Constitutive modelling of high strength low alloy steel under hot compression test

Wilasinee Kingkam¹, Ning Li¹, Hong Pang¹, Cheng-zhi Zhao¹,², He-xin Zhang¹,²,* and Zhi-ming Li³

¹College of Materials Science and Chemical Engineering, Harbin Engineering University, Harbin 150001, China
²Key Laboratory of Superlight Materials and Surface Technology, Ministry of Education, Harbin Engineering University, Harbin 150001, China
³College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China

*E-mail: zhanghx@hrbeu.edu.cn

Abstract. The HSLA steel was studied on an MMS-200 thermal mechanical simulation in the temperature range of 800-1100 °C and a strain rate range of 0.1-1 s⁻¹. The isothermal hot compression tests were used to investigate the flow behaviour of HSLA steel and develop a constitutive equation based on an Arrhenius equation. A modification of Zener–Hollomon parameter was considering the strain rate compensation after hot compression for improve the accuracy of the developed constitutive equation. The comparison of the results shows that the experimental flow stress data are in good agreement with the predicted flow stress data. The average absolute relative error with a correlation coefficient was found to be 6.81% and 0.96, respectively.

1. Introduction
The hot working processes at a high-temperature deformation and material flow behavior during hot deformation of metals are mostly complex [1-3]. Hot working processes such as forging, rolling and so on are important to explain the changed in the mechanical response of steel under external loadings. The deformation temperature and strain rate are both parameters significantly affect in the softening and dynamic recrystallization mechanisms. The constitutive equation for the hot deformation is the mathematical representation of the flow stress behavior of metals and alloys can be introduced into the finite element formula for simulating the response of materials under specified loading condition [4-5]. Therefore, many researchers have been attempted to develop the constitutive equation to describe the hot deformation behavior of the materials.

High strength low alloy steel (HSLA) is a type of steel widely used for ship construction, gas pipeline and the part of transportation industries [6]. Nowadays, HSLA steel has been improving with suitable chemical composition and thermomechanical processes in order to enhance application in heavy industries and automotive. The flow stress characterizes of HSLA steels is necessary to improve in industrial of the hot forming process. During hot deformation processes, the flow properties can determine the power requirements of industrial equipment manufacturers including the mechanical properties and dimensional accuracy of finished products. During hot deformation processes, the flow
properties can determine the power requirements of industrial equipment manufacturers including the mechanical properties and dimensional accuracy of finished products. The relationships between the constitutive equation and the relating process variables such as flow stress of the deforming material are required and it is important to calculate the flow stress [7].

2. Experimental procedures
The materials studied in the experimental was HSLA steels. The chemical composition of HSLA casting consists of low carbon content was listed in table 1. The specimens were cut into a small size with a diameter of 8 mm and height 15 mm. Uniaxial compression tests were performed by MMS-200 thermal-mechanical simulator. The specimens were heated from room temperature to 1250 °C with a heating rate of 20 °C/s, and cooled to a deformation temperature. The hot compression test was operated at temperature of 800-1100 °C with strain rates 0.1, 1 and 10 s⁻¹. The total true strain for each specimen was 0.55. After compression testing finished, all specimens were quenched immediately in water.

| C   | Si | Mn | P  | S  | Cr | Mo | Ni | Al | Cu | Nb | Ti | V  |
|-----|----|----|----|----|----|----|----|----|----|----|----|----|
| 0.01| 0.14| 1.38| 0.01| 0.008| 0.21| 0.13| 0.51| 0.019| 0.39| 0.027| 0.006| 0.009|

3. Results and discussion

3.1. Stress-strain curves

Figure 1. True stress-strain of the experiment and predicted HSLA steel at (a) 0.1 s⁻¹, (b) 1 s⁻¹ and (c) 10 s⁻¹.

True stress-strain curves of HSLA steel obtained from the hot compression test are shown in figure 1. It was found that the peak stress is sensitive to temperature and strain rate. When the flow stress being shifted to lower stresses and lower strains with the deformation temperature are increased [8-9]. The results also show that the dynamic recrystallization takes place in the samples at the conditions of high temperature and low strain rate. Besides, the flow stress rising to a peak and followed by softening state until to a stable state.

3.2. Deformation constitutive equations
The Arrhenius equation is often explained the relationship between flow stress, strain rate, and temperature [10]. Moreover, the effects of temperature and strain rate on the deformation behaviour can be shown clearly by Zener Hollomon parameter (Z) in an exponential equation [11-12]. Both equations are given by:

\[ Z = \dot{\varepsilon} \exp \left( \frac{Q}{RT} \right) \]
\[ \dot{\varepsilon} = A f(\alpha) \exp \left( -\frac{Q}{RT} \right) \]  

(2)

where \( Z \) is the Zener-Hollomon parameter, \( \dot{\varepsilon} \) is the strain rate \((s^{-1})\), \( R \) is the universal gas constant and \( Q \) is the activation energy of hot deformation \( (kJ \cdot mol^{-1}) \) with \( \alpha, \beta, n, \) and \( n \) are materials constant by \( \alpha = \beta / n \).

Substituting (the power law and exponential law of \( f(x) \)) equation (1) into equation (2) with the suitable function and taking the natural logarithm of both sides leads to equations (3)-(4) as follows:

\[ \ln \dot{\varepsilon} = n_1 \ln \sigma + \ln A - Q / RT \]  

(3)

\[ \ln \dot{\varepsilon} = \beta \sigma + \ln A - Q / RT \]  

(4)

Consideration any flow stress at a strain rate of 0.55 \( s^{-1} \) are used to analyzed equations. (1), (3) and (4) to determine material constants. The value of \( \alpha, \beta \) and \( n_1 \) can be obtained by the average slopes of linear fitting of \( \ln \dot{\varepsilon} - \sigma \) and the slopes of the plots of \( \ln \dot{\varepsilon} - \ln \sigma \) are shown in figure 2 (a-b). The values of \( \beta \) and \( n_1 \) can be calculated as 14.527 and 0.0899 MPa\(^{-1}\) and the material constant \( \alpha (\beta / n_1) \) was calculated as 0.00618 MPa\(^{-1}\).

The relationship between \( \ln \dot{\varepsilon} - \ln[\sinh(\alpha \sigma)] \) obtained from substituting the values of the strain rate and flow stress for all temperature conditions are shown in figure 2c. The value of the material constant (\( n \)) obtained from the average slope of the lines in the \( \ln \dot{\varepsilon} - \ln[\sinh(\alpha \sigma)] \) plots were 10.594. For the fixed strain rate, by taking the partial derivative of equation (5), the activation energy (\( Q \)) can be calculated as:

\[ Q = R \frac{\partial \ln(\sinh(\alpha \sigma))}{\partial(1/T)} \dot{\varepsilon} \]  

(5)

The value of \( Q \) can be calculated from the slope of every plots in the lines of \( \ln \dot{\varepsilon} - 1000 / T \) plots (figure 2d). Thus, activation energy \( Q \) in the studied HSLA steel was determined to be 361.138 kJ.mol\(^{-1}\). These \( Q \) values obtained from the experiment fall in the range that reported by previous researchers. For comparison, the activation energy evaluated by Zhang et al. [13] was 368.56 kJ/mol and Wei and Liu [14] was 360.063 kJ/mol. Figure 3 shows the relationship between \( \ln[\sinh(\alpha \sigma)] \) - \( \ln Z \). From the slope of every plot, the straight line can be used to determine the value of \( \ln A \). Thus, the exact values of \( A \) can be calculated as \( 3.256 \times 10^{12} \) \( s^{-1} \). In a similar way, the material constants values \( (n, \beta, \alpha, n \text{ and } \ln A) \) as well as activation energy (\( Q \)) can be calculated for all condition of HSLA steel. The presents the values of constitutive constants and deformation activation energy of the HSLA steel are given in table 2.

**Table 2. Values of constitutive constants and deformation activation energy of HSLA steel.**

| \( n_1 \) | \( \beta \) | \( \alpha \) | \( n \) | \( \ln A \) | \( Q \) (kJ/mol) |
|-----------|-----------|-----------|------|--------|-------------|
| 14.527    | 0.0899    | 0.00618   | 10.594 | 35.723 | 361.138     |
Figure 2. Relationship between (a) \( \ln \dot{\varepsilon} - \sigma \), (b) \( \ln \dot{\varepsilon} - \ln \sigma \) (c) \( \ln \dot{\varepsilon} - \ln[\sinh(\alpha \sigma)] \) and (d) \( \ln \dot{\varepsilon} - 1000 / T \).

Figure 3. Relationship between \( \ln[\sinh(\alpha \sigma)] \) and \( \ln Z \).

3.3. Compensation of strain

It is well known that the strain is a significant effect with the deformation activation energy (Q) and material constants (\( \alpha, \beta, n \) and \( \ln A \)) [15]. Thus, the compensation of the strain can take effect on the prediction of the flow stress accuracy to take into account in order to derive the proper constitutive equations. In this work, the material constant values were determined at different strains in the range of 0.1-0.55 at the intervals of 0.05, the corresponding fitting curves of the variation of material constants with a function of strain shown in figure 4. These material constants values were the polynomial function of the strain. A third order polynomial are shown in equation (6) and the coefficients of polynomial fitting curves of HSLA steel are listed in table 3.

\[
\alpha = \alpha_0 + \alpha_1 \dot{\varepsilon} + \alpha_2 \dot{\varepsilon}^2 + \alpha_3 \dot{\varepsilon}^3
\]
\[
n = n_0 + n_1 \dot{\varepsilon} + n_2 \dot{\varepsilon}^2 + n_3 \dot{\varepsilon}^3
\]
\[
Q = Q_0 + Q_1 \dot{\varepsilon} + Q_2 \dot{\varepsilon}^2 + Q_3 \dot{\varepsilon}^3
\]
\[
\ln A = A_0 + A_1 \dot{\varepsilon} + A_2 \dot{\varepsilon}^2 + A_3 \dot{\varepsilon}^3
\]

(6)

In this study, the materials constants are evaluated at a particular strain in the range of 0-0.55. Therefore, the constitutive equation relating to flow stress and Zener-Holloman parameter as following:
\[
\sigma = \frac{1}{\alpha} \ln \left\{ \left( \frac{Z}{A} \right)^{1/n} + \left[ \left( \frac{Z}{A} \right)^{2/n} + 1 \right]^{1/2} \right\}
\]

(7)

Table 3. Coefficients of polynomial fitting curves for material coefficients of HSLA steel.

|   | \( \alpha_0 \) | \( n_0 \) | \( Q_0 \) | \( A_0 \) | \( \ln A_0 \) |
|---|---|---|---|---|---|
| \( \alpha_1 \) | -0.063 | 38.31 | 392.38 | -1277.1 | -235.7 |
| \( \alpha_2 \) | 0.174 | -152.34 | 654.73 | -235.7 | 163.43 |
| \( \alpha_3 \) | -0.154 | 140.79 | 235.7 | 654.73 | 163.43 |

Figure 4. The variation of material constants with a function of strain (a) \( \alpha \), (b) \( n \), (c) \( Q \) and (e) \( \ln A \).

3.4. Verification of the developed constitutive equations

A comparative study between the experimental and predicted hot deformation behaviour of HSLA steel results was carried out to verify the constitutive equations for HSLA steel after hot compression test is shown in figure 5.

Figure 5. Comparison between the experimental and predicted flow stress from the developed constitutive equation.

The prediction of the constitutive equation was also quantified using standard statistical parameters such as the correlation coefficient \( R^2 \) and average absolute relative error (AARE). The experimental of flow stress were plotted versus flow stress prediction base on develop constitutive equation as
shown in figure 5. The correlation coefficient exists between experimental data and predicted data, and the R is 0.966. The AARE is calculated by equation (8):

\[ AARE = \frac{1}{N} \sum_{i=1}^{n} \left| \frac{E_i - P_i}{E_i} \right| \times 100 \]  

where E is the experimental value and P is the predicted value obtained from the constitutive equation and N is the total number of data, respectively. Therefore, the AARE of experimental and predicted data is 6.81%. These results also confirm the accuracy of the developed constitutive equations with HSLA steel strain compensation and the proposed constitutive equations can effectively predict the flow behaviour steel used to simulate the process of hot forming using a finite element method.

4. Conclusions

The hot deformation behaviour of HSLA steel was studied using hot compression tests. Base on the experimental data, the constitutive analysis of HSLA steel was carried out. The conclusions can be demonstrated as follows:

1. The true stress-strain curves of the HSLA steel shows the characteristics of dynamic recrystallization or dynamic recovery at different temperatures and strain rate. The flow stress increases with the increasing of strain rate and decreasing of deformation temperature.

2. The dependence of flow stress on strain and temperature can be calculated using the constitutive equation and the material constants were determined. The activation energy of this experimental for HSLA steel was determined as 361.138 kJ mol\(^{-1}\).

3. The influence of the strain was incorporated in the constitutive equation by examining the effect of strain on material constants (i.e. \(\alpha, \beta, n\) and In A) base on the experimental data. The third order polynomial was used to represent the strain in these material constants with having a good correlation. The average absolute relative error associated (AARE) related to total temperature prediction and strain rate was 6.81% and the correlation coefficient (R) was 0.966.

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