The investigation on the unstable flow behavior of Ti17 alloy in $\alpha+\beta$ phase field using processing map

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In this study, five existing instability criteria (Prasad’s, Murty’s, Sematin’s, Gegel’s and Malas’s criterion) were employed to delineate the unstable flow regions for Ti17 alloy during hot deformation. Experimental stress–strain data obtained from isothermal hot compression tests in the temperature range of 780–860 °C and strain rate range of 0.001–10 s$^{-1}$ were utilized to develop the instability maps. These domains were validated through detailed microstructure observation. The material exhibited stable flow at lower strain rates while adiabatic shear band and flow localization occurred at higher strain rates ($\geq 1$ s$^{-1}$). It was observed that the maps at strain of 0.9 developed by Prasad’s and Murty’s criteria have a good ability for predicting unstable flow at high strain rates and entire temperatures. However, the Sematin’s criterion under-predicts the instability regions in the test temperatures and strain rates. On the contrary, the Gegel’s and Malas’s criteria over-predict the instability domains, especially for the low strain rate region.

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1. Introduction

Titanium alloys have a wide range of applications, especially in the aerospace industry [1,2]. Ti17 (Ti–5Al–2Sn–2Zr–4Mo–4Cr) alloy has been extensively accepted in the aerospace applications because of its attractive combination of properties such as high specific strength, excellent fracture toughness and good heat/corrosion resistance [3]. However, the alloy is rather difficult to deform into a complex shape because of its poor formability. In addition, its hot workability is limited by the narrow range of forging temperature and the generation of various deformation defects, such as shear bands, cracking and flow instability [4,5]. Therefore, the characterization of deformation behavior is essential for the optimization of hot forging processes of titanium alloy.

In order to characterize the hot forming processes, a series of approaches and methods have been proposed. Front and Ashby [6] introduced a deformation map showing the area of dominant flow mechanisms in the plot of normalized stress vs. deformation temperature. The map can be used to identify the dominant deformation mechanism for a given test condition. However, the map can be only available to pure materials or sample alloys under steady-state conditions. Raj [7] suggested the damage nucleation map, presenting the nucleation of deformation damage as a function of temperature and effective strain rate. Sematiin and Lahoti [8] and Montheillet et al. [9] considered that plastic instability behavior was related to the work-hardening rate and the strain rate sensitivity parameter, and then established a phenomenological criterion by using test methods. Prasad [10,11] has developed the so-called dynamic material model under which the workpiece is considered as a dissipater of power. However, Prasad et al. assumed the strain rate sensitivity parameter (m) a constant, which was questioned by some scholars. For this reason, Murty et al. [12,13] proposed a much stricter plastic instability a criterion in which m is a variable. Gegel [14] derived a novel stability criterion based on the second law of thermodynamics theory and Liapunov stability equation. Malas [15] replaced $\eta$ in Gegel criterion with m and then built another group of stability criteria. However, there is no unique instability criterion that can be applied to delineate the stable and unstable region for all kinds of materials, designer needs to establish a suitable instability criterion or examine the applicability of the existing theories for the intended materials based on detailed microstructural observations [16,17].

The present work was mainly focused on the characterization of the flow instability during hot working of Ti17 titanium alloy based on the various instability criteria. Further, the flow instability was validated for Ti17 alloy forging by microstructural observation.

2. Experimental procedure

The material used for compression test was Ti17 alloy. The chemical composition is given in Table 1, and the initial microstructure is a typical lamellar microstructure with 15–25 μm length and
\[ \xi_1 = 5 - \alpha < 0 \] (4)

3.2. Prasad’s criterion

Prasad et al. [10] have developed an instability criterion on the basis of extremum principles in irreversible thermodynamics as applied to the continuum of large plastic flow. The flow instability will occur during hot forging if

\[ \xi_2(\dot{\varepsilon}) = \frac{\partial \ln \left( \frac{m}{m+1} \right)}{\partial \ln \dot{\varepsilon}} + m < 0 \] (5)

Unstable flow during hot deformation is predicted when dimensionless instability parameter \( \xi_2(\dot{\varepsilon}) \) becomes negative. This criterion has been applied to a large variety of materials and the predictions were validated with the microstructural observations [19]. However, it is worth emphasizing that, this criterion is derived based on the assumption that \( m \) is a constant and flow stress follows the constitutive equation of power law [16].

3.3. Murty’s criterion

Murty et al. [11,12] considered that strain rate sensitivity parameter \( m \) is not a constant, and suggested that the efficiency of dissipation can be calculated directly by obtaining \( J \) from the numerical integration procedure. This procedure has been carried out as follows.

The efficiency of power dissipation for a non-linear dissipater may be expressed as

\[ \eta = \frac{J}{J_{\text{max}}} = 2 \left( 1 - \frac{1}{\sigma \dot{\varepsilon}} \int_{0}^{\dot{\varepsilon}} \sigma d\dot{\varepsilon} \right) \] (6)

Then a new condition for the instability has been established as

\[ \xi_3(\dot{\varepsilon}, T) = \frac{2m}{\eta} - 1 < 0 \] (7)

This instability criterion is valid for any type of constitutive relation due to a strict theory basis, but it is difficult to take the calculation of integration.
3.4. Gegel’s and Malas’s criteria

Considering a Lyapunov function \( L(\eta, s) \), Gegel [14] suggested the following conditions for the stable material flow

\[
0 < m \leq 1
\]

\[
\frac{\partial \eta}{\partial \ln \dot{\varepsilon}} < 0
\]  
(8)

\[
s \geq 1
\]  
(9)

\[
\frac{\partial s}{\partial \ln \dot{\varepsilon}} < 0
\]  
(10)

\[
\frac{\partial m}{\partial \ln \dot{\varepsilon}} < 0
\]  
(11)

where \( s \) is the temperature sensitivity and can be written as

\[
s = \frac{\partial \ln \sigma}{\partial (1/T)}
\]  
(12)

Similarly, on the basis of the Lyapunov function \( L(m, s) \), Malas [15] proposed that the parameter \( m \) can be used to substitute the \( \eta \) in Gegel’s criterion. Apart from Eqs. (8), (10) and (11), the new condition for material flow is given by the strain rate sensitivity \( m \) as

\[
\frac{\partial m}{\partial \ln \dot{\varepsilon}} < 0
\]  
(13)

Then the instability criteria can be written as

\[
\xi_4 = m < 0
\]  
(14)

\[
\xi_5 = -\frac{\partial \eta}{\partial \ln \dot{\varepsilon}} < 0
\]  
(15)

\[
\xi_6 = s - 1 < 0
\]  
(16)

\[
\frac{\partial s}{\partial \ln \dot{\varepsilon}} < 0
\]  
(17)

\[
\xi_8 = -\frac{\partial m}{\partial \ln \dot{\varepsilon}} < 0
\]  
(18)

It should be pointed out that in both Gegel’s and Malas’s flow instability criteria, the flow stress with respect to strain rate should be convex in nature and the material should exhibit flow softening with increase in temperature. Furthermore, as per Malas’s criteria, the strain hardening should increase with decreasing strain rate and increasing temperature.

4. Results and discussion

4.1. Hot deformation behavior of Ti17 alloy

Typical true stress–true strain curves at 860°C and different strain rates are shown in Fig. 2, which are representative of the \( \alpha+\beta \) deformation behavior. All the curves exhibit flow softening at all strain rates. In addition, the stress–strain curves of Ti17 alloy display significant oscillatory flow at higher strain rates (\( \gtrsim 1 \text{s}^{-1} \)). Those broad oscillations may be induced by instable deformation. However, it should be noted that different mechanisms can exhibit similar stress–strain behavior and conclusions based on the shapes of the curves may be erroneous. For example, oscillatory stress–strain curves have been observed during dynamic recrystallization as well as during unstable flow. Flow softening may indicate lamellar globularization [20], DRX [21], adiabatic heating band [22], voids and cracks formation [23], etc. In view of this difficulty, further analysis of the flow stress in terms of its variation with temperature and strain rate should be conducted to evaluate the mechanisms of hot deformation.

![Fig. 2. Typical true stress–true strain curves obtained on Ti17 alloy at 860°C and different strain rates.](image)

![Fig. 3. Instability map developed as per Semiatin’s criterion for Ti17 alloy. The shaded regime corresponds to flow instability \((\xi_1)\).](image)

4.2. Variant instability maps

Different instability parameters have been formulated (Eqs. (4), (5), (7), (14)–(18)) and plotted in Figs. 3–7. The values of \( \alpha \) evaluated using the flow stress data of Ti17 alloy at different temperatures and strain rates and a strain of 0.9 are given in Table 2. It can be seen from Table 2 that the stable flow predicted by the criterion was at lower strain rate since \( \xi_1 \) is greater than zero. At the high strain rate of 10 \text{s}^{-1}, the value of \( \xi_1 \) is below zero and the magnitude increases with temperature. Therefore, plastic instability and flow localization are predicted to occur in this material at temperature higher than 830°C and strain rates faster than 1 \text{s}^{-1} as shown in Fig. 3.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Strain rate (s⁻¹)</th>
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<tbody>
<tr>
<td></td>
<td>0.001</td>
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<tr>
<td>780</td>
<td>1.88</td>
</tr>
<tr>
<td>800</td>
<td>2.93</td>
</tr>
<tr>
<td>820</td>
<td>2.32</td>
</tr>
<tr>
<td>840</td>
<td>6.82</td>
</tr>
<tr>
<td>860</td>
<td>8.18</td>
</tr>
</tbody>
</table>

Table 2: Values of \( \xi_1 \) parameter (Eq. (4)) calculated at different temperatures and strain rates and a strain of 0.9.
The instability map developed by Prasad’s criteria using the data obtained from the compression tests at strain of 0.9 is presented in Fig. 4. The contour number represents the efficiency of power dissipation ($\eta$), and the shaded regime corresponds to instability parameter ($\xi_2$). It can be seen that the efficiency of power dissipation $\eta$ increases with the increasing of deformation temperature and decreasing of strain rate. The peak of $\eta$ appears in the high temperature and low strain rate regime, indicating a good workability. Also, the criterion predicts a flow instability region in the entire temperature range and strain rate range of $1-10 \, \text{s}^{-1}$. It may be noted that the yielding and oscillation in the flow curves (Fig. 2) and the phenomenological criterion instability predictions are also in support of this prediction.

Fig. 5 shows the predicted stable and unstable domains of material flow in the temperature and strain rate window using the Murty’s instability criterion. It could be observed that the map developed as per criterion shows similar domains as that of Prasad’s flow instability criterion (Fig. 4). However, the domains of this instability map are a little wider than the unstable domains revealed in Fig. 4.
Microstructural validation and comparison of instability criteria

Microstructural study on the deformed specimens was carried out to confirm the predictions made by the previous criteria, and to make a comparison of the instability criteria.

Due to the strict theoretical inferences and calculations of Murty’s criterion, validation of all the unstable domains of the Murty’s criterion based instability map would collectively corroborate these five instability maps (Figs. 3–7). The micrographs of the specimens deformed at unstable regions are shown in Fig. 8. The specimen deformed at 780 °C/10 s\(^{-1}\) (representative area at low temperature and high strain rate) shows adiabatic shear band in the microstructure (Fig. 8a). A similar observation was made by Wang et al. [24] which suggested the adiabatic shear band may be occurred at low strain of 0.36. Another deformation condition (860 °C/10 s\(^{-1}\)) in the unstable domain manifests flow localization (Fig. 8b). The microstructure of the specimen deformed at 780 °C/1 s\(^{-1}\), which is also lied in the unstable domain predicted by the Prasad’s, Murty’s, Gegel’s and Malas’s criteria, reveals a small number of break-up and kinked α lamellas (Fig. 8c). And the specimen deformed at 860 °C/1 s\(^{-1}\) shows intense kinked and several globularized α phase (Fig. 8d). The local kinking of α lamellas may be induced the significant oscillatory flow of the stress–strain curves at high strain rates (≥ 1 s\(^{-1}\)) in Fig. 2. The microstructure of the specimen deformed at 800 °C/0.001 s\(^{-1}\) which represents the domain predicted by Gegel’s and Malas’s criteria is shown in Fig. 8e. It can be observed that the microstructure shows homogeneous distribution of globularized α phase and a few residual lamellar α. Such a microstructure is not bad for the component as mentioned in Ref. [4]. In contrast, typical microstructure in the stable domain (860 °C/0.001 s\(^{-1}\)) exhibits much homogenous distribution of equiaxed α (Fig. 8f), which is desirable and expected to augment the material’s performances.

Also it has been observed that instability map developed as per Gegel’s criterion as well as Malas’s criterion shows similar and much greater unstable domains than the other criteria. However, these domains are interconnected. Microstructure evolution of the sample deformed at 840 °C/0.01 s\(^{-1}\) is shown in Fig. 8g. It may be noted that this hot processing condition falls within the unstable domain of map developed as per Gegel’s and Malas’s criteria but lie outside the unstable domain of instability map developed by Prasad’s and Murty’s criteria. It can be found from Fig. 8g that the microstructure does not indicate any kind of flow instability.

The comparison of all the instability maps and the microstructure validation shows that Semiati’s criterion under–predicts the instability regions in the deformation temperatures and strain rates. The reason for the under prediction of Semiati’s criterion could be attributed to the fact that the criterion was just developed on the basis of force equilibrium approach and applied for plane strain compression test [18]. That is, the parameter of α is defined and derived by the rate of flow softening and the strain rate sensitivity parameter except for temperature factor. Gegel’s and Murty’s criteria found to over-predict the instability domains. These criteria can predict the flow instability at high temperature and low strain rate (Figs. 6 and 7), which is not predicted by Prasad’s and Murty’s criteria under the test conditions. It is maybe related to the wedge cracking. However, the instability map developed by Prasad’s and Malas’s criteria could predict the unstable domains for Ti17 alloy during the hot processing more precisely than the other instability criteria.

It can be seen from the processing map of Ti17 alloy that all kinds of instability criteria are not consistent completely. Therefore, these criteria should be chosen carefully and considered comprehensively in practical application. In the present research, the Murty’s...
instability criteria should be selected for more accurate predictions because of its strict theoretical inferences and calculations.

5. Conclusions

The instability of Ti17 alloy has been studied based on the various existing instability criteria, including Semiatin's criterion, Prasad's criterion, Murty's criterion, Gegel's and Malas's criteria. Instability maps were developed based on these criteria to delineate the unstable domains employing stress–strain data obtained from isothermal hot compression tests in the range of 780–860 °C and 0.001–10 s⁻¹. From the analysis of the obtained results and microstructure observation, the following conclusions are drawn:

1. It has been observed that Semiatin's criterion under-predicts the instability regions whereas Gegel's and Malas's criteria over-predict the instability domains in the studied temperatures and strain rates at a certain strain of 0.9.
2. The maps at strain of 0.9 developed by Prasad's and Murty's criteria have been found to predict the unstable domains for Ti17 alloy with high reliability.
3. The material exhibited stable flow at lower strain rates while flow instabilities occurred at higher strain rates (≥1 s⁻¹) and
entire temperatures. The microstructural manifestations of these instabilities are in the form of adiabatic shear band and flow localization.

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References