Effect of Microstructure on the Johnson-Cook Constitutive Model Parameters of Ti-6Al-4V Alloy

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Abstract. Constitutive models are widely used to predict the mechanical behavior of materials. In this research, the Johnson-Cook (J-C) constitutive model parameters of Ti-6Al-4V (Ti64) alloy with different microstructural details were fitted based on the mechanical properties over a broad range of strain rates and temperatures. The results indicate that the microstructural details have a significant effect on the mechanical properties and the J-C model parameters of Ti64. The five material parameters (A, B, n, C, m) in J-C model of Ti64 exhibit completely different varying trends as a function of the equiaxed primary α-phase volume fraction and α-platelet thickness. These changes in J-C model parameters of Ti64 can be attributed to the effect of microstructural details on the dislocation nucleation and motion under different deformation conditions.

1. Introduction
As the most famous titanium alloy, Ti-6Al-4V (hereafter, Ti64) has been widely used in the industrial field in the past few decades. Ti64 is a typical dual phase titanium alloy, which contains a large amount of α-phase with hexagonal-close-packed (HCP) structure and a small amount of β-phase with body-centred-cubic (BCC) structure [1]. The mechanical properties of Ti64 depends on the microstructure type and details that can be adjusted by heat treatments [2-4]. Previous studies suggest that Ti64 with bimodal microstructure has the better comprehensive mechanical properties within a wide range of strain rates [5, 6].

Constitutive models can be used to predict the mechanical behavior of materials over a broad range of strain rates and temperatures, which is essential for numerical simulation of material properties such as workability, deformability, and so on. The material constitutive models can be roughly divided into two categories, i.e., empirical and semi-empirical based model and phenomenological and physically based model [7]. In many existing constitutive models, the Johnson-Cook (J-C) model is the most widely used empirical model due to its simple form, small calculation quantity and rapid calculation speed [7-10]. The J-C model parameters of Ti64 have been reported by many literatures [9-12]. The model parameters provided by different researchers are different, indicating that the material states (like microstructures or interstitial element content) have a significant influence on the J-C model parameters of Ti64. However, the effect of microstructural details on the J-C model parameters of Ti64 has not been extensively studied.

In this work, the microstructure of Ti64 was first adjusted through different heat treatment processes. The mechanical behavior of the heat-treated alloys was then tested at different strain rates and temperatures. The J-C model parameters of Ti64 with different microstructural details were fitted
based on the mechanical properties data. Finally, the dependence of these model parameters on the microstructural details was revealed and discussed.

2. Experimental Procedure

2.1. Material and Heat Treatments
The materials used were forged bar stocks of commercial Ti64 with a diameter of 30 mm. The beta-transus temperature ($T_{β}$) determined by differential scanning calorimetry is 993 °C. Some bars were annealed in the two-phase (α+β) regions to gain three bimodal microstructures with different primary α-phase volume fractions (denoted as B1, B2 and B3). Other rods were solution treated above $T_{β}$ and were then cooled in different ways to gain three lamellar microstructures with different α-platelet thicknesses (denoted as L1, L2 and L3). The specific heat treatment process parameters are summarized in Table 1.

| Material | Heat treatment processes $^a$ |
|----------|-------------------------------|
| B1       | 973 °C / 1 h / AC + 600 °C / 2 h / AC |
| B2       | 953 °C / 1 h / AC + 600 °C / 2 h / AC |
| B3       | 933 °C / 1 h / AC + 600 °C / 2 h / AC |
| L1       | 1013 °C / 30 min / WQ + 600 °C / 2 h / AC |
| L2       | 1013 °C / 30 min / AC + 600 °C / 2 h / AC |
| L3       | 1013 °C / 30 min / FC + 600 °C / 2 h / AC |

$^a$ AC: Air cooling, WQ: Water quenching, FC: Furnace cooling.

2.2. Mechanical Properties Tests and Microstructure Analysis
The heat-treated Ti64 were sectioned from the centre area of the bars into several compression cylinders for quasi-static (4 mm in diameter and 8 mm in thickness) and dynamic (4 mm in diameter and 4 mm thick) compression tests. Quasi-static compression tests were performed at both room and elevated (200–900 °C) temperatures under a strain rate of $10^{-3}$ s$^{-1}$ using an MTS 810 hydraulic servo machine. Tests were continuously conducted until the samples fractured or the strain exceeds 90%. Elevated temperature compression tests were carried out in a high-temperature environmental chamber. Samples were held for 60 s at the target temperature before compression. Dynamic compression tests were carried out at room temperature under a strain rate range of about 1600–5500 s$^{-1}$ utilizing a split Hopkinson pressure bar (SHPB) apparatus [9, 12].

Optical microscope (OM) and transmission electron microscope (TEM) were employed to analyse the microstructural details of the heat-treated forged bars. Samples for OM studies were prepared by electrochemical polishing, followed by etching in Keller’s reagent. The metallographical features of Ti64 were observed by a ZEISS Axio Observer A1m OM. TEM analyses were conducted by a JEOL JEM-2100 system at an accelerating voltage of 200 kV.

3. Results and Discussion

3.1. Microstructural Details of Ti64
Figure 1 shows the optical microstructures of the Ti64 obtained by different heat treatments. When annealed below $T_{β}$, the microstructure of Ti64 consists of equiaxed primary α ($α_P$) and transformed β ($β_T$), which is called the bimodal microstructure. The volume fraction of $α_P$ in the bimodal microstructure increases with decreased annealing temperature, as shown in Fig. 1(a)-(c). When annealed above $T_{β}$, the microstructure of Ti64 is composed of acicular or plate-like α, which is called
the lamellar microstructure. The thickness of these α-platelets in the lamellar microstructure increases as the cooling rate decreases, as presented in Fig. 1(d)-(f).

Figure 2 presents the TEM images of the Ti64 with different microstructural details. In bimodal microstructure (Fig. 2(a)-(c)), $\beta_f$ consists actually of small α plates precipitated from β matrix. The lath features of the α phase are more obvious in lamellar microstructure (Fig. 2(d)-(f)) under TEM observation. Figure 2 also shows that the dislocation density in Ti64 is low after heat treatments.

**Figure 1.** Optical metallographical microstructures of Ti64 after heat treatments: (a) B1, (b) B2, (c) B3, (d) L1, (e) L2 and (f) L3.

**Figure 2.** TEM images of the substructures in the heat-treated Ti64: (a) B1, (b) B2, (c) B3, (d) L1, (e) L2 and (f) L3.
The $\alpha_p$ volume fraction in three bimodal microstructures was counted statistically according to the principle of stereology [13]. Statistics were performed over 15 OM photographs. The average $\alpha$-platelet thickness in three lamellar microstructures was determined by the statistics of over 20 TEM pictures [14]. The microstructural details of the heat-treated Ti64 were listed in Table 2.

### Table 2. Microstructural details of the heat-treated Ti-64.

| Material | Microstructural details |
|----------|-------------------------|
| B1       | Bimodal microstructure. The equiaxed primary $\alpha$ volume fraction is 14.34 (± 1.63)%.
| B2       | Bimodal microstructure. The equiaxed primary $\alpha$ volume fraction is 38.16 (± 1.76)%.
| B3       | Bimodal microstructure. The equiaxed primary $\alpha$ volume fraction is 57.06 (± 2.15)%.
| L1       | Lamellar microstructure. The average $\alpha$-platelet thickness is 0.55 (± 0.05) $\mu$m.
| L2       | Lamellar microstructure. The average $\alpha$-platelet thickness is 0.86 (± 0.05) $\mu$m.
| L3       | Lamellar microstructure. The average $\alpha$-platelet thickness is 1.98 (± 0.09) $\mu$m.

3.2. Mechanical Properties of Ti64 at Different Temperatures and Strain Rates

Figure 3 shows the true stress-strain curves of Ti64 with different microstructural details obtained at different temperatures and strain rates. At room temperature and quasistatic strain rate (Fig. 3(a)), the strength (flow stress) of Ti64 increases with decreased $\alpha_p$ volume fraction and $\alpha$-platelet thickness. Conversely, the ductility (fracture strain) is worse in Ti64 with less $\alpha_p$ and narrow $\alpha$-platelet. This indicates that increasing the $\alpha_p$ content or the $\alpha$-platelet thickness can improve the ductility but reduce the strength of Ti64. Fig. 3(b) presents the stress-strain behavior of Ti64 with L2 microstructure deformed at elevated temperatures. When the test temperature rises, Ti64 displays the significant thermal softening effect [2], i.e., the flow stress declines with increased strain after yielding. As the temperature reaches or exceeds 500 °C, the plastic deformation ability of the alloy is greatly improved. Ti64 with other microstructures have similar deformation behavior. However, alloys with B1, L1 and L2 microstructures have higher maximum peak stress but faster decline in flow stress at elevated temperatures (Fig. 3(c)). Fig. 3(d) shows the mechanical behavior of Ti64 with L3 microstructure at room temperature and high strain rates. The flow stress of Ti64 increases with increased strain rate, expressing the strain rate hardening effect. When the strain rate exceeds 4000 s$^{-1}$, the fracture stress of Ti64 declines with increased strain rate, indicating that the ductility of this alloy deteriorates further at higher strain rates. Alloys with other microstructures have similar dynamic mechanical behavior. However, alloys with B1, L1 and L2 microstructures have higher flow stress but lower fracture strain at high strain rates (Fig. 3(e)). More researches on the influence of microstructural details on the mechanical properties of Ti64 can be found in Refs. [2, 14, 15].

3.3. Determination of J-C Model Parameters for Ti64 with Different Microstructural Details

J-C model was first proposed by Johnson and Cook [8], in which strain hardening effect, strain rate hardening effect and thermal softening effect are decoupled. In this case, the flow stress ($\sigma$) of materials during plastic strain ($\varepsilon$) can be expressed as:

$$\sigma = \left( A + B \dot{\varepsilon}^n \right) \left( 1 + C \ln \dot{\varepsilon}^* \right) \left( 1 - T^m \right).$$

Where $A$ is the yield stress (MPa) at reference temperature and reference strain rate, $B$ is the strain hardening coefficient (MPa), $n$ is the strain hardening exponent, $C$ is the strain rate hardening coefficient, $m$ is thermal softening exponent, $\dot{\varepsilon}^* = \dot{\varepsilon} / \dot{\varepsilon}_{ref}$ is the dimensionless strain rate with $\dot{\varepsilon}_{ref}$ being the reference strain rate ($10^3$ s$^{-1}$ in this work), and $T^m = (T - T_r) / (T_m - T_r)$ is the dimensionless homologous temperature with $T_r$ being the reference temperature (20 °C in this work) and $T_m$ the melting temperature (1660 °C [12]). All the five material parameters ($A$, $B$, $n$, $C$, $m$) in J-C
model can be easily determined based on the above-mentioned mechanical properties data. The specific fitting steps of each parameter can be found in Refs. [7, 16].

Figure 3. Typical mechanical behavior of Ti64 with different microstructural details at: (a) room temperature and a strain rate of $10^{-3}$ s$^{-1}$, (b) and (c) elevated temperature (200–900 °C) and a strain rate of $10^{-3}$ s$^{-1}$, and (d) and (e) room temperature and high strain rates (1640–5490 s$^{-1}$).

Figure 4 shows the J-C model constants of Ti64 as a function of microstructural parameters ($\alpha_p$ volume fraction and $\alpha$-platelet thickness). Fig. 4(a) indicates that the fitted parameters can better predict the dynamic mechanical behavior of Ti64. As shown in Fig. 4(b)-(f), except for $C$, the remaining parameters ($A$, $B$, $n$ and $m$) have a similar variation trend in the Ti64 having both microstructures.

The parameters involving the basic strength ($A$, $B$ and $n$) show different varying trends. The $A$ value of Ti64 decreases with increased $\alpha_p$ volume fraction and $\alpha$-platelet thickness (Fig. 4(b)). The decline trend of $A$ value is more obvious in lamellar microstructure, indicating the yield behavior of Ti64 is more sensitive to the $\alpha$-platelet thickness. The $B$ value of Ti64 first decreases and then increases with the increasing $\alpha_p$ volume fraction and $\alpha$-platelet thickness (Fig. 4(c)). The $B$ value of bimodal microstructure is higher than that of lamellar microstructure. The $n$ value of Ti64 increases with increased $\alpha_p$ volume fraction and $\alpha$-platelet thickness, as shown in Fig. 4(d). The increase degree of $n$ is more obvious in bimodal microstructure. $B$ and $n$ are parameters that reflect the work hardening behavior of the materials [17]. Dislocations are easier to activate and move in large-sized $\alpha$ phases, attributing to the loss of $\alpha/\beta$ interfaces [2, 18]. High-density dislocations make it more prone to entanglement and interaction during continuous plastic deformation, leading to the higher stress concentration level. Hence, the Ti64 containing more large-sized $\alpha$ phases possesses higher strain hardening extent ($n$ value) but lower yield stress ($A$ value). Besides, the varying trend of $A$ and $n$ is opposite, indicating that the product of $A$ and $n$ is roughly constant [17]. The variation of $B$ value with $\alpha_p$ volume fraction and $\alpha$-platelet thickness presents the non-monotonic characteristics, and the reasons need further study.

The parameter $C$ related to strain hardening exhibits the exact opposite varying trend in Ti64 as the $\alpha_p$ volume fraction and $\alpha$-platelet thickness increases, as shown in Fig. 4(e). In bimodal microstructure, the $C$ value increases with increased $\alpha_p$ volume fraction. However, in lamellar
microstructure, it decreases with increased α-platelet thickness. This suggests that Ti64 with high α_p volume fraction or small α-platelet thickness will display a more pronounced strain rate hardening effect. More dislocations will generate in α_p during deformation [18]. These high-density defects interact more severely under high strain rate loading conditions, resulting in the increase of C value in Ti64 with bimodal microstructure having more α_p phases. In lamellar microstructure, the hindering effect of the α/β phase interfaces on dislocation motion may be dominant during high-strain-rate deformation process. This leads to the higher C value in the Ti64 consisted of narrow α-platelets.

For parameter m involving thermal softening effect, it decreases with increased α_p volume fraction and α-platelet thickness (Fig. 4(f)). The larger the m value is, the smaller the σ^* value and the bigger the σ value is. Namely, a high m value means a small thermal softening effect. Therefore, Ti64 containing less α_p or narrow α-platelets will experience a milder thermal softening during deformation at elevated temperatures, consistent with the stress-strain behavior shown in Fig. 3. As mentioned above, the dislocation density is higher in the α_p phase or the wide α-platelet. More defects mean higher distortion energy stored up in the alloy, which facilitates the dynamic recrystallization (DRX) process and further the thermal softening effect [19]. Hence, the Ti64 containing more large-sized α phases has lower m value and more obvious thermal softening effect.

4. Summary
In this work, the J-C model parameters of Ti64 with different microstructural details were extracted based on the mechanical properties of this alloy over a broad range of strain rates and temperatures. The results show that the microstructural details have a significant effect on the J-C model parameters of Ti64. The yield stress (A value) and thermal softening exponent (m value) decreases with increased α_p volume fraction and α-platelet thickness. The strain hardening coefficient (B value) first decreases and then increases with the increasing α_p volume fraction and α-platelet thickness. The strain...
hardening exponent \((n \text{ value})\) increases with increased \(\alpha_p\) volume fraction and \(\alpha\)-platelet thickness. The parameter \(C\) exhibits the opposite varying trend in Ti64 with bimodal and lamellar microstructures. These changes in J-C model parameters of Ti64 can be attributed to the effect of microstructural details \((\alpha_p\) volume fraction and \(\alpha\)-platelet thickness\) on the dislocation nucleation and motion under different deformation conditions.

Above results obtained in this study suggest that, to make the numerical simulation results more accurate, when choosing the constitutive model and its parameters of titanium alloys, not only the composition but also the microstructure states should be considered.

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6. References
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