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Tensile behavior and failure model of Ti–6Al–4V under different orientation and strain rate

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Abstract

In this paper, the objective was to investigate the coupling effect of different orientation and strain rate on the failure behavior of Ti–6Al–4V. The measurement was completed with the quasi static and dynamic tensile test under different orientation of 0°–90° and strain rate ranging from 0.0001–3500 s⁻¹. The strain rate term of the Johnson-Cook (J-C) failure model that considered the coupling effect of different orientation and strain rate was modified. The simulation was accomplished with the modified J-C failure model. The results indicated that the model provided a practicable method to describe the failure behavior under different orientation and strain rate. Finally, the failure form of specimen tested under different orientation and strain rate was analyzed in detail by the scanning electron microscopy (SEM).

1. Introduction

Titanium alloy is extensively used in aerospace, shipbuilding, chemical industry and other fields mainly due to their excellent qualities, including low density, high strength, outstanding corrosion resistance and heat resistance [1–3]. However, the failure damage of key components of titanium alloy occurs frequently under strong impact during the service process [4], so it is necessary to have knowledge on the failure behavior of titanium alloy under different strain rate. Since titanium alloy is a kind of strain rate sensitive material [5], the research on its failure behavior focuses on high strain rate loading [6]. Many scholars have carried out experiment on failure behavior of titanium alloy and studied the failure model, such as J–C failure model [7], Zerilli–Armstrong(Z-A) model [8] and GTN model [9]. The J–C failure model, which well described the relationship in failure strain and stress triaxiality, strain rate and temperature, is well widely used in finite element simulation [10]. Verleysen et al. [11] established the J-C failure model by quasi-static and dynamic tensile, and it was found that the failure behavior of Ti–6Al–4V was effectively represented by the J–C failure model. Wang et al. [12] based on J-C constitutive and fracture models of Ti–6Al–4V to describe the stress state along the adiabatic shear band and found that the new J-C model has a high accuracy. Xiao et al. [13] explored the effect of strain rate on the failure behavior, the J-C failure model of Ti–6Al–4V was modified and the results of model were in accordance with the experiment. Bobbili et al. [14] modified J-C constitutive and failure model of Ti–10V–2Fe–3Al and these results showed that the constitutive and failure model was capable describing the plastic flow and failure behavior when the strain rate and the temperature was high. Biswas et al. [15] investigated the impact of strain rate on the tensile behavior of Ti–6Al–4V in a wide strain rate range of, \(1 \times 10^{-3} \sim 8 \times 10^{3} \text{s}^{-1}\). The J-C constitutive and failure model was modified and the accuracy of the model was verified. Bobbili et al. [16] modified J-C constitutive and failure model of Ti–5.8Al–3.0Sn–3.33Zr–0.38Nb–0.32Mo–0.33Si under different strain rate, it was observed that the simulations of plastic flow and failure behavior were in good accordance with the experiment. However, most studies on failure model concentrated on the impact of strain rate. Significant performance differences were also discovered under different orientation of titanium alloy, like Ti–5.6Al–4.8Sn–2.0Zr–1.0Mo–0.85Nd–0.34Si [17], Ti–15Mo–2.7Nb–3Al–0.2Si [18] and Ti–6Al–4V [19]. Although there had been some works on mechanical properties under different
orientation of this alloy, few investigations had been done on the coupling effect of different orientation and strain rate. In this study, the coupling effect of different orientation and strain rate on the failure behavior of Ti–6Al–4V was explored by quasi static and dynamic tensile test at room temperature. A modified J-C failure model was established to describe the coupling effect of different orientation and strain rate on failure strain. The simulation about the failure behavior was completed with the ANSYS/LS-DYNA. The accuracy of the J-C failure model was verified by experiment and the model provided a method to express the failure behavior under different orientation and strain rate. Finally, failure behavior of tested specimen was investigated by SEM.

2. Experiment method

2.1. Experiment specimen

The Ti–6Al–4V used in the experiment was obtained after being rolled and pre-stretched. The alloy composition (% by mass) is Al5.5, V4.2, Fe0.08, C0.06, H0.01 etc, and the rest is Ti.

Figure 1(a) illustrates the orientation of specimen acquisition. The size of the specimen used for the quasi static tensile and the dynamic tensile was designed in figures 1(b) and (c), respectively. The thickness of specimen used in both experiments was 2 mm. Each set of experiment was repeated at least three times for the promoting accuracy in test data.

2.2. Tensile test

The change of strain rate in two kinds of experiments was determined by the tensile velocity (V) and the gauge distance (L) of specimen. The formula of strain rate [20] was shown in equation (1):

\[ \dot{\varepsilon} = \frac{V}{L} \]  

(1)

The universal test machine, with structure as reported in figure 2, was used for performing the quasi static tensile test. The strain rate was 0.0001 s⁻¹, 0.001 s⁻¹, 0.01 s⁻¹ and 0.1 s⁻¹, respectively.

The dynamic tensile test was carried on using the split hopkinson tension bar (SHTB). The main parts of the SHTB are displayed in figure 3. The experiment principle was that the specimen was clipped in the middle of the input bar and the output bar, and the input bar was promoted by the hit of the impact bar, so that the data can be obtained by the strain gauge. In the conventional SHTB [21], the specimen was clipped with the input bar through thread, the interference signal would be generated in the thread clearance and the space in the middle of the specimen and the screw hole bottom of the input bar, which would lead to the experimental results were incorrect. Hence, the plate specimen was adopted in the experiment, which was pressed with screw between the input rod and the output rod. Strain rate was 1500 s⁻¹, 2500 s⁻¹ and 3500 s⁻¹, respectively.

2

Mater. Res. Express 6 (2019) 126320 B Zhou et al
3. Results and discussions

3.1. Tensile behavior analysis

Figure 4 depicts the failure strain under different orientation and logarithms of strain rate. It can be discovered that different orientation and strain rate played a significant role in the failure behavior. No matter how the orientation changed, the failure strain under high strain rate was much larger than that under quasi-static. There are apparent discrepancies in failure strain under different orientation, at any the strain rate. Failure strain
changed irregularly with the increased of orientation when the strain rate ranged from 0.0001 s$^{-1}$ to 0.1 s$^{-1}$. However, the failure strain decreased first, then increased and then decreased with the increase of orientation when the strain rate was high. And it was noted that the maximum failure strain was various when the strain rate was high. The maximum failure strain was 0° while the strain rate below 3500 s$^{-1}$. The maximum failure strain was 45° while the strain rate increased to 3500 s$^{-1}$.

Aimed to further analyze the sensitivity of the failure strain in strain rate and different orientation, the sensitivity of the failure strain ($m$) was introduced. The formula was shown in equation (2):

\[ m = \frac{\ln(\varepsilon / \varepsilon_0)}{\ln(\dot{\varepsilon} / \dot{\varepsilon}_0)} \]  

where $\dot{\varepsilon}$ and $\dot{\varepsilon}_0$ are the current strain rate and the reference strain rate, respectively, $\varepsilon$ and $\varepsilon_0$ are the failure strain under the current strain rate and the failure strain under the reference strain rate, respectively. In this study, the reference strain rate was 0.01 s$^{-1}$.

The $m$ at room temperature was obtained which given in table 1. ‘-’ meant that the calculation results were negative and had no significance. The results exhibited that failure strain was more sensitive under high strain rate, no matter how the orientation changed. This was identical with figure 4 that the failure strain increased suddenly with the strain rate from quasi-static to high. The sensitivity was diverse under different orientation, at any strain rate. The strain is the most sensitive at 0° and it meant that the failure strain at 0° was more sensitive to strain rate. The failure behavior under different orientation and strain rate was significantly various. The difference between the different orientation was more obvious when the strain rate was high. Therefore, it was essential to study the failure behavior under different orientation and high strain rate.

Table 1. The sensitivity of the failure strain($m$) under different orientation and strain rate.

| Strain rate/s$^{-1}$ | Orientation/° | 0  | 30 | 45 | 60 | 90 |
|----------------------|---------------|----|----|----|----|----|
| 0.1                  | 0             | 0.10 | —  | —  | 0.02 | —   |
| 1500                 | 30            | 0.16 | 0.08 | 0.10 | 0.10 | 0.10 |
| 2500                 | 45            | 0.18 | 0.10 | 0.12 | 0.11 | 0.10 |
| 3500                 | 60            | 0.18 | 0.10 | 0.13 | 0.13 | 0.11 |

Figure 4. Failure strain under different orientation and strain rate.
3.2. Modified J-C failure model

The failure behavior of material was a phenomenon with complex physical and mechanical mechanism [22]. In the dynamic finite element method, erosion was included in the simulation of failure. The unit was deleted when the characteristic parameters (stress, strain or other parameters) achieved the specific critical value.

The failure model in J-C model [13] was a widely used failure criterion. J-C failure model definition unit was shown in equation (3):

$$D = \sum \frac{\Delta \varepsilon^p}{\varepsilon^f}$$

Where, \(D\) is failure parameter, \(D\) ranges from 0 to 1, when \(D\) is 0 means that at the initial stage, when \(D\) achieves 1 means that the material fails; \(\Delta \varepsilon^p\) is the plastic strain increment of a time step; \(\varepsilon^f\) is the failure strain at the current time step, stress state and strain rate. The failure strain [23] can be expressed as:

$$\varepsilon^f = (D_1 + D_2 \exp(D_3 \sigma^*)) (1 + D_4 \ln \varepsilon^*) (1 + D_5 T^*)$$

(4)

Where, \(D_1, D_2, D_3, D_4\) and \(D_5\) are material parameters; \(\sigma^*\) is stress triaxiality; \(\varepsilon^* = \varepsilon / \varepsilon_0\) is the dimensionless plastic strain rate; \(\varepsilon_0\) is the reference plastic strain rate; \(T^*\) is the dimensionless temperature.

At present, the parameters of original J-C failure model for Ti–6Al–4V were as follows: \(D_1 = 0.1192, D_2 = 1.5, D_3 = 3.7653, D_4 = -0.0335\) and \(D_5 = 2.1724\). Also, it has been reported from figure 4 that the distinction of failure behavior under different orientation and strain rate was obvious and it indicated that original J-C failure model cannot adequately delegate the failure behavior.

This paper established a modified J-C failure model to depict the failure behavior coupling effect of different orientation and strain rate. So, a new J-C failure model was used for the prediction of failure behavior, which would improve the strain rate term (\(D_4\)), modified J-C failure model was shown in equations (5) and (6):

$$\varepsilon^f = (D_1 + D_2 \exp(D_3 \sigma^*)) (1 + f(\varepsilon, \theta) \ln \varepsilon^*) (1 + D_5 T^*)$$

(5)

$$D_4 = f(\varepsilon, \theta)$$

(6)

Where, \(\varepsilon\) is strain rate, \(\theta\) is orientation (0°–90°).

As for the solution of \(D_4\), it can be learned from equation (4) that the failure strain and logarithm of the strain rate had a linear relationship. The least square method was used for fitting, and the reference strain rates were 0.001 s⁻¹, 0.01 s⁻¹ and 0.1 s⁻¹. \(D_4\) at different orientation and strain rate was obtained as showed in table 2.

### Table 2. \(D_4\) under different orientation and high strain rate.

| Orientation/° | Strain rate/s⁻¹ | 0 | 30 | 45 | 60 | 90 |
|--------------|-----------------|---|----|----|----|----|
|              | 1500            | 0.01592 | 0.01095 | 0.01347 | 0.01177 | 0.01578 |
|              | 2500            | 0.0204 | 0.01565 | 0.01808 | 0.01557 | 0.016 |
|              | 3500            | 0.02235 | 0.01691 | 0.02177 | 0.02016 | 0.01976 |

Figure 5. \(D_4\) fitting surface graph.
The function of $D_4$ in equation (6) can be demonstrated as a coupling of orientation and strain rate. The fitting of the $D_4$ was complex owing to the different orientation and wide range of the strain rate in the test. Hence, the $D_4$ was fitted by the 1stOpt software. Figure 5 reveals the $D_4$ fitting surface graph, it was discovered that the correlation coefficient ($R^2$) between the calculated results and the fitted results was 0.9639. It was demonstrated that the fitting surface graph can well represent the relationship between $D_4$ and orientation and strain rate, and the fitting function expression was given in equation (7).

Figure 6. Comparison of experiment and simulation: $\ddot{z} = 2500 \, \text{s}^{-1}, \theta = 60^\circ$.
3.3. Validation of the J-C failure model

Simulations were completed by using ANSYS/LS-DYNA to investigate the failure behavior under different orientation and strain rate. Figures 6(a)–(e) demonstrates the tensile process of Ti–6Al–4V. Figure 6(f) was the failure form in experiment. It can be concluded that the simulation can accurately simulate the failure process, and the ultimate failure mode was in good agreement with the experiment. It also been seen that the plastic deformation in the simulation was small, which was in agreement with the experiment.

It can be learned from figure 7 that the simulation results of the failure strain under different orientation and strain rate displayed good coincidence with the experiment. With the increased of orientation, the trend of simulation and experiment was essentially same under the same strain rate, and the model maximum error was 10%. Simulation and experiment error was acceptable within experiment tolerance. Compared with the experiment, it was found that the simulation was smaller. The reason of the error was that the stress triaxiality and temperature term did not consider the effect of different orientation. It also can be learned that the failure strain increased with the increase of the strain rate, no matter how the orientation changed.

3.4. Fracture morphology analysis

The fracture specimen of Ti–6Al–4V failed under all high strain rate and orientation is demonstrated in figure 8. It can be seen that the fracture surface under different orientation and high strain rate was uneven, and the dimple was different in depth. Each fractured surface consisted of many dimples which resulted in the ductile fracture [24]. The fracture mechanism was dominated by void nucleation, growth and polymerization. It was clearly seen that the shape of the dimple was mainly equiaxed, the shape and size of the dimple was different, and the big dimple contained some small dimple. It can be noted that the dimple size and depth gradually increased with the increase of the strain rate, which caused the failure strain became larger (figure 7).

The difference of dimple direction (yellow arrow) was obvious under same strain rate (figure 8). Because the grain arrangement of titanium alloy was various under different orientation [25], deformation of grain was different when the loading was acted, which led to the different direction of dimple. The direction of dimple disparity became more and more obvious with the increased of strain rate, which resulted in the larger disparity of failure strain. The higher the strain rate was, the more the void appeared. As the strain rate increases, the recrystallization became insufficient, the work hardening cannot be eliminated in time, and the stress concentration cannot be eliminated timely, leading to premature void inside the material. More ridge-like tear edge was appeared with the strain rate increased to 3500 s$^{-1}$. The reason was that the significantly increase of strain between adjacent dimples would result in the stress concentrated. The larger the strain rate was, the faster the deformation was, and the edge of the dimple quickly shrank into a line and eventually tearing. The shape and size of the dimple was relatively uniform when the strain rate was less than 3500 s$^{-1}$. Large dimple was appeared

\[
D_k = 9.86 \times 10^{-7} + 4.59 \times 10^{-6} \varepsilon - 2.56 \times 10^{-10} \varepsilon^2 - 1.41 \times 10^{-3} \theta + 7.24 \times 10^{-3} \theta^2 - 1.23 \times 10^{-6} \theta^3 + 6.6 \times 10^{-9} \theta^4
\]
at 90° (Figure 8(c1)) and 45° (Figure 8(c3)) when the strain rate was 3500 s⁻¹, and the shape of the dimple became uneven. The shape of the dimple was clearly distinguishable from other orientations when the orientation was at 60° (Figure 8(c2)) and the strain rate was 3500 s⁻¹.

4. Conclusions

This paper was aimed to investigate the coupling effect of different orientation and strain rate on the failure behavior of Ti–6Al–4V. Some significant conclusions can be acquired from the analysis of the results:

(1) The failure behavior at room temperature was impacted significantly by different orientation and strain rate. The failure strain decreased first, then increased and then decreased with the increase of orientation when the strain rate was high. The sensitivity of failure strain was various under different orientation and strain rate, and the most sensitive orientation was at 0°. The maximum failure strain was at 0° when the high
strain rate below 3500 s\(^{-1}\). The maximum failure strain was at 45° while the strain rate increased to 3500 s\(^{-1}\).

(2) The new J-C failure model was modified and verified. The ultimate failure mode was in good coincidence with the experiment. The trend of simulation and experiment was essentially same under same strain rate. The maximum error between the simulation and the experiment was 10\%, which indicated that the new model can exact predict the failure behavior under different orientation and strain rate.

(3) The failure mode was ductile fracture, no matter how the orientation and strain rate changed. The difference of dimple direction was obvious under different orientation and high strain rate. The dimple at 45° was the biggest and the dimple shape at 60° was obviously distinction with other orientations when the strain rate was 3500 s\(^{-1}\). The higher the strain rate was, the bigger the dimple was, and the larger the failure strain became. The direction of dimple disparity became more and more obvious with the increased of strain rate, which resulted in the larger disparity of failure strain.

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