INVESTIGATION ON ZENER-HOLLOMON PARAMETER OF A MEDIUM CARBON LOW ALLOY OF 1Cr-1Mn-1.5Ni-1Si-0.1V UNDER HOT COMPRESSION TEST

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Abstract
The aim of this study is to investigate the hot compression behaviour of a medium carbon low alloy steel of 1Cr-1Mn-1.5Ni-1Si-0.1V at temperature range of 850 to 1100 °C and strain rate of 0.001 to 0.5 s⁻¹ for strain of 0.8. The influences of the Zener-Hollomon parameters, strain and strain rate imposing on the flow stress were analyzed in the temperature range. Deformation activation energy of the material was determined using logarithmic, sinusoidal and hyperbolic equations. The experimental results show that the dynamic softening is accelerated with increase of deformation temperature and decrease of strain rate. The relation between Zener-Hollomon parameter Z and ε for studied material derived and the hot deformation activation energy Q was found from this work is 245 kJ/mol.

1. INTRODUCTION
Structural steels with minimum yield strength of 1380 MPa are often referred as ultra high strength steels (UHSS)⁹. The applications of these steels are in critical cases such as pressure vessels, aircraft undercarriages, rocket motor casings, turbine motors. In addition to their high strength to weight ratio, these steels must have good ductility, toughness, fatigue resistance and weldability⁹. The material that used in this study is a medium carbon low alloy steel with ultra high strength that is microalloyed with vanadium. This steel is produced by electroslag refining (ESR).
At present, no investigations on warm-hot forging process of this steel have been reported. This study investigates hot compression behavior of this material at hot deformation temperature range and strain rate. This study is aimed at determining the activation energy for deformation, and relations of Z, flow stress and dynamic recrystallization.

2. EXPERIMENTAL PROCEDURES
The chemical composition of the material is shown in Table1. The Ar₁ and Ar₃ temperatures were found to be as 746°C and 787°C, respectively, by differential scanning calorimetry (DSC) method. Cylindrical samples of size Φ8mmx12mm were machined from an annealed billet. In order to determine the stress-strain behavior of the alloy, uniaxial one-hit hot compression tests were performed on a servo-hydraulic 600KN computerized Material Testing System (MTS, Model 8500) equipped with a resistance furnace. The deformation tests were carried out according to the test schedule in Fig. 1. In order to minimize the friction, thin pieces of mica sheet were laid between punch and specimen as a lubricant material.
Table 1. Chemical composition (wt%) of studied steel.

<table>
<thead>
<tr>
<th>Component</th>
<th>Wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.28-0.33</td>
</tr>
<tr>
<td>Cr</td>
<td>0.90-1.10</td>
</tr>
<tr>
<td>Ni</td>
<td>1.40-1.60</td>
</tr>
<tr>
<td>Mn</td>
<td>0.90-1.10</td>
</tr>
<tr>
<td>Si</td>
<td>0.90-1.10</td>
</tr>
<tr>
<td>Cu_{max}</td>
<td>0.15</td>
</tr>
<tr>
<td>V</td>
<td>0.05-0.15</td>
</tr>
<tr>
<td>P_{max}</td>
<td>0.015</td>
</tr>
<tr>
<td>S_{max}</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Fig. 1. Schematic representation of the thermomechanical processing conditions

3. RESULT AND DISCUSSION

3.1. Flow stress during hot deformation

The true stress-true strain curves of studied steel compressed at 850, 950, and 1100°C at different strain rates are shown in Fig. 2. The peak stress and peak strain of this material are shown in Table 2. True stress-true strain curves during hot compression at various strain rates and temperatures of (a) 850°C, (b) 950°C, (c) 1100°C.
Fig. 2. True stress-true strain curves during hot compression at various temperatures and strain rates of (a) 0.001 s\(^{-1}\), (b) 0.01 s\(^{-1}\), (c) 0.1 s\(^{-1}\), 0.5 s\(^{-1}\).

Table 2. Peak stress and peak strain at different temperatures and strain rates

<table>
<thead>
<tr>
<th>(\dot{\varepsilon}) (s(^{-1}))</th>
<th>T(K)</th>
<th>(\varepsilon_F)</th>
<th>(\sigma_F) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>1123</td>
<td>0.8</td>
<td>306.67</td>
</tr>
<tr>
<td></td>
<td>1223</td>
<td>0.8</td>
<td>142.80</td>
</tr>
<tr>
<td></td>
<td>1373</td>
<td>0.8</td>
<td>82.95</td>
</tr>
<tr>
<td>0.01</td>
<td>1123</td>
<td>0.8</td>
<td>330.42</td>
</tr>
<tr>
<td></td>
<td>1223</td>
<td>0.8</td>
<td>217.22</td>
</tr>
<tr>
<td></td>
<td>1373</td>
<td>0.8</td>
<td>97.46</td>
</tr>
<tr>
<td>0.1</td>
<td>1123</td>
<td>0.8</td>
<td>477.13</td>
</tr>
<tr>
<td></td>
<td>1223</td>
<td>0.8</td>
<td>326.28</td>
</tr>
<tr>
<td></td>
<td>1373</td>
<td>0.8</td>
<td>157.54</td>
</tr>
<tr>
<td>0.5</td>
<td>1123</td>
<td>0.8</td>
<td>476.38</td>
</tr>
<tr>
<td></td>
<td>1223</td>
<td>0.8</td>
<td>316.77</td>
</tr>
<tr>
<td></td>
<td>1373</td>
<td>0.8</td>
<td>269.16</td>
</tr>
</tbody>
</table>
Fig. 3. True stress-true strain curves during hot compression at various strain rates and temperatures of (a) 850 °C, (b) 950 °C, (c) 1100 °C.

It could be observed from Fig. 2 and Fig. 3 that the influences of temperature and strain rate on flow stress are significant. The flow stress increases with decrease in temperature and increases in strain rate. The flow curve typically shows work hardening region followed by dynamic softening due to recovery/recrystallization. The work hardening is predominant at lower temperatures and higher strain rates. On the contrary, the extent of dynamic softening is more at higher temperatures and lower strain rates. This is due to the fact that higher temperatures and lower strain rates offer higher mobility to the grain boundary and longer time for nucleation and growth of dynamically recrystallized grains [3].

3.2. Constitutive Equations for flow stress prediction

The correlation between the flow stress ($\sigma$), temperature ($T$) and strain rate ($\dot{\varepsilon}$), particularly at high temperatures, could be expressed by an Arrhenius type equation[4]. Further, the effects of temperature and strain rate on deformation behavior could be represented by Zener-Hollomon Parameter ($Z$) in an exponent type equation[5]. These are mathematically expressed as

$$Z = \varepsilon^\dot{\varepsilon} \exp\left(\frac{Q}{RT}\right) = f(\sigma) = \left\{\begin{array}{ll}
A^\dot{\varepsilon} \sigma^n & \text{if } A > 0 \\
A^\dot{\varepsilon} \exp(\beta \sigma) & \text{if } A < 0 \\
A[\sinh (\alpha \sigma)]^n & \text{if } A = 0
\end{array}\right. \tag{1}$$

Here, $R$ is the universal gas constant (8.31 $J$ mol$^{-1}$ K$^{-1}$); $T$ is the absolute temperature in K; $Q$ is the activation energy (J mol$^{-1}$); $\varepsilon^\dot{\varepsilon}$ represents the strain rate and $A$, $A'$, $A''$, $n$, $\beta$ and $\alpha$ (S, $\beta/n$) are material constants. In the above equations, the Zener-Hollomon parameter $Z$ is temperature compensated strain rate and $Q$ is the deformation activation energy.

3.3. Determination of Hot Working Constants

By taking the natural logarithm from each side of the Eqs. (1), (2) and (3), the following expressions could be derived for peak stress:
Under the condition of constant temperature during the hot deformation process the partial differentiation of Eqs. (4), (5) and (6) yields the following equations, respectively:

\[ \ln \sigma^* + \frac{Q}{R} \left( \frac{1}{T} \right) = \ln A + n \ln \sigma_p \quad (4) \]

\[ \ln \sigma^* + \frac{Q}{R} \left( \frac{1}{T} \right) = \ln A' + \beta \sigma_p \quad (5) \]

\[ \ln \sigma^* + \frac{Q}{R} \left( \frac{1}{T} \right) = \ln A + n \ln \left[ \tanh(a \sigma_p) \right] \quad (6) \]

It follows from these expressions that the slope of the plot of \( \ln \sigma^* \) against \( \ln \sigma_p \) and the slope of the plot of \( \ln \sigma^* \) against \( \sigma_p \) can be used for obtaining the value of \( n' \) and \( \beta \), respectively. These plots are shown in Figures 4(a) and (b). The linear regression of these data results in the average value of 7.4996 and 0.0289 for \( n' \) and \( \beta \), respectively. This gives the value of \( \alpha = \beta / n' = 0.0038 \). According to Eq. (9), the slope of the plot of \( \ln \left[ \tanh(a \sigma_p) \right] \) can be used for obtaining the value of \( n \) (Fig. 4(c)). The average value of \( n \) was determined as 5.39 \(^{[6]} \).

\[ Q = R n \left[ \frac{\partial \ln \sigma_p}{\partial (1/T)} \right]_T \quad (10) \]

**3.4. Calculation of the activation energy**

The activation energy for deformation at a constant strain rate, was derived by partial differentiation of Eqs. (4), (5) and (6) that yields the following equations, respectively:

\[ \ln \sigma^* + \frac{Q}{R} \left( \frac{1}{T} \right) = \ln A + n \ln \sigma_p \quad (4) \]

\[ \ln \sigma^* + \frac{Q}{R} \left( \frac{1}{T} \right) = \ln A' + \beta \sigma_p \quad (5) \]

\[ \ln \sigma^* + \frac{Q}{R} \left( \frac{1}{T} \right) = \ln A + n \ln \left[ \tanh(a \sigma_p) \right] \quad (6) \]
It follows from these expressions that the slope of the plots of $Q$ or $\ln \tanh (\alpha \sigma_p)$ versus the reciprocal of absolute temperature can be used for obtaining the value of $Q$. These plots are shown in Fig. 5. The linear regression of these data results in the average value of 245, 219 and 227 $\text{KJ/mol}$ for activation energy from Eqs. (10), (11) and (12), respectively.

There is a significant difference between these values. Analysis of the correlation coefficient ($R^2$) of these regression values reveals that Eq. (10) has better fit to experimental data. Therefore, the activation energy of hot working was considered to be 245 $\text{KJ/mol}$. 

### 3.5. Peak Stress as a Function of the Zener-Hollomon Parameter

According to Eqs. (1) through (5), the plots of $\ln \sigma_p$, $\ln \sigma_p$, and $\ln \tanh (\alpha \sigma_p)$ may be used to find the relationship between $Z$ and $\sigma_p$. The corresponding curves are shown in Figure (6), and the resultant regression equations are as follows:

\[
Z = e^{\ln(248 \times 10^5)} = 0.00147 \times \sigma_p^{3.499} \quad (13)
\]

\[
Z = e^{\ln(248 \times 10^5)} = 3.96 \times 10^7 \times \exp(0.0245 \times \sigma_p) \quad (14)
\]

\[
Z = e^{\ln(248 \times 10^5)} = 1.78 \times 10^{10}[\sinh(0.0036 \times \sigma_p)]^{1.844} \quad (15)
\]

Among these relations, the hyperbolic sine equation (Eq. (13)) has the highest correlation coefficient and the power and the exponential law have good fit. In summary, the peak stress of medium carbon low alloy steel (Ni-Cr-Mn) under deformation condition used in this study may be expressed as Eq. (16) as a result Eq. (15).

\[
Z = 1.78 \times 10^{10}[\sinh(0.0036 \times \sigma_p)]^{1.844} \quad (16)
\]
4. CONCLUSIONS

Isothermal uniaxial compression tests are performed on medium carbon low alloy steel (Ni-Cr-Mn) at strain rates of 0.001 to 0.5 s\(^{-1}\) over a temperature range of 850 to 1100 °C to a strain of 0.8 and are summarized as follow:

1. It was shown that for correct calculation of the activation energy of hot working, one of the three expressions of Z, namely, the power law, exponential law, and hyperbolic sin law, results in the appropriate value. For this steel, the power law was found to be the appropriate relation, which resulted in the value of 245 KJ/mol.

2. The material constant in equation of $Z = \sigma^4 \exp \left( \frac{Z}{RT} \right) = f(\sigma) = \left\{ A' \sigma^4 \exp \left( \frac{Z}{RT} \right) \right\}$ for this steel was found.

3. The relation between Zener-Hollomon parameter Z and $\sigma_p$ for studied material derived that is $Z = 1.78 \times 10^{10} \left[ \sinh \left( 0.0036 \times \sigma_p \right) \right]^{4.44}$

REFERENCES