Effect of microstructure on the high-temperature deformation behavior of Ti-48Al-2W intermetallic compounds

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Abstract

The effect of microstructure on high-temperature deformation behavior of Ti-48Al-2W intermetallic compounds has been investigated in compressive tests performed at 1100 and 1200°C. The microstructures were controlled as near \( \gamma \), duplex and near lamellar structure by heat treatments of cast ingots at 1250, 1300 and 1350°C, respectively. The stress–strain curve exhibits a peak stress, which is followed by a gradual decrease into a steady state with increasing the strain. The peak flow stress was the highest in the near lamellar structure. The flow softening rate is higher in the near lamellar structure than that in the near \( \gamma \) structure. The flow softening behavior of near \( \gamma \) Ti-48Al-2W was due to a dynamic recrystallization of \( \gamma \) grains. The flow softening behavior in near lamellar Ti-48Al-2W was occurred by kinking, rotating and globularization of lamellars. The flow localization and shear bands were observed in near lamellar structure during the high-temperature deformation. The flow localization parameters were calculated from the analysis based on the instability condition. The flow localization in the near lamellar structure was due to a higher flow softening rate. © 1999 Published by Elsevier Science S.A. All rights reserved.

Keywords: TiAl Intermetallic compounds; Flow softening; Dynamic recrystallization; Shear band; Flow localization

1. Introduction

TiAl-base intermetallic compounds have been investigated for aerospace and automotive engine components due to their attractive properties such as low density, good elevated temperature strength, high resistance to oxidation and excellent creep properties [1–3]. Thermomechanical treatment has been used for the homogenization and grain refinement in order to optimize the required mechanical properties of TiAl-base intermetallic compounds [4–8]. Several studies have been conducted to evaluate the hot workability and to investigate the microstructure evolution during hot working of TiAl-base intermetallic compounds. Most of the previous researchers reported the flow softening behavior during high-temperature deformation of TiAl-base intermetallic compounds [6–17]. It is well established that the flow softening of the \( \gamma \) single phase or near \( \gamma \) phase is attributed to the effects of dynamic recrystallization of \( \gamma \) phase [6–8,11–16]. While the flow softening mechanism of \( \gamma \) phase is well documented, the flow softening of lamellar phase may occur by mechanism other than the dynamic recrystallization such as kinking and reorientation of lamellar boundaries and spherodization of \( \alpha \) phase [9–12,17].

The understanding of softening mechanism and microstructure evolution during the hot working is important to develop a sound processing route to avoid the defects such as micro-cracking and localized shear band, which induce the brittle fracture. It has been reported that the two-phase alloys, such as \( \alpha + \beta \) titanium alloy, are particularly susceptible to shear bands during the hot forging [18]. Therefore, the flow softening mechanism of TiAl-base intermetallic compounds will be dependent on the initial microstructure. In addition, the hot workability and microstructural evolution during high-temperature deformation will be dependent on the initial microstructure sensitively.

In this study, the effect of initial microstructure, near \( \gamma \), duplex and near lamellar, on the high-temperature
compressive deformation behavior of Ti-48Al-2W intermetallic compounds were investigated. The flow softening mechanism was analyzed by observing the microstructure evolution during the deformation. The flow localization behaviors during the compressive deformation were discussed by analyzing the flow softening rate and strain rate sensitivity.

2. Experimental

The Ti-48Al-2W intermetallic compounds were prepared by plasma arc melting in a cold copper hearth. The melted ingots were homogenized at 1250°C for 24 h, 1300°C for 24 h and 1350°C for 2 h in argon atmosphere. Cylindrical compressive specimens, with a diameter of 8 mm and a height of 12 mm, were machined from the homogenized ingots. The high-temperature compressive tests were conducted in vacuum at temperatures of 1100 and 1200°C, and constant strain rates between $10^{-3}$ and $10^{-1}$ s$^{-1}$. Specimens were heated by induction coils with heating rate of 5°C/min and soaked for 300 s at the deformation temperatures before performing the compressive tests. The true stress–true strain curves were obtained from the load-displacement data. The true strain was calculated from the ratio of instantaneous height and initial height of specimen on the assumption of uniform deformation. In order to investigate the microstructural evolution during the deformation, the specimens were quenched from the test temperature by liquid nitrogen immediately after deforming up to various true strains. Optical micrographs were obtained from the cross-sectional surface of the deformed specimens, cut parallel to the compression axis. The cut surfaces were ground by emery paper and polished by diamond paste, and then etched with Kroll’s reagent (1 ml HF + 3 ml HNO$_3$ + 16 ml H$_2$O).

3. Results and discussion

The microstructures of Ti-48Al-2W homogenized at 1250, 1300 and 1350°C are shown in Fig. 1. The optical micrographs of Ti-48Al-2W homogenized at 1250°C for 24 h shows the near γ structure with an average grain size of 75 μm. The lamellar volume fraction increased with increasing homogenization temperature. The duplex structure was obtained after homogenization at 1300°C for 24 h. The lamellar volume fraction was measured as 55% and the average grain size of lamellar grain was measured as 100 μm. The near lamellar structure with a lamellar volume fraction of about 90% was obtained after homogenization at 1350°C for 2 h.

The stress–strain curves obtained from high-temperature compressive tests of homogenized Ti-48Al-2W intermetallic compounds are shown in Fig. 2. The stress–strain curve exhibited a peak stress at a certain strain, then the flow stress decreased gradually into a steady-state value with increasing the strain, which represents a flow softening behavior. The stress–strain
where $\sigma_p$ is peak flow stress, $\dot{\varepsilon}$ is strain rate, $K$ is constant and $m$ is strain rate sensitivity. The strain rate sensitivities, $m$, known as $d \log \sigma_p/d \log \dot{\varepsilon}$, were obtained from the slope of curves in Fig. 3. The strain rate sensitivities were measured as 0.18 and 0.23 in the near $\gamma$ structure, 0.17 and 0.19 in the duplex structure, and 0.18 and 0.21 in the near lamellar structure at 1100 and 1200°C, respectively.

The microstructure evolution during high-temperature deformation was observed to investigate the flow softening mechanism. Fig. 4 shows the change of microstructure in near $\gamma$ Ti-48Al-2W with varying strain during compressive deformation at 1200°C. The initial grain boundaries became wavy and a number of small new grains were formed at initial grain boundaries by dynamic recrystallization at a strain of 0.05. The fraction of recrystallization is measured as 55% at a strain of 0.2. The fraction of recrystallized grains increased to 90% with increasing the strain up to a strain of 0.5. The grain sizes were maintained almost constant up to a strain of 1.2. This indicates that the dynamic equilibrium is obtained due to the balance between the grain refinement through dynamic recrystallization and the grain growth during deformation. This observation is consistent with the stress–strain curve that shows the steady-state flow stress at a strain greater than 0.5, as shown in Fig. 2. The dynamically recrystallized grain size was measured as 12.5 $\mu$m at a strain of 1.2.

Fig. 5 shows the change of microstructure in near lamellar Ti-48Al-2W at strains of 0.05 and 0.2 during compressive deformation at 1200°C. In the near lamellar structure, the shearing of lamellar grains, which are oriented parallel to the compression axis, is observed at a strain of 0.05. At a strain of 0.2, an extensive kinking and rotation of lamellar was observed, and the $\alpha$ phases were globulized at the lamellar grain boundaries. The volume fraction of the globulized phase increased with increasing strain. It is noted that the shear bands were observed at a strain of 0.5 in the near lamellar structure. This indicates that a localized flow occurred during the high-temperature deformation. Fig. 6 shows microstructures of near lamellar structure deformed up to a strain 1.2 at 1200°C. The lamellar grains were fully decomposed into $\alpha$ and $\gamma$ phases in the shear band region, while the lamellar grains remained in the other region, out of shear bands. Fig. 7 shows the transverse sections of the near $\gamma$ structure and near lamellar structure that were deformed up to a strain of 1.2. The evidence of shear localization was clearly observed in the deformed specimen of near lamellar structure.

The flow localization condition occurs during the uniaxial compressive deformation when the deformation is concentrated at a localized region. The flow localization could propagate when the instability condi-
tion was satisfied [18–20]. It is assumed that an instability condition occurs when the following condition is satisfied:

\[ dF = \sigma \, dA + A \, d\sigma = 0 \]  

(2)

When the localization occurs along a direction of pure shear, \( dA = 0 \) in Eq. (2). Since the flow stress is a function of strain, strain rate and temperature, Eq. (2) can be expressed as

\[ 0 = \frac{d\sigma}{d\varepsilon} = \left[ \frac{\partial \sigma}{\partial \varepsilon} \right]_{\varepsilon, T} \, d\varepsilon + \left[ \frac{\partial \sigma}{\partial \varepsilon} \right]_{\varepsilon, T} \, d\varepsilon \]  

(3)

The normalized strain softening rate, \( \gamma^* \), is expressed as:

\[ \gamma^* = \frac{1}{\sigma} \frac{d\sigma}{d\varepsilon} = \left[ \frac{\partial \sigma}{\partial \varepsilon} \right]_{\varepsilon, T} \, d\varepsilon + \left[ \frac{\partial \sigma}{\partial T} \right]_{\varepsilon, T} \, dT \]  

(4)

and the strain rate sensitivity, \( m \), is defined as following,

\[ m = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}} \bigg|_{\varepsilon, T} = \frac{\dot{\varepsilon}}{\sigma} \frac{\partial \sigma}{\partial \dot{\varepsilon}} \bigg|_{\varepsilon, T} \]  

(5)

By inserting Eqs. (4) and (5) into Eq. (3), the following equation can be obtained:

\[ 0 = \gamma^* \sigma \, d\varepsilon + \frac{\sigma}{\dot{\varepsilon}} m \, d\dot{\varepsilon} \]  

(6)

Rearranging Eq. (6),

\[ (\frac{1}{\dot{\varepsilon}}) \frac{d\dot{\varepsilon}}{d\varepsilon} = -\frac{\gamma^*}{m} \equiv \alpha \]  

(7)

The term \(- (1/\dot{\varepsilon})(d\dot{\varepsilon}/d\varepsilon)\) represents the fractional change in strain rate with strain, which is referred as \( \alpha \). The tendency for flow localization increased with increasing strain softening rate and with decreasing strain rate sensitivity. The flow softening rates, which are defined as Eq. (8), during the deformation of the near \( \gamma \) structure and near lamellar structure are shown in Fig. 8.

\[ \gamma^* = \frac{1}{\sigma} \frac{d\sigma}{d\varepsilon} \]  

(8)

where \( \gamma^* \) is the flow softening rate, \( \sigma \) is flow stress and \( \varepsilon \) is true strain. Fig. 8 shows that the flow softening rate

Fig. 4. Microstructures of near \( \gamma \) Ti-48Al-2W intermetallic compounds deformed at 1200°C with a strain rate of 10\(^{-3}\) s\(^{-1}\). (a) Deformed up to a strain of 0.05, (b) deformed up to a strain of 0.2, (c) deformed up to a strain of 0.5, and (d) deformed up to a strain of 1.2.
is higher in the near lamellar structure than in the near γ structure at a fixed strain. The flow softening in Ti-48Al-2W is attributed to the effect of microstructure change during the deformations such as dynamic recrystallization in near γ and globulization of α phase in the near lamellar structure. It was reported that the decrease of flow stress with increasing stain after peak stress is due to an increase of volume fraction of recrystallized grains. The rate of recrystallization increased with decreasing strain rate and with increasing temperature. As a result, the flow softening rate increased with increasing temperature and with decreasing strain rate.

Theoretically, the flow localization starts when \( x \geq 0 \) as shown in Eq. (7). Semiatin and Lahoti [18] and Jonas et al. [19] showed experimentally that the materials with \( x \) parameters of 5 or greater are susceptible to flow localization. The flow localization parameters, \( x \), of the near γ and near lamellar structures with varying strain are shown in Table 1. In the near γ structure, the maximum flow localization parameters were measured as 5.0 at 1100°C and 4.7 at 1200°C, while the maximum flow localization parameters were measured as 10.0 at 1100°C and 18.1 at 1200°C in the near lamellar structure. Considering the instability condition of \( x > 5 \) for significant flow localization, the localized flow and shear band would be expected to occur during the deformation in the near lamellar structure but not in the γ structure. This prediction is well confirmed by the microstructural observation as shown in Fig. 7. It is also noted that the localization parameters are larger than 5 at low strain (\( \varepsilon = 0.05 \) and \( \varepsilon = 0.2 \)) in the near lamellar structure. This means that the flow localization and shear band initiated at low strain. When a flow-localized region is formed, the localized region could self-propagate easily because the localized region is a softer region than the other region. Thus, an extensive shear band was formed in the near lamellar structure.

The schematic diagrams of microstructural evolution during the compressive deformation in near γ and near lamellar structure are illustrated in Fig. 9. In the near γ structure, the observed flow softening behavior was attributed to the dynamic recrystallization of γ phases during high-temperature deformation. The dynamic recrystallization of γ grains initiated at grain boundaries at low strain. The volume fraction of recrystallized...
Fig. 6. Microstructures of near lamellar Ti-48Al-2W intermetallic compounds after deformation up to a strain of 1.2 at 1200°C with strain rate of $10^{-3} \text{s}^{-1}$. (a) Unlocalized deformed region and (b) localized shear deformed region.

Fig. 7. The transverse cross-sections of cylindrical specimens compressive deformed up to a strain of 1.2 at 1200°C with strain rate of $10^{-3} \text{s}^{-1}$ in near $\gamma$ and near lamellar Ti-48Al-2W.

4. Conclusions

The effect of initial microstructure on high-temperature compressive deformation behavior of Ti-48Al-2W intermetallic compounds was investigated. The microstructures were controlled as near $\gamma$, duplex and near lamellar structure by heat treatments at 1250, 1300 and 1350°C. The stress–strain curves of near $\gamma$, duplex and near lamellar Ti-48Al-2W showed a flow softening.

Fig. 8. The variations of flow softening rate during high-temperature compressive deformation of near $\gamma$ and near lamellar Ti-48Al-2W.

were sheared, kinked and rotated at low strain. At the same time, the $\alpha$ phases were globulized at the lamellar grain boundaries. The deformation was concentrated at the globulized region because the globulized region is softer than the other region. As a result, the shear band was formed along the globulized regions in the near lamellar structure.
Table 1
The flow localization parameters, $\alpha$, measured at various strains in near $\gamma$ and near lamellar Ti-48Al-2W

<table>
<thead>
<tr>
<th>Initial microstructure</th>
<th>Deformation condition</th>
<th>Flow localization parameter, $\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\dot{\varepsilon} = 0.05$</td>
<td>$\dot{\varepsilon} = 0.2$</td>
</tr>
<tr>
<td>Near $\gamma$</td>
<td>$1100^\circ C/10^{-1}$ s$^{-1}$</td>
<td>2.35</td>
</tr>
<tr>
<td></td>
<td>$1200^\circ C/10^{-3}$ s$^{-1}$</td>
<td>4.5</td>
</tr>
<tr>
<td>Near lamellar</td>
<td>$1100^\circ C/10^{-1}$ s$^{-1}$</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>$1200^\circ C/10^{-3}$ s$^{-1}$</td>
<td>18.1</td>
</tr>
</tbody>
</table>

Fig. 9. Schematic representations of the microstructure evolution during high-temperature deformation of near $\gamma$ and near lamellar Ti-48Al-2W.

behavior during the deformation at 1100 and 1200°C. The highest peak stress and largest amount of flow softening were exhibited in the near lamellar structure. The flow softening was due to a dynamic recrystallization of $\gamma$ grains in the near $\gamma$ structure, while the flow softening occurred by kinking, rotating and globularization of lamellar in the near lamellar structure. The flow localization and shear bands were observed in the near lamellar structure during the high-temperature deformation. The flow localization in the near lamellar structure was due to a higher flow softening rate.

References