Dynamic Deformation and High Velocity Impact Behaviors of 
TI-6Al-4V Alloys

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Abstract. Deformation behaviors under quasi-static and dynamic compression and high velocity impact condition of Ti-6Al-4V ELI (extra low interstitial) alloys in two different conditions were investigated. Mill annealed (MA) alloy, consisted of equiaxed α, and thermomechanically treated (TMT) alloy, consisted of mixed structure of equiaxed α and transformed β, were prepared. Compression tests were performed in low strain rate regime using hydraulic testing machine and were performed in high strain rate regime using split Hopkinson pressure bar. High velocity impact tests were also performed by impacting the test projectiles made of these alloys against a steel target at a velocity of ~400m/s. The compression test results showed that deformation behaviors were influenced by the strain hardening exponent at low strain rate regime, and by both the strain hardening exponent and the strain-rate hardening rate at high strain rate regime. TMT alloy showed higher strength but almost similar fracture strain as MA alloy at a high strain rate of ~6000/s, due to the effect of strain-rate hardening. The high velocity impact test results showed that the projectile of TMT alloy withstood without fracture at higher impact velocity, but the maximum amounts of deformation prior to crack were nearly the same for both alloys. These results were in accord with the results of compression tests at high strain rate regime, that is, higher strength but same fracture strain of TMT alloy compared to MA alloy.

1. Introduction

Ti-6Al-4V, a typical α + β titanium alloy, has been used for structural materials of aircraft due to its high specific strength and excellent mechanical properties. The mechanical properties of this alloy are closely related with the microstructural features such as the shapes, sizes or fractions of α and β phases [1]. In addition, this alloy showed superior ballistic properties against armor piercing rounds than steel or aluminum armor, and is employed as an armor material for combat vehicles [2].

It is known that mechanical behaviors under the dynamic deformation condition such as ballistic impact are different to those under the quasi-static deformation conditions. A few researches have been performed to examine the effects of microstructure on the mechanical properties under the dynamic deformation condition and on the ballistic properties for this alloy [3,4], but the relationship between mechanical properties and behaviors at high velocity impact is not clearly understood until now.

The objective of this research is to investigate the effects of the mechanical properties at quasi-static and dynamic deformation condition on the high velocity impact behaviors. Performing the compression tests both at low strain rate (2x10⁻³~2/s) regime and at high strain rate (3000~6000/s) regime, mechanical properties and deformation behaviors of Ti-6Al-4V alloys in two different conditions are examined. High velocity impact behaviors are characterized by impacting the test projectiles made of these alloys against a steel target at the velocity of ~400m/s. Results of the quasi-static and dynamic compression tests and the high velocity impact tests are compared.
2. Materials and experimental procedures

Ti-6Al-4V ELI (extra low interstitial) grade alloys in two different conditions were used in this experiment. One was as-received billet, supplied with mill annealed condition (hereinafter referred to as MA alloy) and the other was thermomechanically treated alloy at 950°C (hereinafter referred to as TMT alloy). The chemical composition of each alloy is given in Table 1 and the microstructure is presented in Fig. 1. The MA alloy exhibited primary equiaxed α microstructure with an average grain size of 14µm and volume fraction of 90%. TMT alloy had the mixed microstructure of equiaxed α and transformed β. The average grain size and volume fraction of primary α were 10µm and ~40% respectively.

| Table 1 Chemical composition of Ti-6Al-4V ELI alloy (wt%) |
|----------------|---|---|---|---|---|---|---|---|---|
| Materials     | Al | V  | Fe | C  | O  | N  | H  | Ti | Bal. |
| MA            | 5.96 | 3.88 | 0.1 | 0.001 | 0.097 | 0.006 | 0.0076 |  |
| TMT           | 6.23 | 4.12 | 0.19 | 0.01 | 0.11 | <0.01 | 0.0004 |  |

Fig. 1 Microstructures of (a) MA and (b) TMT alloy. Kroll’s reagent etched.

Two compression tests at different strain rate regimes were performed to measure mechanical properties and examine deformation behaviors. Quasi-static compression tests at low strain rate (2x10³~2/s) regime were performed using Instron 8502 hydraulic testing machine at the constant crosshead speeds of 1, 10, 100, 1000mm/min by using cylindrical specimens of 10mm in diameter and 10mm in height. These speeds corresponded to the strain rate of 2x10⁻³, 2x10⁻², 2x10⁻¹, 2/s respectively. MoS paste was applied to reduce the friction between ram and specimen. Dynamic compression tests at high strain rate (3000~6000/s) regime were performed using split Hopkinson pressure bar (SHPB) facility [5]. The striker, incident and transmitter bars were maraging steel rods of 14.7mm diameter. Strain rates were controlled by changing the length and impact velocity of striker bar. Cylindrical specimens, 5mm in diameter and 5mm in height, were used and the same lubricant was applied. After the tests, specimens were sectioned parallel to the loading direction and then the deformed microstructures were examined using scanning electron microscope (SEM).

High velocity impact tests were performed to simulate the real ballistic behavior. The projectiles, 12.5mm in diameter and 25mm in length with hemispherical nose, were machined from two alloys. These projectiles were launched from the Cal.50 ballistic testing gun with the velocity range of 350~450m/s, and impacted to the target placed at 25m from the muzzle. Mild steel plates, 20mm thick with the hardness of HRB ~90, were used for target. The tests were started with low impact velocity. The impacted projectiles were recovered and examined whether the crack or fracture occurs or not. The tests were repeated with increasing impact velocities until the crack or fracture occurs. The amount of deformation was measured in the recovered projectiles.

3. Results and discussion

1) Compression tests

The examples of quasi-static compressive true stress-strain curves of MA and TMT alloy at the strain rate of 2x10⁻³~2/s are shown in Fig. 2(a). For all of the specimens, after initial yielding, the
flow stress increases due to the strain hardening up to maximum flow stress, then starts to decrease and fracture occurs finally. The decrement of flow stress with increasing strain is due to the effect of unstable deformation such as development of flow localization, microcrack, and so on. Thus, unstable deformation can be thought to occur at the maximum true stress ($\sigma_{\text{max}}$), and strain at $\sigma_{\text{max}}$ is defined as a strain of unstable deformation ($\varepsilon_u$). The shapes of flow curves of two alloys are similar at same strain rate, but are varied with strain rate. Fig. 2(b) shows variations of $\sigma_{\text{max}}$ and $\varepsilon_u$ with log strain rates. It can be seen that unstable deformation is initiated at lower strain as the strain rate increases, and this leads to the decrement of $\sigma_{\text{max}}$. In the viewpoint of unstable deformation, TMT alloy has higher $\sigma_{\text{max}}$ but lower $\varepsilon_u$ than MA alloy. From this result, TMT alloy can be thought to be more susceptible to the unstable deformation at this low strain rate regime.

The examples of dynamic compressive true stress-strain curves at the strain rate of 3000–6000/s are shown in Fig. 3(a). Flow stress increases with increasing strain and fracture occurs after the small drop of stress. Comparing with the flow stress curves in Fig. 2(a), the increment of stress level and the decrement of fracture strain ($\varepsilon_f$) are obvious, which are characteristics of dynamic deformation. Another difference is that fracture occurs soon after $\sigma_{\text{max}}$ without large flow softening. This behavior shows that the fracture mechanism in this strain rate regime is different from that at low strain rate regime. The variations of $\sigma_{\text{max}}$ and $\varepsilon_f$ with strain rate are shown in Fig. 3(b). $\sigma_{\text{max}}$ slightly increases, while $\varepsilon_f$ decreases with increasing strain rate. MA alloy shows higher $\varepsilon_f$ than TMT alloy, but as the strain rate increases, the difference in $\varepsilon_f$ between two alloys decreases, resulting in almost similar $\varepsilon_f$ near the strain rate of ~6000/s.

Fig. 4 (a) and (b) show the variations of compressive flow stress at true strain of 0.1 versus strain rate at low strain rate (2x10$^{-3}$~2/s) regime and high strain rate (3000–6000/s) regime. Flow stress is linearly proportional to the logarithm of strain rate at low strain rate regime while it has linear relationship with strain rate at the high strain rate regime, due to the different mechanisms of dislocation motion [5].
Fig. 4 Variations of flow stress at \( \varepsilon = 0.1 \) as a function of strain rate: (a) at low strain rate (2x10\(^3\)/s~2/s) regime and (b) at high strain rate (3000~6000/s) regime.

From all true stress-strain curves such as Fig. 2(a) and flow stress-strain rate relation for strain of 0.1~0.2 (Fig. 4(a) for \( \varepsilon = 0.1 \)) at low strain rate regime, the strain hardening exponent \((n=d(\log \sigma)/d(\log \varepsilon))\) and the strain rate sensitivity \((m=d(\log \sigma)/d(\log \dot{\varepsilon}))\) are calculated and these are shown in Table 2, where \( \dot{\varepsilon} \) is strain rate. According to the previous results on the plastic instability in compression, both \( n \) and \( m \) affect the flow localization tendency [6,7]. With the high value of \( n \), the tendency for plastic instability decreases and flow localization is suppressed into higher strain. As shown in Table 2, MA alloy has higher \( n \) value than TMT alloy has, and \( n \) decreases with strain rate. This result shows good agreement with the variation of \( \varepsilon_u \) in Fig. 2(b). Generally the effect of \( m \) on the flow localization is important in case of high strain rate deformation or high temperature deformation at which thermal softening occurs. Calculated \( m \) in Table 2 is very small because the compression is performed at low strain rate and at room temperature. So, the effect of \( m \) on flow instability is thought to be negligible in this condition.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Strain rate (2/s)</th>
<th>Strain rate sensitivity (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2x10(^3)/s</td>
<td>2x10(^2)/s</td>
</tr>
<tr>
<td>MA</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>TMT</td>
<td>0.15</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 3 shows the strain hardening exponent \((n)\) and the strain-rate hardening rate \((R=d\sigma/d\varepsilon)\) at high strain rate regime calculated from true stress-strain curves such as Fig. 3(a) and flow stress-strain rate relation for 
\( \varepsilon = 0.1 \)~0.2 (Fig. 4(b) for \( \varepsilon = 0.1 \)) respectively. Because flow stress is linearly proportional to strain rate at high strain rate regime, \( R \) is used instead of \( m \). In this strain rate regime, \( n \) is not varied with strain rate. MA alloy has higher \( n \) value than TMT alloy has, but \( R \) is higher at TMT alloy.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Strain rate (2/s)</th>
<th>Strain-rate hardening rate (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3000/s</td>
<td>4000/s</td>
</tr>
<tr>
<td>MA</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>TMT</td>
<td>0.10</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Ti-6Al-4V alloy is known to be very susceptible for adiabatic shear band (ASB) formation at dynamic compression and torsion due to its high strength, low density and low thermal conductivity. ASB occurs when local thermal softening outweighs strain hardening and strain rate hardening. So, high strain hardening and high strain rate hardening can retard the formation of ASB [8]. Higher \( \varepsilon_f \) of MA alloy than that of TMT alloy can be explained by the higher \( n \) value of MA alloy. But, in high strain rate regime, the effect of strain rate hardening becomes greater. Due to the higher \( R \) value, TMT alloy can be more hardened than MA alloy as the strain rate increases. So, higher \( R \)
value of TMT alloy can rationalize the previous observation that as the strain rate increases, the difference in $\varepsilon_f$ between two alloys decreases, which is shown in Fig. 3(b).

Fig. 5 shows the deformed microstructure after the compression test at various strain rates. All of specimens are fractured with crack at the angle of 45 degrees to the loading direction regardless of strain rates, but the fracture modes are varied with the strain rate. As the strain rate increases from $2 \times 10^{-3}$/s to 2/s, the shear deformation adjacent to the crack becomes severe and localized. At the strain rate of $\sim$2600/s, ASB is formed and fracture occurs by crack along it, but deformation of grains outside of ASB is smaller than at low strain rates.

Comparing the microstructures between two alloys deformed at $\sim$2600/s, the grains at the outside of ASB of MA alloy are more deformed than those of TMT. This seems to be the effect of strength difference originated from different microstructures, equiaxed $\alpha$ in MA alloy and mixed structure of equiaxed $\alpha$ and transformed $\beta$ in TMT alloy.

![Deformed microstructures in the fractured compression specimens at various strain rates for (a) MA alloy and (b) TMT alloy](image)

Fig. 5 Deformed microstructures in the fractured compression specimens at various strain rates for (a) MA alloy and (b) TMT alloy

2) High velocity impact tests
The shape of projectiles before and after the high velocity impact tests is shown in Fig. 6(a). Deformation occurs at the forward section of projectile and as the impact velocity increases, crack occurs at the angle of 45 degrees to the impact direction. Dent is formed at target, but due to the large deformation of projectile, there are not measurable variations in penetration depth at target with impact velocity. The impact test results are shown in Table 4. The velocity at which crack initiates is higher at TMT alloy (409m/s) than at MA alloy (369m/s) by $\sim$10%.

![Shape of projectiles before and after the impact tests, and deformation profile of the projectiles impacted at maximum deformation velocity](image)

Fig 6 (a) Shape of projectiles before and after the impact tests, and (b) deformation profile of the projectiles impacted at maximum deformation velocity.

The dimensional changes in impact area of deformed projectiles are compared in Fig. 6(b) for the projectiles at maximum impact velocity without cracking in TMT (408m/s) and MA (378m/s) alloys. Although impact velocity of TMT alloy is higher than that of MA alloy by 30m/s, the amounts of
deformation of two projectiles are nearly the same; radial strain of 19% in MA alloy and 20% in TMT alloy and longitudinal strain of 17% in MA alloy and 18% in TMT alloy. Approximate calculation yields that the average strain rate of projectile is $\sim 4000/s$ assuming that projectile has cylindrical shape and decelerates linearly during the impact. Considering that deformation occurs at the forward section only, the actual strain rate of the forward section may exceed more than 2 times of this average strain rate.

Table 4 Projectile appearances after high velocity impact test

<table>
<thead>
<tr>
<th>Material</th>
<th>$V_{\text{impact}}$ [m/s]</th>
<th>Result</th>
<th>Material</th>
<th>$V_{\text{impact}}$ [m/s]</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>MA</td>
<td>368</td>
<td>Deformed</td>
<td>TMT</td>
<td>407</td>
<td>Deformed</td>
</tr>
<tr>
<td></td>
<td>369</td>
<td>Cracked</td>
<td></td>
<td>408</td>
<td>Deformed</td>
</tr>
<tr>
<td></td>
<td>378</td>
<td>Deformed</td>
<td></td>
<td>409</td>
<td>Cracked</td>
</tr>
<tr>
<td></td>
<td>383</td>
<td>Crack</td>
<td></td>
<td>416</td>
<td>Cracked</td>
</tr>
</tbody>
</table>

In the high velocity impact tests, two deformed projectiles at the highest impact velocities have nearly the same strains, which are in good agreement with results of dynamic compression test, as shown in Fig. 3(b). Meanwhile, the difference in flow stress between two alloys does not decreases up to the strain rate of 6000/s as shown in Fig. 4(b). For this reason, impact velocity of TMT alloy at which crack initiates can be thought to be higher than that of MA alloy. So, TMT alloy can absorb more deformation energy than MA alloy until the fracture due to higher strength.

4. Conclusions

Compression tests of Ti-6Al-4V ELI alloys with two different conditions were performed to investigate the influence of strain rates on the mechanical properties and deformation behaviors. The strain at which unstable deformation occurs ($\varepsilon_u$) is affected by the strain hardening exponent ($n$) at low strain rate ($2\times 10^3$~$2/s$) regime, while the fracture strain ($\varepsilon_f$) by adiabatic shear band is affected by both $n$ and the strain-rate hardening rate ($R$) at high strain rate ($3000$~$6000/s$) regime.

Due to a high $n$ value, MA alloy shows higher $\varepsilon_u$ at low strain rate regime and higher $\varepsilon_f$ at high strain rate regime than TMT alloy. While having lower $n$ value than MA alloy, TMT alloy shows higher $R$ value at high strain rate regime. For this reason, the difference in $\varepsilon_f$ between two alloys decreases with strain rate, whereas difference in flow stress is preserved as the strain rate increases.

From the high velocity impact tests performed to examine the behaviors at real ballistic condition, two alloys show almost similar maximum strains prior to fracture, while TMT alloy withstand without crack at higher impact velocity. These results are in accord with the results of compression test at high strain rate regime, nearly the same $\varepsilon_f$ but higher flow stress of TMT alloy compared to MA alloy. It can be concluded that TMT alloy shows superior fracture resistance than MA alloy under high velocity impact condition.

References