Modeling of hot deformation behavior of high phosphorus steel using Johnson-Cook model

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Abstract: To describe the hot deformation behavior of high phosphorus steel, isothermal hot compression test was performed using Gleeble 3800 thermo-mechanical simulator in the temperatures ranging from 750-1050°C at constant strain rates of 0.001-10 s⁻¹. Based on the experimental results, Johnson-Cook model was developed to predict the values of flow stress. Johnson-Cook model shows a fairly good agreement with experimental and predicted values. Average absolute relative error (AARE), and relative error (RE) of JC model are calculated as 24.356%, and -19.97% to 33.179%, respectively.

Keywords: Hot deformation behavior, Johnson-Cook Model, Flow stress

1. Introduction

High phosphorus steel has widely used in structural applications due to its corrosion resistance properties. Phosphorus is added intentionally in steel in the form of ferro-phosphorus (23% to 26% P), to increase strength, machinability and corrosion resistance. Phosphorus also having some negative effects on the steel as it creates brittleness by segregating at the grain boundaries. However, this can be overcome by adding small amount of carbon because it displaces phosphorus from the grain boundaries due to site competition effect. Additional heat treatment in the dual phase region also remove phosphorus away from grain boundaries, results improved ductility and toughness [1]. Hot deformation process is a very vital step during industrial processing of any metal or an alloy. To depict the metal flow pattern and metallurgical transformations during metal forming process, understanding of flow behaviors of metal during hot deformation is very important [2-6]. Due to these complications in the
path of hot deformation behavior of materials, leads to the assumptions that computer aided model can describe the material response under varying load conditions more easily and accurately. For this purpose, various constitutive equations were used to simulate and model the flow behavior of metals and alloys [7, 8]. Many researchers have tried to develop constitutive model based on the experimental results to describe the deformation behavior of metals and alloys [9]. Johnson Cook (J-C) model is the most widely used constitutive model to predict the deformation behavior of materials at varying processing parameters such as temperature, strain and strain rate [10]. Compared to other models, the J-C model can predict the deformation behaviors of materials at elevated temperatures [11, 12] at less material parameters and time [13]. Although there are some studies present on the hot deformation behavior of high P steel in the literature, but the prediction of flow behavior using Johnson-Cook model is lacking. Hence, there is need to predict the flow behavior using Johnson-Cook model in comprehensive manner. In the present study, isothermal hot compression tests were performed upto total true strain of 0.7 using Gleeble 3800 thermo-mechanical simulator in the temperatures ranging from 750°C-1050°C at constant strain rates from 0.001 to 10 s⁻¹. Johnson-Cook model is used to model and predict the flow behavior of high phosphorus steel.

2. Experimental Methodology

2.1 Material and Methods

Initially iron scrap was melted in the furnace followed by addition of ferrous-phosphorus, graphite and ferro-silicon. Solid plate of dimensions 200mm x 400mm x 40mm was obtained using sand mould casting followed by cutting into smaller pieces of dimensions 30mm x 40mm x 30mm with the help of power hacksaw [14]. Table 1 shows the chemical composition of high phosphorus steel.

Table 1. Chemical composition (in wt %) of high phosphorus steel.

| Elements | Si  | P  | C  | Mn | Cr  | Ni  | Cu  | Al  | W  | Fe  |
|----------|-----|----|----|----|-----|-----|-----|-----|----|-----|
| Wt %     | 0.26| 0.13| 0.05| 0.2| 0.13| 0.07| 0.02| 0.003| 0.02| 99.12|

2.2 Hot Compression
Hot compression test were conducted on cylindrical specimen of length 15mm and 10mm diameter with the help of Gleeble 3800 thermo-mechanical simulator under vacuum. To control the temperature during the experiment, K-type thermocouple was spot welded at the center of the specimen. To minimize friction and temperature gradient, ISO-T anvil, nickel based lubricant and graphite foil were used. Specimens were heated up to the austenitization temperature of 1050°C with heating rate of 5°C for 10s, followed by cooling with the cooling rate of 1°Cs⁻¹ to the deformation temperatures ranging from 750°C-1050°C. Specimens were deformed up to true strain of 0.7 using constant strain rates ranging from 0.001- 10 s⁻¹. In-situ water quenched the specimens to preserve and avoid and metadynamic phenomena after deformation.

3. Results and discussions

3.1 Flow behavior

Sample stress-strain curves at deformation temperature of 750°C at constant strain rates ranging from 0.001 s⁻¹ to 10 s⁻¹ is depicted in fig.1. It has been observed that flow stress increases with increasing strain rate for a particular temperature. Stress-strain curve at low strain rates (0.001 and 0.01 s⁻¹) shows peak stress after strain hardening, followed by softening due to dynamic recrystallization (DRX). At higher strain rates (0.1, 0.5, 1 and 10 s⁻¹), the flow stress increased in whole range of testing strain. Peak stress shifted towards higher strain with increasing strain rates.
3.2 Johnson-Cook Model

Johnson-Cook (J-C) model was used to predict the flow behavior of high phosphorous steel during hot deformation considering the influences of temperature, strain and strain rates, and is represented by equation (1) [15, 16].

\[
\sigma = \left( \sigma_o + B \varepsilon^* \right) \left( 1 + C \ln \varepsilon^* \right) \left( 1 - T^* \right)
\]

where \( \sigma \) is flow stress, \( \sigma_0 \) is yield stress, \( \varepsilon \) is equivalent plastic strain. Dimensionless strain rate \( \dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_0 \), where \( \dot{\varepsilon} \) and \( \dot{\varepsilon}_0 \) are strain rate and reference strain rate, respectively. \( B, n, C \) and \( m \) are the material constants.

\[ T^* = (T - T_r) / (T_m - T_r), \]

where \( T \) is the absolute temperature, \( T_m \) \( (T_m = 1525^\circ C \) for present material) and \( T_r \) are the melting temperature and reference temperature, respectively. To calculate the value of material constants, reference temperature is taken as \( 750^\circ C \) \( (T \geq T_r) \), and reference strain rate as \( 10 \text{ s}^{-1} \) in the present study.

Value of yield stress \( \sigma_0 \) is found to be 81.04137 MPa at reference temperature and strain rate (Fig.1). To determine the value of material constants \( B, n, C, \) and \( m \) at reference temperature and strain rate, equation (1) can be rewritten as,
\[
\sigma = \left( \sigma_o + B\varepsilon^n \right)
\]  \hspace{1cm} (2)

On taking natural logarithm of both sides, Equation (2) can be represented as equation (3).

\[
\ln(\sigma - \sigma_o) = \ln(B) + n \ln(\varepsilon)
\]  \hspace{1cm} (3)

Substituting the values of yield stress at corresponding strain, equation (3) gives the relationship between \(\ln(\sigma - \sigma_o)\) and \(\ln(\varepsilon)\) (Fig. 2), and the value of \(n\) and \(B\) are obtained as 0.10068 and 172.1747, respectively.

![Graph](image)

Fig.2 Relationship between \(\ln(\sigma - \sigma_o)\) and \(\ln(\varepsilon)\).

Substituting the values of \(n\) and \(B\) in equation (1) at reference temperature, it can be expressed as equation (4). Figure 3 shows the graph between \(\sigma/(\sigma_o + B\varepsilon^n)\) and \(\ln\varepsilon^*\) at different strains, and obtained the average value of \(C\) as 0.07442.

\[
\sigma/(\sigma_o + B\varepsilon^n) = 1 + C\ln\varepsilon^*
\]  \hspace{1cm} (4)
Fig.3 Relation between $\sigma/(\sigma_o+B\varepsilon^n)$ and $\ln \varepsilon^*$. 

At reference strain rate equation (1) can also be rewritten as equation (5).

$$\sigma / (\sigma_o + B\varepsilon^n) = 1 - T^{*m}$$

(5)

Taking natural algorithm on both sides of the equation (5),

$$\ln[1 - (\sigma / (\sigma_o + B\varepsilon^n))] = m \ln T^*$$

(6)

According to equation (6), the graph between $\ln [1-(\sigma/(\sigma_o+B\varepsilon^n))]$ and $\ln T^*$ plotted (Fig. 4), and the value of $m$ can be calculated as 0.18247.

Fig.4 Relationship between $\ln [1-(\sigma/(\sigma_o+B\varepsilon^n))]$ and $\ln T^*$. 
After determining all value of material constants, J-C model can be summarized as equation (7).

\[
\sigma = (81.0417 + 172.1747 \varepsilon^{0.1068}) \left(1 + 0.07442 \ln \varepsilon^*\right)(1 - T^{0.18224})
\] (7)

The values of flow stress are predicted at different temperatures, strain and strain rate using equation (7), and the comparison between experimental and predicted value of flow stress were plotted, as depicted in fig. 5. It can be seen from the graph, that the values of flow stress at reference strain rate are closer to that of experimental values. Further, the values of flow stress tend to move farther from the experimental values with increasing temperatures and strain rates. Thus, it can be said from fig. 5 that Johnson-Cook model gives a fairly good agreement between the experimental and predicted flow stress.

![Flow Stress Graph](image)

Fig.5 Comparison between experimental and predicted value of flow stress using JC model at deformation temperature 750°C.

The accuracy and predictability of the Johnson-Cook model can be evaluated by relative error (RE) and average absolute relative error (AARE), and can be expressed by equation (8) and (9), respectively.

\[
AARE(\%) = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{\sigma_E - \sigma_P}{\sigma_P} \right| \times 100
\] (8)
\[ RE = \left( \frac{\sigma_E - \sigma_p}{\sigma_E} \right) \times 100 \]  \hspace{1cm} (9)

where \( \sigma_p \) and \( \sigma_e \) are the predicted and experimental flow stress values, respectively. \( N \) is the total number of data which is employed for investigation purpose. Relative error and average absolute relative error are used to analyze the accuracy and predictability of the flow stress values in phenomenological model. Average absolute error is used to calculate the optimized value, whereas correlation coefficient provides the closeness information of experimental and predicted values [17]. Average absolute error is calculated step by step and is therefore considered as an unbiased statics for measuring the predictability of the model. The average absolute error, and relative error, of Johnson Cook model are 24.356\%, and -19.97\% to 33.179\%, respectively. These values show fairly good predictability.

4. Conclusions

In the present study, isothermal hot compression tests were conducted in the temperature ranging from 750\(^\circ\)C-1050\(^\circ\)C at constant strain rates of 0.001-10 s\(^{-1}\). Experimental data obtained from the isothermal test were used to predict the flow stress values using Johnson-Cook model. Following conclusions are drawn from the present study.

1. It has been observed from the flow curves that the values of flow stress increases with increasing strain rate for a particular temperature. The true stress-strain curve shows initially strain hardening followed by thermal softening due to DRX at low strain rates of 0.001-0.01 s\(^{-1}\) and deformation temperature of 750\(^\circ\)C.

2. Johnson-Cook model shows a fairly good agreement with experimental and predicted values. Average absolute relative error (AARE), and relative error (RE), of JC model are calculated as 24.356\%, and -19.97\% to 33.179\%, respectively.

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