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Hot Deformation Behavior of High Strength Low Alloy Steel by Thermo Mechanical Simulator and Finite Element Method

Kingkam W [1], Li N[1], Zhang H X[1, 2] and Zhao C Z[1, 2]

[1]College of Materials Science and Chemical Engineering, Harbin Engineering University, Harbin 150001, China
[2]Key Laboratory of Superlight Materials and Surface Technology, Ministry of Education
E-mail: zhaochengzhi@hrbeu.edu.cn

Abstract. The hot deformation behavior of HSLA steel was investigated by using a MMS-200 thermal mechanical machine at different conditions and with deformation temperature of 800-1100 ^{o}C and strain rate of 0.1-10 S^{-1}. FEM was analyzed the deformation characteristics of hot compression through Deform-3D software. It was discovered that the flow stress increases with increasing strain rate and decreasing temperature. The activation energy and stress exponent during hot deformation were calculated using hyperbolic sine constitutive equations. The result from the experiment represents the activation energy and stress exponent during hot compression of 222.256 kJ/mol. and 10.84. The prediction of distribution stress values from the constitutive equation in Deform-3D can be matched with the experimental results.

1. Introduction

High strength low alloy steel (HSLA) is a type of steel widely used for structural construction. Steels with low carbon content and very small additions of strong carbide or carbonitride forming elements such as Nb, V, and Ti to strengthening precipitation and grain refinement are called microalloyed or high strength low alloy steel [1]. These steels are much stronger and tougher than ordinary carbon steels, more ductile, highly formable, weldable and highly resistant to corrosion. Nowadays, HSLA steel has been improved with suitable chemical composition and thermo mechanical treatment in order to reinforce its application in heavy industries and automotive.

Recently, HSLA steel has been investigated for several features, including its hot deformation behaviors. Hot deformation process is necessary to improve the effectiveness of HSLA steel. With the increasing use of FEM (finite element method) to simulate the specimen behavior under the various parameter of compression test. The relationships between the constitutive equation and the relating process variables such as strain rate and temperature to the flow stress of the deforming material is required, and it is important to calculate the flow stress[2]. Flow stress can be defined as the resistance of a material against plastic deformation and it is expressed as a function of temperature, strain, and strain rate. Hence, FEM technique provides an effective approach for evaluating and determining the distribution and variation of thermo mechanical parameters in deformed specimens during hot working [3,4].

In this paper, the influence of characteristic hot deformation behavior of HSLA steel during compression test at different temperature and strain rate will be investigated. The general constitutive equations were used to determine the hot deformation constants of the material from experimental studies. In addition, the numerical analysis was carried out by Deform-3D simulation of the deformation characteristics in the hot compression process.

2. Experimental

The HSLA steel casting ingot was used for investigating this experiment. The chemical composition of HSLA steel is shown in Table 1.

Table 1. Chemical composition of High strength low alloy steels (wt%)

C	Si	Mn	Cr	Mo	Ni	Al	Cu	Nb	Ti	V
0.0031	0.151	0.766	0.190	0.136	0.517	0.0243	0.365	0.0408	0.0020	0.0145

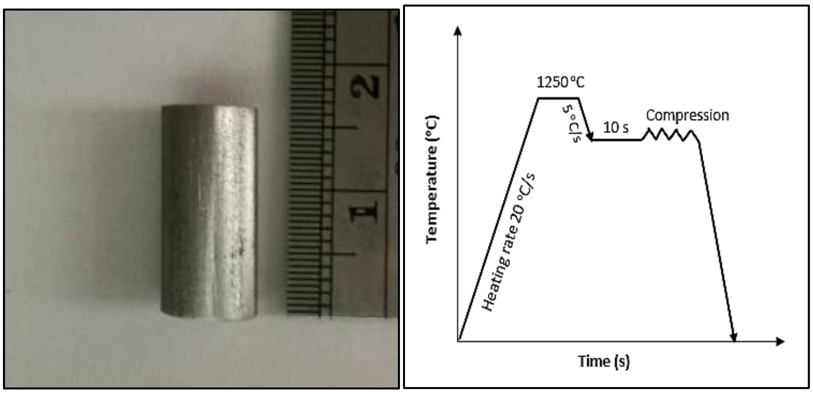

Figure 1. The cylindrical specimen and schematic of the hot compression test

Figure 2. MMS-200 thermal-mechanical simulator

The cylindrical specimens were machined with 8 mm in diameter and 15 mm in height. Hot compression test was performed by MMS-200 thermal-mechanical simulator. The specimens were heated from room temperature to 1250 °C at a heating rate of 20 °C/s for 5 min and then cooled to a deformation temperature with cooling rate 5 °C/s. After holding for 10 s. Compression deformation temperatures were conducted at 800, 900 and 1100 ℃ , respectively with different strain rates from 0.1, 1 to10 s^{-1}.The cylindrical specimens and schematic of hot compression experiment as shown in Figure.1 and Figure.3 shows the specimens after the hot compression test.

Finite element method (FEM) simulate the hot compression process was performed using the above true stress-strain data, and modify the true stress-strain data based on the difference value of resulting FEM load-displacement data and that of experimental. FEM to simulate the hot compression process was performed using the modified true stress-strain data again and recalculated the difference value of resulting the experimental data. Repeat the process till the entire match. Finite element simulation of the above hot compression has been performed using a commercial software package Deform-3D.

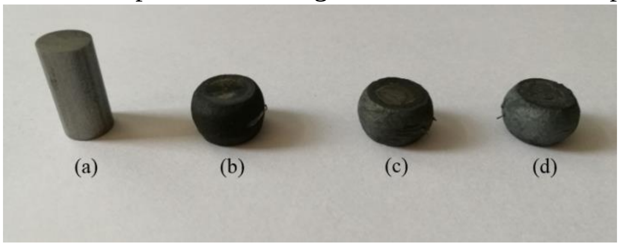

Figure 3. Specimens after hot compression test under different temperature at strain rate 1 s^{-1}
(a) Original specimen, (b) 800 ^oC, (b) 900 ^oC and (c) 1100 ^oC

3. Results and Discussion

3.1 Stress-strain curves

The experimental studies of the true stress-strain curves for HSLA steel deformed at different deformation temperature and strain rate up to a height reduction of 50% are shown in figure.4.The flow stress curve shows the different strain rate at temperature 800 ^oC, it can be observed that the strain peaks increases with the elevating strain rate. Dynamic recrystallization phenomenon occurred at strain rate 0.1 s^{-1} and dynamic recovery occurred when the strain rate is 1 and 10 ^oC

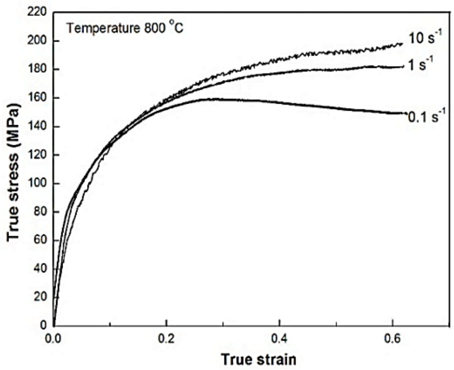

Figure 4. True stress-strain curve for different strain rate at deformation temperature 800 ^oC

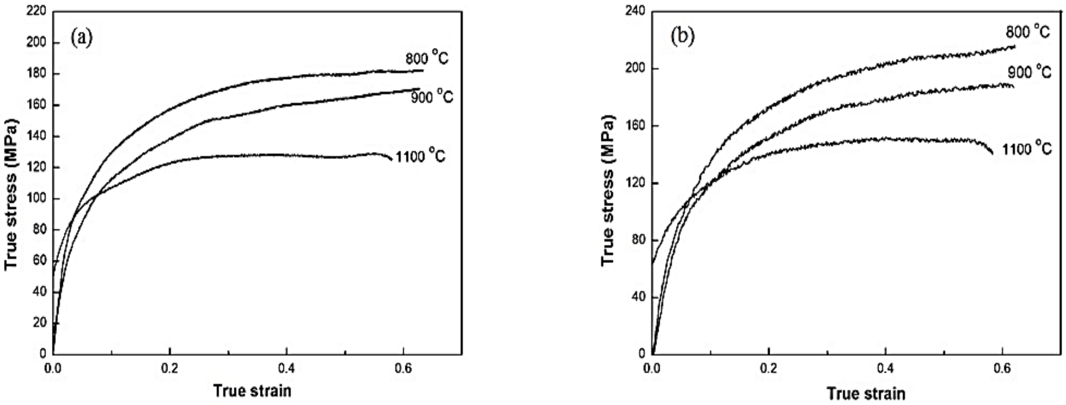

Figure 5. True stress-strain curve at different deformation temperature and strain rate
(a) 1 s^{-1} and (b) 10 s^{-1}

Figure 5. shows the stress-strain curve at different deformation temperature and at strain rate 1 s^{-1} and 10 s^{-1}, it can be observed that the deformation temperature and strain rate have significant effect on the flow stress under all of the conditions tested. The true stress-strain curves exhibit a slightly lower value in flow-stress after obtaining the peak stress. It can also be observed that the flow stress and strain increases with decreasing deformation temperature because the dynamic softening dominates work hardening at higher temperatures [5, 6]. Subsequently, the flow stress curves continuously decreases until a balance with work hardening is achieved and shows dynamic softening. The stress value decreases with increasing deformation temperature, this is because the higher temperatures and lower strain rates provides a longer time for energy accumulation, higher mobilities at boundaries for the nucleation and dynamically recrystallized grains to grow [7]

3.2 Constitutive equation of hot deformation

Constitutive equations usually describe the relation between flow stress and flow strain under different strain rate and temperature. The flow stress-strain data obtained from experimental and can be used to determine the materials constantly. The relationship between the flow stress (σ), temperature (T) and strain rate $(\dot{\varepsilon})$ is expressed by hyperbolic sine function form of the Arrhenius type equation. The effects of strain rate and temperature plastic deformation behavior could be demonstrated by Zener-Holloman parameter [8-10]. In hot deformation, several constitutive equations have commonly been applied by Eq.(1) and (2).

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) \tag{1}$$

$$\dot{\varepsilon} = AF(\sigma) \exp\left(-\frac{Q}{RT}\right) \tag{2}$$

$$\text{Where, } F(\sigma) = \begin{cases} \sigma^n & \alpha\sigma < 8 \\ \exp(\beta\sigma) & \alpha\sigma > 1.2 < 0.8 \\ [\sinh(\alpha\sigma)]^n & all\,\sigma \end{cases}$$

where $\dot{\varepsilon}$ is the strain rate (s^{-1}); Z is the Zener-Holloman parameter; Q is the activation energy of hot deformation (kJ mol^{-1}); R is the gas constant (8.314 J mol^{-1} K^{-1}), T is the absolute temperature (K), σ is the peak stress (MPa) A, α, and n are the materials constants.

The correlation between strain rate and temperature can be expressed by parameter Z as follows.

$$Z = \dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = A[\sinh(\alpha\sigma)]^n \tag{3}$$

Where, Z is the factor of strain rate of compensated with temperature, $\alpha = \beta / n$ α MPa^{-1}, n and β are the constant.

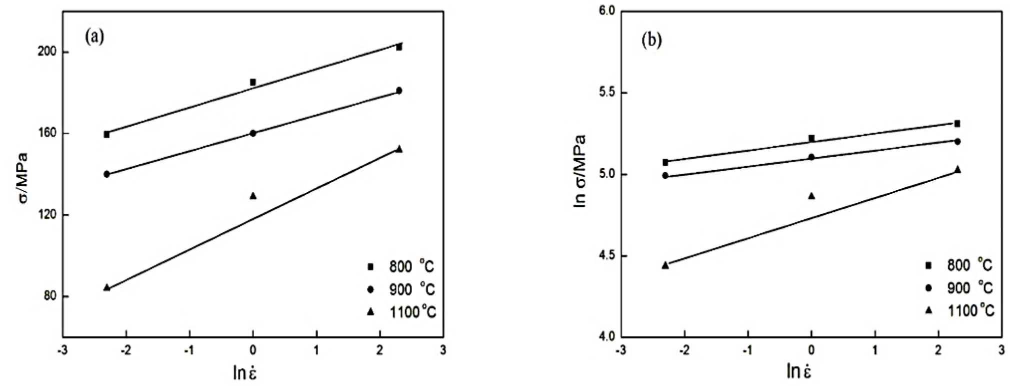

Figure 6. Relationship between strain rate and peak stress (a) ln ε̇-σ and (b) ln ε̇- ln σ

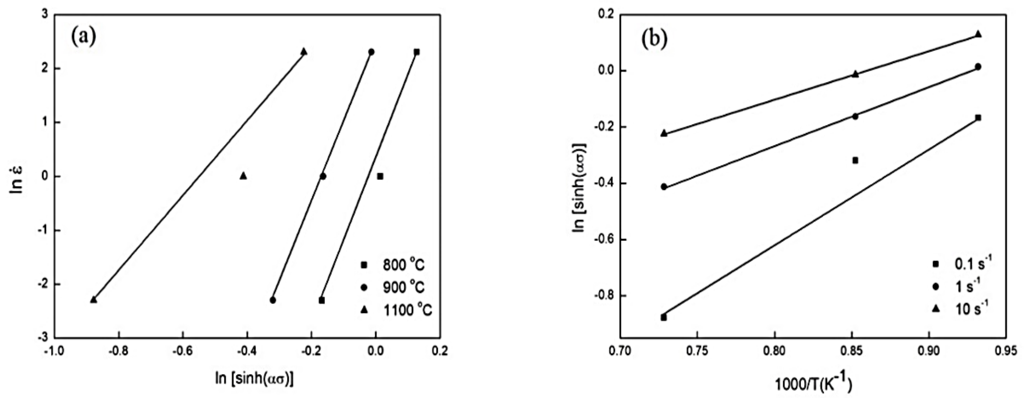

Figure 7. Relationship between (a) $\ln[\sinh(\alpha\sigma)]$- ln ε̇ and (b) $\ln[\sinh(\alpha\sigma)]$-T

The ln ε̇-ln σ and ln ε̇-σ could be obtained when taken logarithm on Eq. (3), especially the temperature is constant. For determining the values of Q, A and α, two parameters n_1 and β was given by Eq.(4) and Eq. (5).

$$n_1 = \left(\frac{\partial \ln \dot{\varepsilon}}{\partial \ln \sigma}\right)_T \tag{4}$$

$$\beta = \left(\frac{\partial \ln \dot{\varepsilon}}{\partial \sigma}\right)_T \tag{5}$$

$$n = \left(\frac{\partial \ln \dot{\varepsilon}}{\partial \ln[\sinh(\alpha\sigma)]}\right)_T \tag{6}$$

According to Eq. (4) and (5), the linear relationship between ln ε̇-ln σ and ln ε̇-σ are shown in Figure.6. The slope are calculated by using the least squares method of linear regression and take slopes reciprocal and averaging with result of value $\beta = 0.0771$ MPa^{-1}, $n_1 = 16.0083$ and $\alpha = 0.0048$. According to Eq. (6), the slope of plots of $\ln[\sinh(\alpha\sigma)]$- ln ε̇ as shown in figure.7 (a) can be obtained the value of n. The average value of stress exponent (n) was defined as 10.8482.

For the all stress values, Eq. (2) can be given by Eq. (7) and then taking the logarithm of both sides and giving partial different the expression for the activation energy at a constant strain rate, for the result can be obtained in Eq.(8)

$$\dot{\varepsilon} = A\left(\sinh(\alpha\sigma)^{n} \exp\left(-\frac{Q}{RT}\right)\right) \tag{7}$$

$$Q = Rn\left(\frac{[\partial \sinh(\alpha\sigma)]}{\partial(1/T)}\right)_{\dot{\varepsilon}} \tag{8}$$

The value of Q can be obtained from the slope of every plot of $\ln[\sinh(\alpha\sigma)]$-T as shown in figure.7 (b). For the average value of activation energy (Q) = 222.256 kJ/mol and A = $3.889\text{x}10^{12}$

Table 2 Parameter of constitutive equation for experimental of HSLA steel

Material constants	Q (kJ/mol)	N	α	β (MPa^{-1})	A (S^{-1})
value	222.256	10.8482	0.0048	0.0771	$3.889\text{x}10^{12}$

3.3 FEM Simulation

The effects of deformation temperature on the stress-strain distribution of HSLS steel are described using the finite element method (FEM). MMS-200 thermal mechanical simulator was used to acquire accurate flow stress curves of HSLA steel. The dimension of the specimens is equally considered in the experiment. The flow stress curves obtained from the experimental studies were functions of temperature, stress and strain rate. These curves were imported into DEFORM-3D for the simulations procedure.

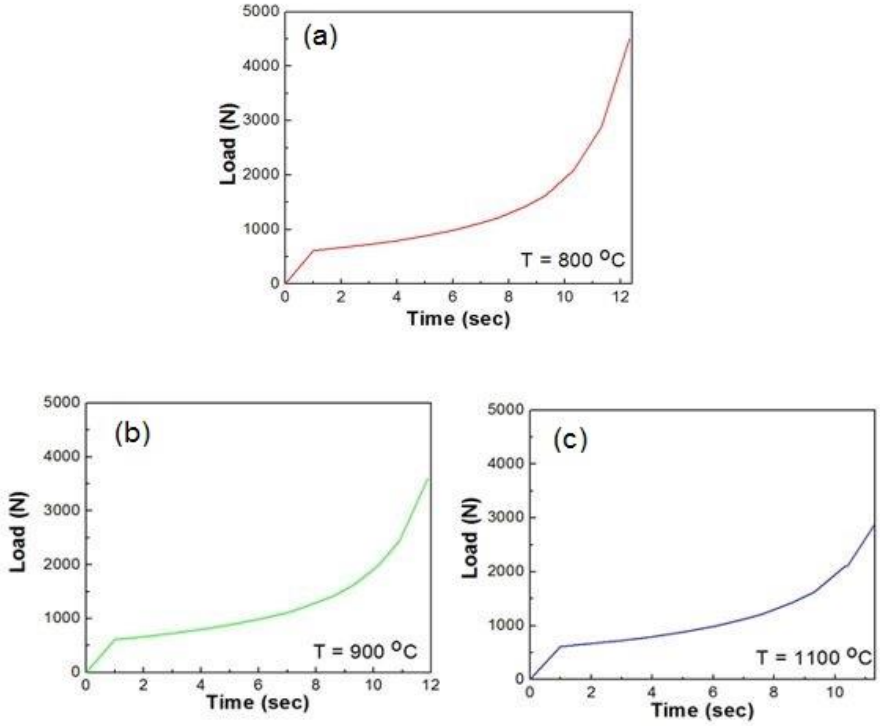

Figure 8. Load-time curve under different temperature at strain rate 1 s^{-1} (a) 800 ^{o}C, (b) 900 ^{o}C, (c) 1100 ^{o}C

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The effect of deformation temperature on the load-time curves at strain rate 1 s^{-1} is shown in figure 8. It can be observed that the variation in load–time curves, which depends on the stress, decreases with the increasing of deformation temperatures. Similarly, the difference in the load–time curves is lower at higher temperature and during the distribution of the effective stress under different temperature; the maximum effective stress changes with the variations in deformation temperatures. When the deformation temperature is lower, the deformation of specimens strain value increases. For the high-temperature conditions, the effective stress distribution value is lower and it shows that the deformation of areas is relatively large as shown in figure 9. The value of maximum effective stress at the temperature 800^{o}C, 900^{o}C and 1100 ^{o}C are 194.98 MPa, 159.77 MPa and 113.62 MPa respectively.

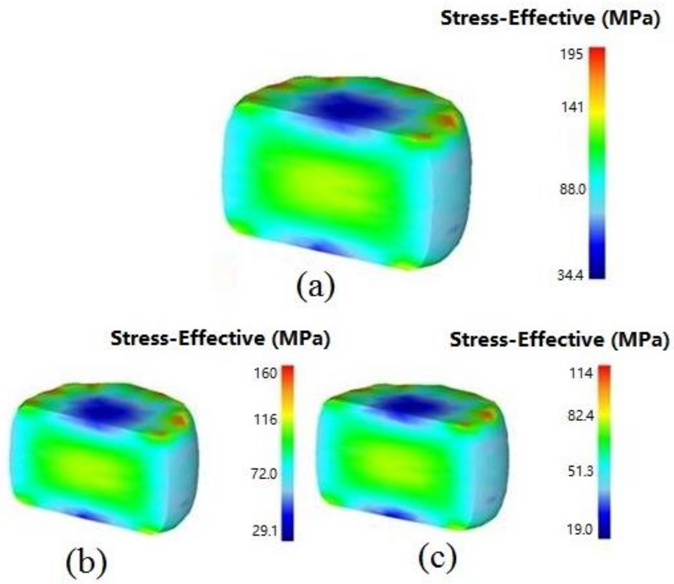

Figure 9. Effect of temperature on the stress distribution at strain rate 1 s^{-1} and height reduction of 50% (a) 800 ^{o}C, (b) 900 ^{o}C, (c) 1100 ^{o}C

4. Conclusion

1. The true stress-strain curves of HSLA steel shows different strain rate at constant deformation temperature. Dynamic recrystallization characteristic surfaces at low strain rate when the higher strain rate dynamic recovery has occurred and stress and strain peaks increases with increasing strain rate and decreasing deformation temperature.
2. The constitutive equation of hot deformation for HSLA steel under the various conditions was calculated the activation energy (Q) by using hyperbolic sine function law. The result from regression analysis shows that the activation energy of hot compression from experimental studies was 222.256 kJ/mol.
3. The simulation of the influence of the strain rate on the state of strain and stress shows that the variation in load–time curves, which depend on the stress, decreases with the increasing deformation temperatures and the distribution of the effective stress under different temperature is similar to the experimental. The prediction of flow stress values from the constitutive equation in Deform-3D can be matched with the results of the experimental.

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