T_{ac3} temperature are express in Eq. 1 and 2, respectively (Suwanpinij *et al*., 2010; Asadi *et al*., 2008):

$$T_{nr} = 887+464C+\left(6645Nb - 664\sqrt{Nb}\right)+\left(732V - 230\sqrt{V}\right)+890Ti+363Al - 357Si \quad (1)$$

$$A_{C3} = 910 - 203\sqrt{C} - 15.2Ni + 44.7Si + 31.5Mo + 104V + 13.1W \quad (2)$$

Using the data of steel composition and Eq. 1 and 2, we found that the non-recrystallization and T_{ac3} temperatureof test steel are 1040 and 870°C, respectively. To clarify the effects of testing parameters on ferrite formation the test conditions were adjusted as follows. The degree of deformation: 0.1 and 0.3, holding temperature: 650 and 690°C and holding time: 5 and 10 sec were adjusted and controlled by DIL 805 A/D. A schematic of heat cycle and test conditions is shown in Fig. 3 and in Table 1, respectively. The microstructure of tested sample was subsequently investigated to determine the fraction and morphology of ferrite phase.

Model of ferrite formation: Transformation of ferrite was predicted by using mathematicsmodel (Suwanpinij *et al*.,

Fig. 1: Deformation dilatometer model 805 A/D

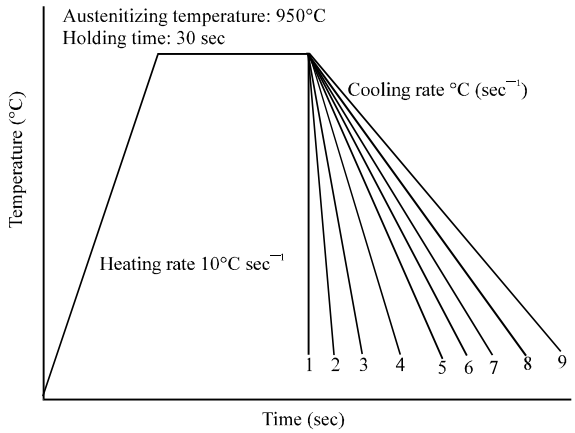

Fig. 2: Schematic diagram of cooling test to determine CCT diagram of steel used in this study; cooling rate: 1 = 1000.0; 2 = 200.0; 3 = 100.0; 4 = 40.0; 5 = 10.0; 6 = 8.0; 7 = 6.0; 8 = 4.0; 9 = 0.8

Table 1: Test parameter

Parameters	Values
$\dot{T}_1$, T_1, t_1	10°C sec^{-1}, 1150°C, 300 sec
$\dot{T}_2$, T_2, t_2, ε_1, $\dot{\varepsilon}_1$	5°C sec^{-1}, 1100°C, 3sec, 0.3, 5 sec^{-1}
$\dot{T}_3$, T_3, t_3, ε_2, $\dot{\varepsilon}_2$	30°C sec^{-1}, 1000°C, 3 sec, 0.4, 10 sec^{-1}
$\dot{T}_4$, T_4, t_4, ε_3, $\dot{\varepsilon}_3$	50°C sec^{-1}, 900°C, 3 sec, 0.1, 0.3, 10 sec^{-1}
$\dot{T}_5$, T_{ROT}, t_{ROT}, $\dot{T}_6$	60°C sec^{-1}, 690 and 650°C, 5 and 10 sec, 100°C sec^{-1}

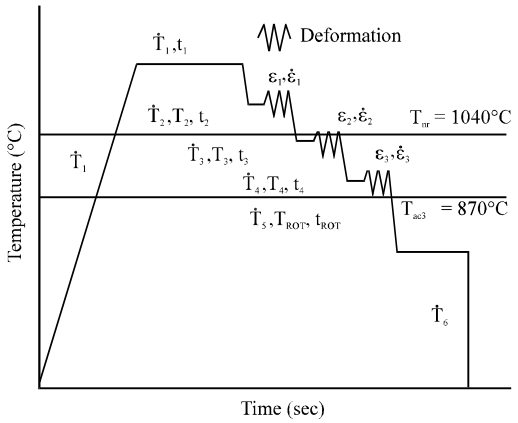

Fig. 3: Schematic diagram of heating cycle and test condition with deformation dilatometer

2010). The expression of ferrite formation is shown in Eq. 3. The symbol (u) describes the fraction of ferrite in maximum. The f_{eq} was obtained from ThermoCalc data and f was obtained from ferrite at constant holding temperature. The g_{f1} function which is related to the behavior of ferrite formation at holding temperature is shown in Eq. 4. The g_{f2} function which is related to the behavior of ferrite formation under deformation condition is shown in Eq. 5.

$$\dot{f}(t) = \left[f_{eq} - f\right]_{+} \times g_{f1}(T) \times g_{f2}\left(D_{\gamma}, \varepsilon\right) \tag{3}$$

$$g_{f1}(T) = \frac{\ln\dfrac{\left(f_{eq} - f(t_s)\right)}{\left(f_{eq} - f(t_E)\right)}}{\left(t_E - t_s\right)} \tag{4}$$

$$g_{f2}\left(D_{\gamma}, \varepsilon\right) = \alpha_1 S_v\left(D_{\gamma}, \varepsilon\right) + \alpha_2 \tag{5}$$

The S_v in g_{f2} function is a total effective nucleation area of ferrite. The S_v depending on austenite grain size and degree of deformationis shown in Eq. 6 (Nemethova *et al.*, 2010).

$$S_v = 429\frac{1}{D_{\gamma}e^{\varepsilon}} + 1571\frac{e^{\varepsilon}}{D_{\gamma}} + \left[157.2\left(1 - e^{-\varepsilon}\right) - 59.47\right]_{+} \text{mm}^{-1} \tag{6}$$

The austenite grain size after recrystallizationis shown in Eq. 7 (Suwanpinij *et al.*, 2010).

$$D\gamma = BD_0^{z}\varepsilon^{-p}\exp\left(-\frac{Q_{gx}}{RT}\right) \tag{7}$$

where, B = 100 $mm^{2/3}$. The Q_{gx} is recrystallization energy. The value of Q_{gx} is 28 kJ mol^{-1}. The parameter z and p are constants and the value of 1/3 and 0.37 were applied, respectively. The D_0 is the austenite grain size before recrystallization and $D_{\bar{a}}$ is the newly recrystallized austenite grain size.

To investigate the amount of ferrite formation from transformation of austenite, the specimen was heated up to 1150°C. Then, it was held at that temperature for a while in order to homogenized temperature. Then, the specimen was rapidly cooled. After that the sample was then heated up to 650-810°C and held for 15 min to determine ferrite fraction at any holding temperature.

RESULTS AND DISCUSSION

Ferrite formation temperature: After test with dilatometer, the microstructure of the specimen was subsequently analyzed with optical microscope equipped with image analyzer. Ferrite formation is diffusion transformation that needs time for transformation. The higher cooling rate reduced the formation of ferrite. The CCT diagram was made by plotting the starting point of transformation and the ending point of transformation at constant cooling rate. This data was obtained by using DIL 805 A/D. The change in length of test specimen during testing with dilatometer versus temperature was plotted as shown in Fig. 4. The specimen was cooled down to room temperature at constant cooling rate. During cooling, the specimen was shrunk with decreasing temperature. When the temperature of specimen reached to a point, the slope of diagram was change in the direction to expand the length of specimen. This turning point represent the so-called start transformation. The length of specimen was increased with decreasing temperature. Until a point, the specimen started to shrink again with decreasing temperature. This point of start to shrinkage of specimen during decreasing temperature is the so-called end transformation. Data of start and end of phase transformation would be used to plot in semi-logarithm scale diagram. Then draw a line to indicate the area of phase transformation.

The CCT diagram of the steel used in this study is shown in Fig. 5. It found that temperature of ferrite formation is 650-700°C. The maximum cooling rate of ferrite transformation is 40°C sec^{-1}. Time for transformation of ferrite in hot deformation for example in hot rolling should be <10 sec. Therefore, temperature for ferrite formation is in 650-700°C.

Volume fraction of ferrite: Investigated parameter in this study are deformation degree, holding time and holding

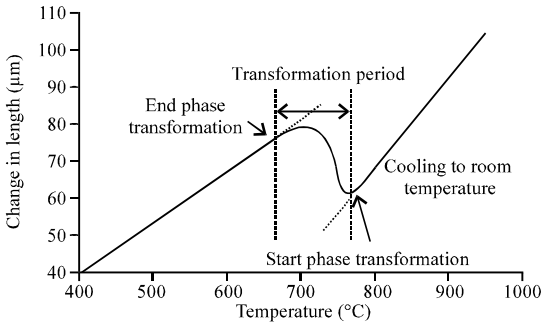

Fig. 4: Phase transformation at constant cooling

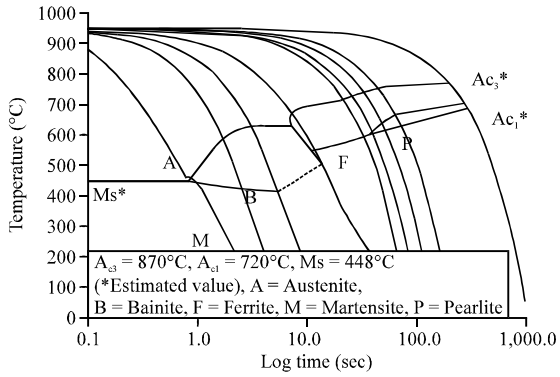

Fig. 5: CCT diagram of test steel used in this study

temperature. The deformation test was carried out by deformation dilatometer model DIL 805 A/D. The microstructure of test specimen was investigated by using optical microstructure equipped with image analyzer. The effect of holding temperature and holding time were shown in Fig. 6. The result showed that short holding temperature lead to increasing of volume fraction of ferrite. For long holding time the volume fraction of ferrite is tend to increase. Lower holding temperature acceleratesthe phase transformation rate and time is important for diffusion transformation of ferrite formation.

For increasing of deformation degree, volume fraction of ferrite obviously increased. The effect of deformation degree on volume fraction of ferrite is shown in Fig. 7. The result showed that increasing deformation degree increased the volume fraction of ferrite in all test conditions. This is due to the deformation in non-recrystallization increase nucleation site of ferrite formation and increase driving force for phase transformation of ferrite (Suwanpinij *et al*., 2009). The deformation degree in 0.3 and holding time in 10 sec obtain volume fraction of ferrite for >70%. This is a desirable condition for the production DP steel.

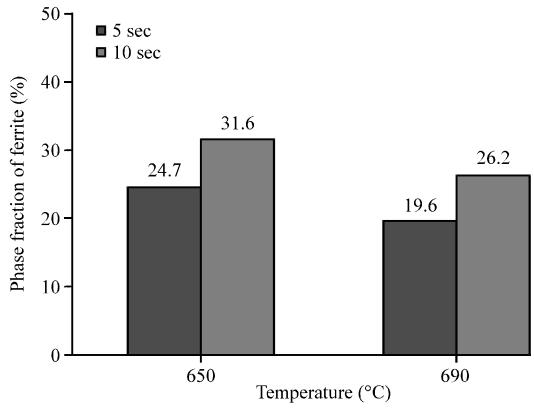

Fig. 6: Effect of holding temperature and holding time on volume fraction of ferrite

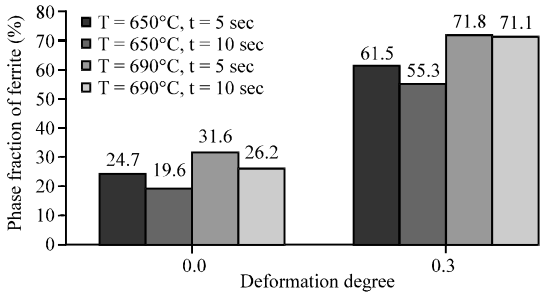

Fig. 7: Effect of deformation degree on volume fraction of ferrite

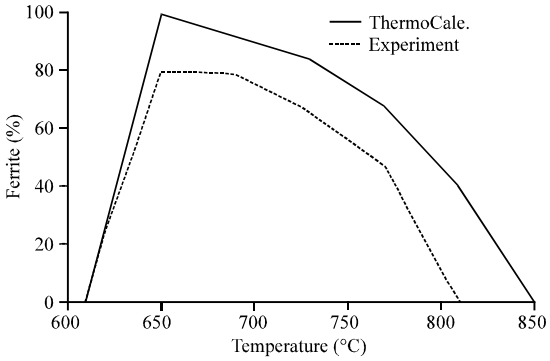

Fig. 8: The comparison of ferrite fraction between experiment and ThermoCalc data

Processing map to predict ferrite formation: The ferrite formation model was used to predict volume fraction of ferrite. The fraction of ferrite in holding temperature was plotted in comparison with ferrite fraction from ThermoCalc data as show in Fig. 8. The result showed that volume fraction of ferrite decrease when holding temperature

increase. The ferrite fraction was obtained from the experiment lower than ThermoCalc data. So in the experiment, the diffusion is incomplete. These data was used for determination of $[u]_+$ and g_{fl} function.

The austenite grain size in 1150°C was determined by experiment. The austenite grains size before recrystallize is 118 μm. The austenite grain size after recrystallization was computed by Eq. 7. The result showed that austenite grains size after recrystallization is 66 μm. The S_v value was computed by using Eq. 6. The S_v function was shown in Fig. 9. The total effective nucleation are S_v, depend on austenite grain size anddegree of deformation. The result showed that fine austenite grain increased S_v value. Increasing deformation degree effect on S_v value obviously. The ferrite formation was calculated by Eq. 3. The result of ferrite formation was plotted at a constant holding time. This diagram is called "Processing map". The deformation degree and temperature is in x and y axis, respectively. The line in processing map is ferrite fraction.

The processing map of holding time of 5 sec^{-1} on ferrite formation is shown in Fig. 10a. The result showed that lower holding temperature can reduce deformation degree for induce ferrite formation. Increasing holding temperature decreased ferrite formation. Increasing deformation degree induced ferrite formation. Effect of holding time of 10 sec on ferrite formation is shown in Fig. 10b. The result showed that increasing holding time increased the area of ferrite formation and reduced deformation degree for ferrite formation.

The holding temperature below 650°C showed that ferrite formation was reduced when increasing of the deformation degree. This is because of the

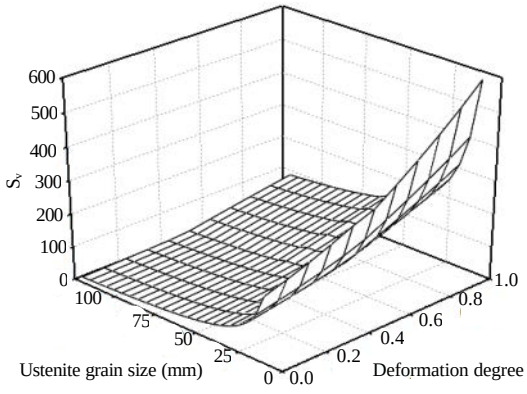

Fig. 9: The S_v austenite grain size as a function of deformation degree

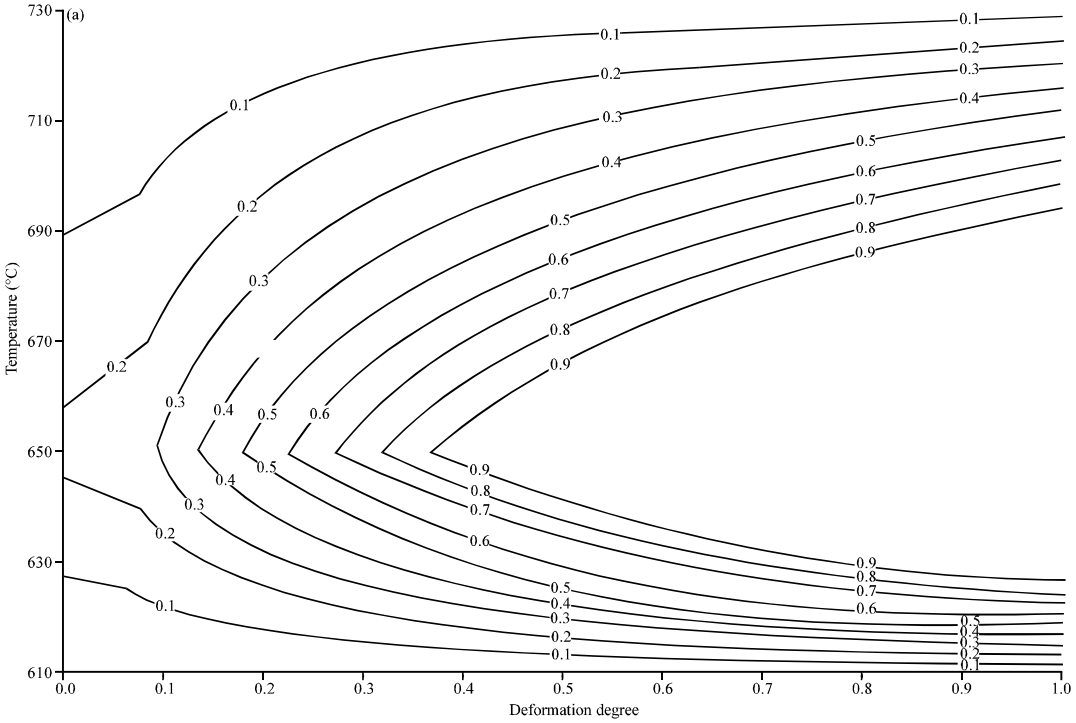

Fig. 10: Continue

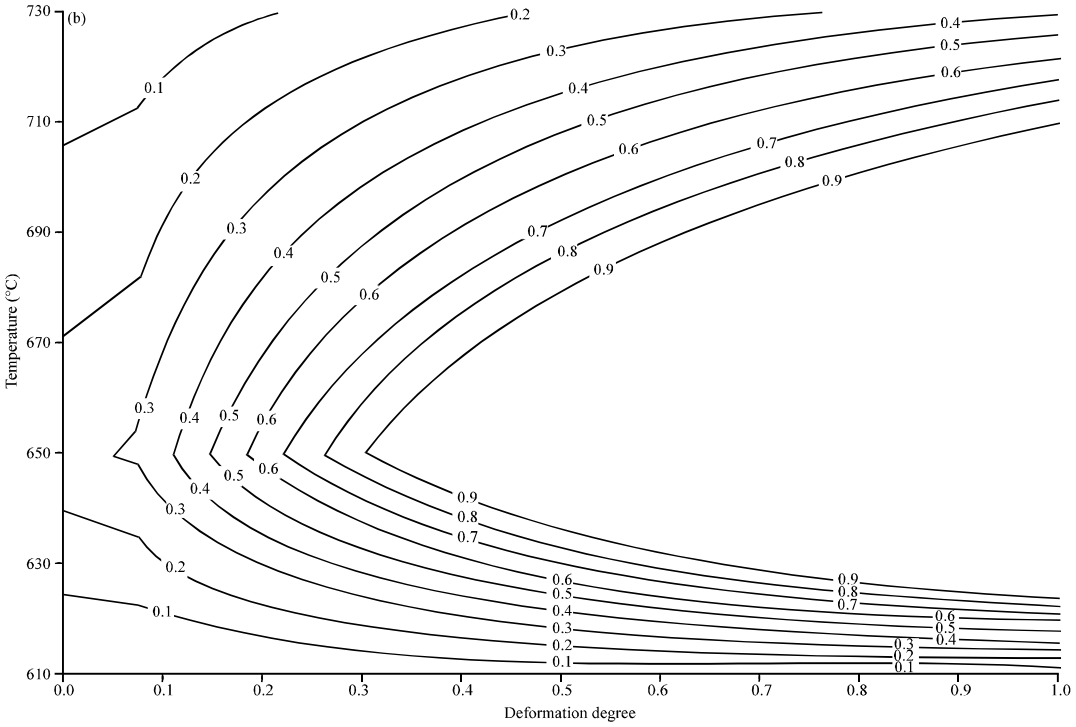

Fig. 10: Processing map of ferrite formation in: a) 5 sec ; b) 10 sec

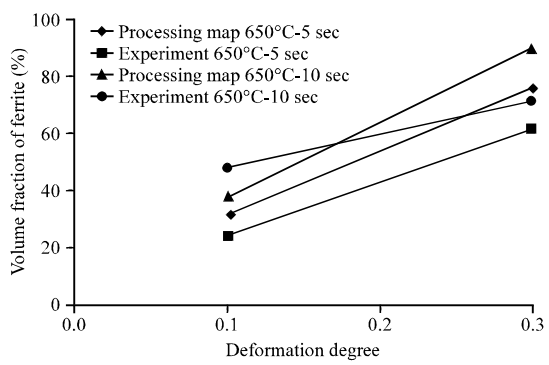

Fig. 11: The comparison ferrite fraction was obtain from processing map and experiment as holding temperature 650°C

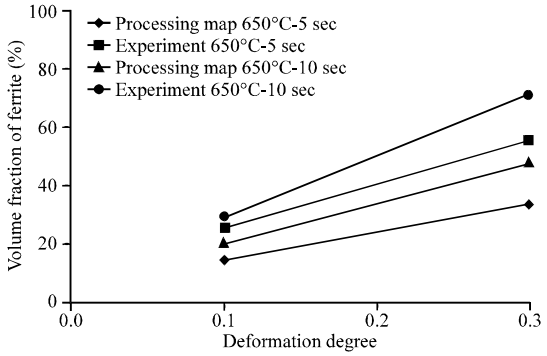

Fig. 12: Comparison ferrite fraction was obtain from processing map and experiment as holding temperature 690°C

formation of bainite in lower holding temperature. Therefore, the ferrite fraction from the experiment and processing map are shown in Fig. 11 and 12. It found that comparative results obtained from hot deformation like hot rolling simulationusing deformation dilatometer and the calculated results using a mathematical model showed similar trends of hot rolling parameter.

CONCLUSION

In this study, the fraction of ferrite formation during hot deformation of low carbon steel is investigated using deformation dilatometer that considers the effects of deformation degree and deformation temperature and the conclusions are as follow:

- The CCT diagram of carbon steel containing manganese and niobium indicated that the range of ferrite formation temperature is in between 650 and 700°C

- Increasing deformation degree increased volume fraction of ferrite. This was due to the increasing deformation degree that lead to increasing the nucleation site of ferrite and also affected grain refinement of ferrite
- Comparative results obtained from hot rolling simulation using deformation dilatometer and the calculated results using a mathematical model showed similar trends of hot rolling parameter influences on ferrite formation and also shared comparable values

REFERENCES

Asadi, A.M., M. Goodarzi and S. Kheirandish, 2008. Kinetics of Austenite Formation in Dual Phase Steels. ISIJ Int., 48: 1251-1255.

Kuziak, R., R. Kawalla and S. Waengler, 2008. Advanced High Strength Steels for Automotive Industry: a Review, 8: 103-117.

Nemethova, L., T. Kvackaj, M Fujda., R. Misicko, J. Tiza and M. Kvackaj, 2010. Austenite Grain Size Change of Nb-V Steel in Dependence on Controlled Rolling Conditions. Acta Metall. Slovaca, 16 (2): 102-108.

Niakan, H. and A. Najafizadeh, 2010. Effect of Niobium and Rolling Parameters on the Mechanical Properties and Microstructure of dual Phase Steels. Materials Science and Engineering A., 527 (21-22): 5410-5414.

Suwanpinij, P., J. Rudnizki, U. Prahl and W. Bleck, 2009. Investigation of the Effect of Deformation on γ-α Phase Transformation Kinetics in Hot-Rolled Dual Phase Steel by Phase Field Approach. Steel Rest. Int., 80 (9): 616-622.

Suwanpinij, P., N. Togobytska, U. Prahl, W. Weiss, D. Homberg and W. Bleck, 2010. Numerical Cooling Strategy Design for Hot Rolled Dual Phase Steel. Steel Res. Int., 81 (11): 1001-1009.

Wang, W., M. Li, C. He, X. Wei, D. Wang and H. Du, 2010. Experimental Study on High Strain Rate Behavior of High Strength 600-1000 MPa dual Phase Steels and 1200 MPa fully Martensitic Steels. Materials and Design, 47: 510-521.