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MATHEMATICAL MODELING FOR 34CrMo4 STEEL DURING HOT COMPRESSION

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Abstract

In this investigation, hot compression tests were performed at 900 °C−1100 °C and strain rate of 0.001−0.1 s^{-1} to study hot deformation behavior and flow stress model of 34CrMo4 steel. Based on Zener–Hollomon parameter in a hyperbolic sinusoidal equation form, the flow stress curves are predicted for 34CrMo4 steel. The polynomial fitting results are used. The validity of the model was demonstrated by comparing the experimental data with the numerical results. The predicted stress–strain curves are in a very good agreement with those obtained experimentally, both illustrating the occurrence of dynamic recrystallization. Also, in both cases, the peak and steady-state stresses raised with decreasing temperature and increasing strain rate.
Key words: Hot compression test; 34CrMo4 steel; Dynamic recrystallization; Mathematical model

Introduction

During hot rolling, forging and forming several metallurgical phenomena such as work hardening (WH), dynamic recovery (DRV), and dynamic recrystallization (DRX) occur simultaneously.

It is very important to understand the flow stress behavior and changes of microstructures during hot working to achieve desired mechanical properties after deformation. Some researches [1-7] have been done on microstructure evolution during hot deformation and mechanical characteristics in hot deformation. Moreover, many researchers have studied different models for predicting material behaviors. For instances hot steel behavior was described by the use of Avrami equations [8-11].On the other hand, the constitutive equations have been utilized in several papers for different

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materials [12,13]. In this article, the constitutive equations have been applied and they have been used to predict the flow stress of 34CrMo4 in elevated temperatures.

According to the US Department of Transportation (DOT) specifications 3AA [14], there are different steels authorized for the manufacturing of on-board compressed natural gas (CNG) cylinders in vehicles. One of the main characteristics of these cylinders is exhibiting leak-before-break behavior and several works have been dedicated to optimize their material performance as well as their fabrication methods [15-21]. Hot deformation is among the widely used methods in manufacturing of natural gas cylinders. Because the process for producing natural gas cylinder is a commonly hot tube spinning method, so in this research the modeling for elevated temperature flow behavior has been proposed. Mechanical behaviors of this steel have been investigated [22-24], but mathematical modeling of hot deformation behavior in this alloy has not been studied yet.

Experimental

For studying the hot deformation behavior of 34CrMo4 steel, hot compression experiments were considered. The compression specimens were machined in cylindrical shape with height to diameter ratio of 1.5 and the height of 15mm. This ratio was used in several works to ensure a homogenous deformation. Usually the barreling is more effective at very high strains. So, the reduction in height has been chosen 60% (true strain: 0.9) at the end of the compression tests to avoid barreling, as was used earlier [25-27]. Graphite was used to minimize the friction and barreling [26-31]. To achieve the same metallurgical history for all specimens, they were annealed at 900 ˚C for 1hour. Hot compression tests were conducted under isothermal condition at three different strain rates of 0.001, 0.01 and 0.1s^{-1} and at temperatures of 900, 1000, and 1100 °C. All specimens were heated up to 1150 °C and hold for 15min and then cooled to the deformation temperature at which it was held for 4min to eliminate the thermal gradient before deformation, and then the samples were deformed to total true strain of 0.9. The hot compression tests were conducted through a controllable furnace adapted on tensile test machine. The chemical composition of the 34CrMo4 alloy chosen for the present study is listed in Table 1.

Table 1. composition of the materials used in this study.

Element	Wt%
C	0.33
Mn	0.67
Si	0.32
Cr	1.00
Mo	0.21
S	≤0.01
P	≤0.01
Cu	≤0.16

Results and Discussion

Experimental stress-Strain curves obtained at various temperatures and strain rates are reported previously [11]. The effects of temperature and strain rate on flow stress have been thoroughly analyzed in that paper.

Constitutive equations of flow stress for 34CrMo4 steel

Constitutive equations can be used to predict the value of the stress during hot deformation. In order to study the deformation behavior of employed alloy at elevated temperatures, constitutive equations proposed by Zener and Hollomon, have been used [32-35]:

$$Z = \varepsilon^{\circ} \exp(\frac{Q}{RT}) = AF(\sigma) \quad (1)$$

Therefore:

$$\varepsilon^{\circ} = AF(\sigma)\exp(\frac{-Q}{RT}) \quad (2)$$

In this research Z, is Zener-Holloman parameter, Q the apparent activation for hot deformation, A material constant and $F(\sigma)$ is function of flow stress which can be described as follow:

$$F(\sigma) = A_1\sigma^n \qquad \textit{For low stress,} \quad (3)$$

$$F(\sigma) = A_2\exp(\beta\sigma) \qquad \textit{For high stress,} \quad (4)$$

$$F(\sigma) = A_3[\sinh(\alpha\sigma)]^n \qquad \textit{For all stress levels} \quad (5)$$

Substituting function of flow stress ($F(\sigma)$) into Eqs.(2) respectively gives:

$$\varepsilon^{\circ} = B_1\sigma^n \exp(\frac{-Q}{RT}) \qquad \textit{For low stress,} \quad (6)$$

$$\varepsilon^{\circ} = B_2\exp(\beta\sigma)\exp(\frac{-Q}{RT}) \qquad \textit{For high stress,} \quad (7)$$

$$\varepsilon^{\circ} = B_3[\sinh(\alpha\sigma)]^n \exp(\frac{-Q}{RT}) \qquad \textit{For all stress levels,} \quad (8)$$

Here B_1, B_2 and B_3 are the material constants, Taking the logarithm of eqs. (6) and (7), gives:

$$\ln(\varepsilon^{\circ}) = n\ln(\sigma) + \ln(B_1) - \frac{Q}{RT} \quad (9)$$

$$\ln(\varepsilon^{\circ}) = \beta\sigma + \ln(B_2) - \frac{Q}{RT} \quad (10)$$

Therefore:

$$\left(\frac{\partial \ln(\varepsilon^{\circ})}{\partial \ln(\sigma_P)}\right)_T = n \tag{11}$$

$$\left(\frac{\partial \ln(\varepsilon^{\circ})}{\partial \sigma_P}\right)_T = \beta \tag{12}$$

Which are independent of deformed temperatures, also α and β are related to each other:

$$\alpha = \frac{\beta}{n} \tag{13}$$

The values of n and β can be obtained from the lines slope in $\ln(\varepsilon^{\circ})$ - $\ln(\sigma)$ and $\ln(\varepsilon^{\circ})$ - σ plots, respectively. Equation (8) can be written:

$$n\{\ln[\sinh(\alpha\sigma_P)]\} = \ln(\varepsilon^{\circ}) + \frac{Q}{RT} - \ln(B_3) \tag{14}$$

For the given strain rate conditions, differentiating of Eq. (14) gives:

$$Q = Rn\left(\frac{d\{\ln[\sinh(\alpha\sigma_p)]\}}{d\left(\frac{1}{T}\right)}\right)_{\varepsilon^{o}} \tag{15}$$

The value of Q is obtained from the lines slope of $\ln(\varepsilon^{\circ})$ – $\ln[\sinh(\alpha\sigma_P)]$ and $\ln[\sinh(\alpha\sigma_P)]$ – 1/T plots. Moreover, the flow stress can be written as a function of Zener–Hollomon parameter, considering the definition of the hyperbolic law:

$$\sigma = \frac{1}{\alpha}\ln[(\frac{Z}{A})^{1/n} + \sqrt{(\frac{Z}{A})^{2/n} + 1}] \tag{16}$$

Also:

$$Z = \varepsilon^{\circ}\exp(\frac{Q}{RT}) = A[\sinh(\alpha\sigma)]^{n} \tag{17}$$

Then, Z value can now be predicted by substituting Q and the amounts of other deformation parameters into Eq. (17).Therefore, the values of material constants (Q, A, β , n and α) of the constitutive equations were computed under different deformation strains within the range of 0.05–0.9 and the interval of 0.05. The relationships among the true strain with n, α , Q and Ln A for 34CrMo4 are illustrated in Fig.1.

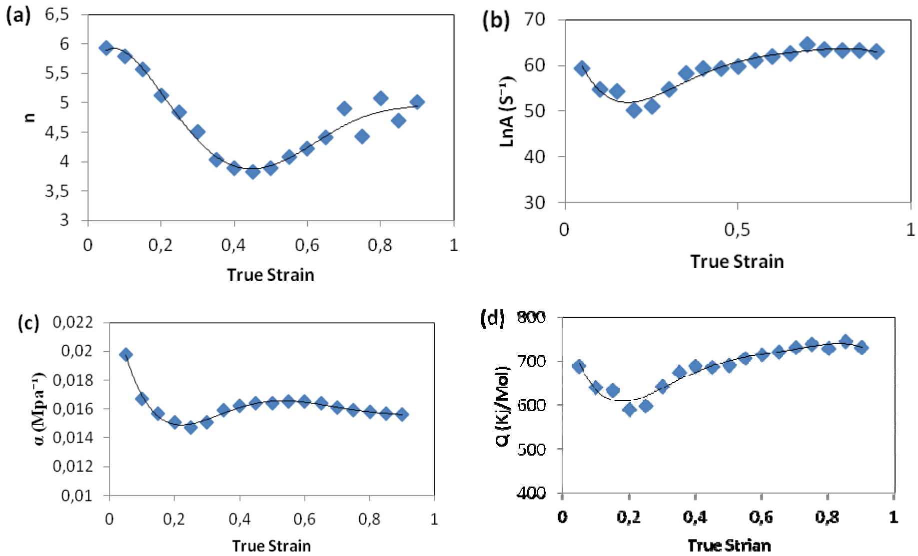

Fig.1. Relationships between: (a) n; (b) Ln A; (c) α ; (d) Q and true strain by polynomial fit of 34CrMo4 alloy.

Also, they can be presented as polynomial fitted by the compensation of strain, as shown in Eq. (18). The polynomial fitting results for n, α , Q and Ln A regarding the investigated alloy are summarized in table2.

$$\alpha = B_0 + B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3 + B_4\varepsilon^4 + B_5\varepsilon^5$$

$$Q = C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\varepsilon^3 + C_4\varepsilon^4 + C_5\varepsilon^5$$

$$\ln A = D_0 + D_1\varepsilon + D_2\varepsilon^2 + D_3\varepsilon^3 + D_4\varepsilon^4 + D_5\varepsilon^5$$

$$n = E_0 + E_1\varepsilon + E_2\varepsilon^2 + E_3\varepsilon^3 + E_4\varepsilon^4 + E_5\varepsilon^5 \quad (18)$$

Table 2. Polynomial fitting results for α , n,Q and Ln A.

α	n	Q	LnA
B_o 0.024	E_o 5.462	C_o 807.712	D_o 69.252
B_1 -0.117	E_1 14.464	C_1 -2884.772	D_1 -241.507
B_2 0.507	E_2 -134.503	C_2 14288.664	D_2 1148.323
B_3 -0.949	E_3 337.309	C_3 -29229.600	D_3 -2230.151
B_4 0.807	E_4 -336.106	C_4 27669.426	D_4 2018.785
B_5 -0.258	E_5 118.598	C_5 -9989.588	D_5 -708.05

Flow stress model

The constants, summarized in Table 2, are substituted into the Eqs. (16), (17) and (18), to predict the flow behavior of 34CrMo4 alloy.

The stress–strain curves predicted by the model at different temperatures and strain rates are illustrated in Fig. 2.

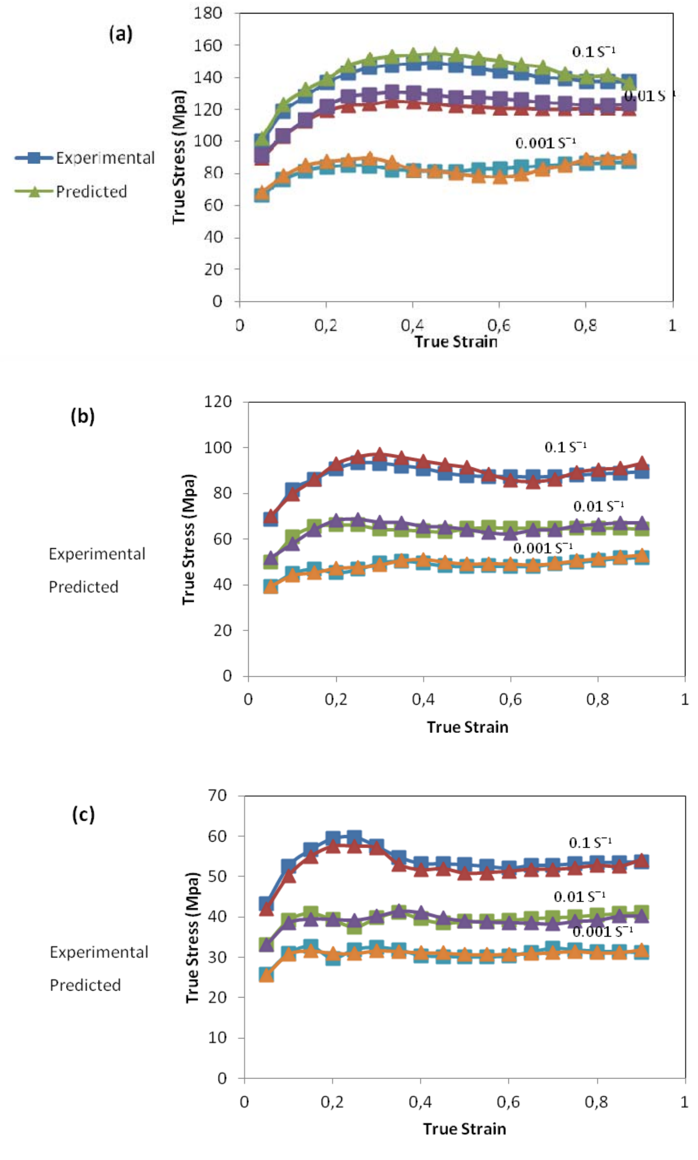

Fig.2. Comparisons between predicted and experimental flow stress curves of 34CrMo4 alloy under different strain rates and deformation temperatures of: (a) 900°C; (b) 1000 °C; (c) 1100°C.

Verification of the Constitutive modeling

In order to verify the above-developed constitutive equation of 34CrMo4 steel at elevated temperatures a comparison between the experimental and predicted results was carried out. A good agreement obtained between the predicted flow stress curves and the true stress–strain curves from the hot-compression. (Fig.2) The model can give good description of stress-strain curves in the range of strain rate and temperature examined. Moreover, this methodology is expected to be applicable for predicting flow stress curves for deformation conditions outside the experimental window. Since the deformation conditions bring in the evolution equation through the Zener-Hollomon parameter, the flow stress behavior can be predicted in the entire domain where the apparent activation energy for hot working is the same.

In order to evaluate the accuracy of the constitutive modeling, the errors between the predicted stress (σ_M) and experimental stress (σ_E) were also calculated as

$$E(\%) = \frac{\sigma_M - \sigma_E}{\sigma_E} \times 100 \qquad (19)$$

A comparison between the experimental and predicted stress by Eq. (17) is carried out. It was seen that the highest error value was less than 5%. The proposed model gives an accurate and precise estimate of the flow stress for 34CrMo4 steel, and can be used to analyze the problems during metal forming process. The mathematical modeling of stress-strain curves precisely predicts the experimental hot deformation behavior of 34CrMo4 steel. Moreover, the multiple peak stress, due to multiple cycles of DRX, has been predicted more accurately.

Conclusions

Hot compression experiments have been performed on 34CrMo4 steel in the temperature range of 900-1100˚C and the strain rate range of 0.001-0.1 s^{-1}. Based on experimental stress–strain data, a constitutive equation incorporating the effects of temperature, strain rate and work-hardening rate of the material is derived by compensation of strain. Comparisons between the experimental and predicted results were carried out and confirmed that the proposed deformation constitutive equations give an accurate model. Also, the errors between the predicted stress (σ_M) and experimental stress (σ_E) were calculated. The highest error was found less than 5%. So, it is expected to be applicable for predicting flow stress curves where the apparent activation energy for hot working is the same. The proposed mathematical model predict multiple cycles of DRX of 34CrMo4 accurately.

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References

[1] J.J. Jonas: *Acta Metallurgical*, 1969, 17, 397.
[2] J. J. Jonas et al., *Acta Mater*., 2009, 57, 2748.
[3] M. Raghavan and E. Shapiro, *Metallurgical Transaction A*, 1980, 11A, 1 17.

[4] Lin Zhang, Caibie Zhang, *Journal of Materials Science and Technology*, 2002, 18, 163.

[5] B.X. Wang, X.H. Liu, G.D. Wang, *Materials Science Eng*ineering A, 2005, 393, 102.

[6] Y.C. Lin, Ming-Song Chen, Jue Zhong, *Materials Letters*, 2008, 62, 2132.

[7] HJ. McQueen, ND. Ryan, E. Evangelista, *Materials Science Forum*. 1993; 113-115:435.

[8] A. Laasraoui, J.J. Jonas, *Metallurgical Transaction A*, 1991, 22, 1545.

[9] Estrin, Y., Mecking, H., *Acta Metallurgical*, 1984, 32, 57.

[10] Byoung Ho Lee, N.S. Reddy, Jong Taek Yeom, Chong Soo Lee, *Journal of Materials Processing Technology*, 2007, 187–188, 766.

[11] S.V. Sajadifar, M. ketabchi, M. Nourani, *Steel Research International*, DOI: 10.1002/srin.201100024.

[12]]Y.C. Lin, M.-S. Chen, J. Zhong, *Computational Materials Science*, 2008, 42 (3) 470.

[13] A.A. Khamei, K. Dehghani, *Journal of Alloys and Compounds*, 2010, 490, 377.

[14] Department of Transportation. Research and Special Programs Admin. Specifications for Packagings: Specification 3AA and 3AAX seamless steel cylinders (ed. 2004). Available at: http://edocket.access.gpo.gov/cfr_2004/octqtr/pdf/49cfr178.37.pdf (Accessed on: March 2, 2011).

[15] Rana, M.D., Selines, R.J. High strength steel and gas storage cylinder manufactured thereof. US4461657 (1984).

[16] Rana, M.D., Selines, R.J. High strength steel. US4578113 (1986).

[17] Hong, S.T., Jang, S.H., Bang, K.H. High tensile steel for deep drawing and manufacturing method thereof. US20100236672 (2010).

[18] Stading, R.C. Method of fabrication a high pressure tank. US4364161 (1982).

[19] Sakaguchi, T., Sakaguchi, Y. High-pressure tank and method for fabricating the same. US6886711 (2005).

[20] Sakaguchi, T., Sakaguchi, Y., Hogan, S.C. High-pressure tank and method for fabricating the same. US20067137526 (2006).

[21] Yang, K.J. Method of fabricating high-pressure gas cylinder. US20070294874 (2007).

[22] A.T. Wilde, *Journal of Magnetism and Magnetic Materials*,2006, 300, L257.

[23] P. S. Song, Y. L. Shieh, *Engineering Fracture Mechanics*,2004, 71, 1577.

[24] K. M. Rajan et al., *Journal of materials Processing Technology*, 2002, 125-126, 503.

[25] E. I. Poliak, J. J. Jonas, *ISIJ International*, 2003, 43, 684.

[26] K. Dehghani, and A. A. Khamei, *Materials Science and Engineering* A, DOI: 10.1016/j.msea.2009.08.059.

[27] R. Ebrahimi, and A. Najafizadeh: *International Journal of ISSI*, 2004, 1, 1.

[28] Yong Niu, Miaoquan Li, Hongliang Hou, Yaoqi Wang, and Yingying Lin, *Journal of Materials Engineering and Performance*, 2010, 19(1), 59.

[29] S. Hotta, T. Murakami, T. Narushima, Y. Iguchi, C. Ouchi, *ISIJ International*, 2005, 45, 338.

[30] M. El Wahabi, J. M. Cabrera, J. M. Prado, *Materials Science and Engineering*, 2003, A343, 116.

[31] Yi. Liu, Rui. Hu, Jinshan. Li, Hongchao. Kou, Hongwei. Li, Hui. Chang, Hengzhi. Fu, *Materials Science and Engineering A*, 2008, 497, 238.
[32] F. J. Humphreys, and M. Hatherly: 1996, 1st ed., Pergamon, Oxford, United Kingdom.
[33] C. M. Sellars, and C. H. J. Davis, eds., 1979, the Metals Society, London.
[34] J. J. Jonas et al, Int. Met. Rev.,1969, 14, 1–24.
[35] C. M. Sellars: Czech. J. Phy., 1985, 35, 239.