Effect of microstructure on the mechanical properties of Ti–5Al–5Mo–5V–1Cr–1Fe alloy

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A R T I C L E   I N F O

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Temperature
Microstructure type
Adiabatic shear bands

A B S T R A C T

Systematic investigation of microstructure on the dynamic behavior of titanium alloys is seldom reported in the literature. In order to further understand this topic, four types of heat treatment and hot processing are designed, resulting in the following microstructures: e.g., bimodal structure, equiaxed structure, basketweave structure and Widmanstätten structure. The mechanical response of Ti–5Al–5Mo–5V–1Cr–1Fe (Ti-55511) is characterized over a wide range of strain rates and temperatures. The findings of this experimental demonstrate that Ti-55511 alloy is a strain rate and temperature sensitive material. The results also show that the Johnson-Cook constitutive equation can be utilized to predict the dynamic behavior of Ti-55511 alloy. Moreover, adiabatic shear susceptibility is affected by microstructure type and tested temperature. Microstructural observation of the samples deformed at high strain rates indicate that the formation of the adiabatic shear band is highly influenced by the microstructure type, and shear failure is the main failure mechanism. To fully utilize the potential of the material, engineers can choose the optimal microstructure to fabricate components according to the service requirements.

1. Introduction

Ti–5Al–5Mo–5V–1Cr–1Fe (Ti-55511), a typical near β titanium alloy, is of great importance in aerospace and automotive industrial applications due to its highly attractive properties, such as high strength-to-weight ratio, excellent combinations of corrosion, toughness and crack growth resistance [1,2].

Compared to Ti–6Al–4V alloy [3,4], Ti-55511 alloy is superior as an aircraft structural material considering its 15–20% weight reduction due to its higher strength-to-weight ratio [5]. This has attracted increasing attention to Ti-55511 alloy over the past decade [6,7]. The mechanical properties have been extensively studied, including strength, fatigue, creep and fracture toughness. Chen et al. [1] pointed out that the sample with higher rolling reduction exhibits higher strength and better ductility due to the refined grain size and fragmentation of the grain boundary α phase. Li et al. [2] found that, due to the evolution of dislocation substructures, the strength of Ti-55511 alloy increased while the ductility decreased with increasing thickness reduction. Ning et al. [8] reported that strain rate sensitivity coefficients increase with increasing deformation temperature. Shi et al. [9,10] studied the crack initiation behavior and fatigue limit of Ti-55511 alloy with basketweave microstructure. They claimed that the yield strength and subsurface-crack initiation ratio in high cycle fatigue regime can both exert positive influences on its fatigue limit. Moreover, the fracture toughness is sensitive to the microstructure. Lin et al. [11] found that strain rate or deformation amount can reduce the fraction of α. In addition, when deformed at larger deformation amounts or higher strain rates, the original lamellar α phases can easily transform into the spheroidal and bulk α phases.

However, the focus of the above-mentioned studies was primarily on low strain rate loading (<100 s⁻¹). In fact, in practical application, components made of Ti-55511 alloy are often loaded at higher strain rate, and the mechanical behavior and failure mechanism of Ti-55511 alloy under high strain rates are still not totally understood though some dynamic experimental investigations have been reported recently [12–15]. Moreover, except for these two above mentioned investigations [1,9], systematic assessments of microstructural effects on mechanical behavior of Ti-55511 alloy are rather scarce, and in dynamic
loading conditions are nearly non-existent. In general, the mechanical properties of Ti-55511 alloy are sensitive to the microstructures [16].

Therefore, one of the goals of this contribution is to gain deeper insight into microstructural effect on the dynamic behavior and failure mechanism of Ti-55511 alloy, and determine the constants of Johnson-Cook constitutive law (J-C model) to enrich the database of J-C model for a larger group of materials. For that purpose, four types of heat treatment and hot processing are designed, and the effect of microstructure on the mechanical behavior of Ti-55511 alloy have systematically studied.

A related subject is that of adiabatic shear susceptibility. The term “adiabatic shear band” (ASB) has been widely accepted by scholars since it was first proposed by Zener and Hollomon [17], and ASBs are found in different dynamic loading processes, such as impact deformation, dynamic punching, and ballistic impact etc. ASB is an important failure mechanism of titanium alloys in high strain rate deformation [18]. The classical explanation of ASB formation is the competition between hardening effect (strain and strain rate) and thermal softening effect [17], and a large amount of analytical and numerical work has been dedicated to the subject [19,20]. Recht [21] noted that “catastrophic shear failure” would occur when materials deformed above the critical cutting speed. Batra and Kim [22] pointed out that shear band begins to grow when the shear stress has dropped to 90% of its maximum value. Culver [23] claimed that thermal instability could occur at a strain value near the static fracture strain. To date, researchers usually using critical strain rate [21], critical stress [22], and critical strain [23] to evaluate the adiabatic shear susceptibility of materials. However, all of the aforementioned criteria are univariate, in which strain effect, strain rate effect, and thermal conductivity were not considered simultaneously. A different viewpoint show that the value of dynamic mechanical energy is constant, implying that it is a true material property [24].

Hence, the other goal of this contribution is trying to find an effective way to evaluate the adiabatic shear susceptibility for future guidance in titanium alloys processing when subjected to dynamic loading.

2. Material and methods

The material used in the present investigation was in the form of forged bar with a diameter of 61 mm from Beijing Institute of Aeronautical Materials, Aero Engine Corporation of China. The chemical composition of the as-received bar is listed in Table 1, the contents of impurities (wt%) are as follows: 0.02C, 0.03 N, 0.01H, 0.10O, 0.15Zr, 0.1Si, and readers are referred to Ran et al. [5] for further details of the investigated materials.

To investigate the microstructural effect on the dynamic behavior of Ti-55511 alloy, four types of heat treatment and hot processing were designed. The bimodal structure was achieved through typical double annealing after forging at 1133 K (below Tg). For equiaxed structure, it was forged at 1113 K (below Tg) and then heated to 1123 K for 2 h prior to air cooling (AC). For basketweave structure, it was forged at 1183 K (above Tg) and then cooled to 1123 K for 2 h prior to AC. For Widmanstatten structure, it was forged at 1133 K (below Tg) and then heated to 1173 K for 2 h before furnace cooling (FC). The schemes of processing parameters and corresponding microstructure were summarized in Table 2, and the initial microstructures are shown in Fig. 1.

As depicted in Fig. 1, the grain boundaries of basketweave structure and Widmanstatten structure are significant, while the grain boundaries of bimodal structure and equiaxed structure are hard to discern.

Three types of cylindrical specimens were electro-discharged machined from the bars, i.e. quasi-static tensile specimens with a gage length of 25 mm and a diameter of 5 mm, quasi-static compression samples with a length of 25 mm and a diameter of 10 mm, and dynamic compression samples with a length of 5 mm and a diameter of 5 mm. Based on GB/T 228.1–2010 (Metallic Materials-Tensile testing part 1: method of testing at room temperature) [25] and GB/T 7314-2017 (Metallic Materials-Compression testing at room temperature) [26], Quasi-static tensile (0.003 s\(^{-1}\)) and compression tests (0.001 s\(^{-1}\)) were conducted on cylindrical specimens in an INSTRON 5985 testing machine under displacement-controlled conditions.

Dynamic compression tests were carried out at 293 K and elevated temperatures ranging from 373 to 673 K by means of split Hopkinson pressure bar (SHPB) technique (see Fig. 2). For the sake of brevity, we will not describe the technique, and the readers are referred to Chen and Song [27] and Ran et al. [5] for further details. However, the following specific points must be noted. The elevated temperature was regulated by a Delixi TDGCG-2KVA (Hangzhou Zhuouci Instrument Co., Ltd.) controller connected to Nickel–Chromium–Nickel–Silicon thermocouple with a diameter of 1.5 mm, with the thermocouple wrapped around the samples. Prior to testing, the maximum temperature of a test sample was reached and kept around 10 min to establish a uniform temperature state in the specimens. To reduce friction and specimen barreling, vaseline and molybdenum disulfide were used to lubricate the bar-specimen interfaces at room and elevated temperature, respectively. It should be pointed out that 2–3 samples were tested for each loading condition.

When specimen reaches a state of uniform stress, the strain rate, strain and stress histories in the specimen can be determined by Refs. [27,28]:

\[ \dot{\varepsilon} = \frac{2C_0}{L_0} \dot{\varepsilon}_r, t \]  

(1)

\[ \dot{\varepsilon} = \frac{2C_0}{L_0} \int \varepsilon_r, t \, dt \]  

(2)

\[ \sigma_t = \frac{A_0E_0\ddot{\varepsilon}_t, t}{A_t} - \frac{d_0^2}{d_t^2} E_0\dot{\varepsilon}_t, t \]  

(3)

where \(A_0\) is the cross-sectional area of the bars; \(E_0\) and \(C_0\) are the Young’s modulus and elastic bar wave speed in the bar material, respectively; \(A_t\) and \(L_t\) are initial cross-sectional area and length of the specimen, respectively; \(d_0\) and \(d_t\) are the diameters of the bar and specimen, respectively. Here \(\dot{\varepsilon}_r(t), \varepsilon_r(t)\) and \(\ddot{\varepsilon}_t(t)\) represent incident, reflected and transmitted strain histories in the bars at the specimen ends, respectively.

Samples for microstructure observation were sectioned along the axial direction by electrical discharge machining, and metallographic specimens were prepared by standard mechanical grinding, polishing, and etched in Kroll’s reagent. LEICA DMI 3000 M optical microscope (OM) and HITACHI S-4800 scanning electron microscope (SEM) were utilized to characterize the microstructures.

Table 1

<table>
<thead>
<tr>
<th>AI</th>
<th>Mo</th>
<th>V</th>
<th>Cr</th>
<th>Fe</th>
<th>Ti</th>
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<tr>
<td>5.50</td>
<td>4.82</td>
<td>4.82</td>
<td>1.02</td>
<td>1.02</td>
<td>balance</td>
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Table 2

<table>
<thead>
<tr>
<th>Microstructure</th>
<th>Processing parameters</th>
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<tr>
<td>BS</td>
<td>(Tg–30) K Double Annealing</td>
</tr>
<tr>
<td>ES</td>
<td>(Tg–50) K 1123 K/2 h AC</td>
</tr>
<tr>
<td>BWS</td>
<td>(Tg, 20) K 1123 K/2 h AC</td>
</tr>
<tr>
<td>WS</td>
<td>(Tg–30) K 1173 K/2 h FC</td>
</tr>
</tbody>
</table>

Note: BS, ES, BWS, WS shown in the tables indicate bimodal structure, equiaxed structure, basketweave structure and Widmanstatten structure, respectively. Tg is the β-transus temperature. AC and FC are air cooling and furnace cooling, respectively.
3. Results

3.1. Mechanical tests

The results of quasi-static (tensile and compression) tests are illustrated in Fig. 3. The small graphs inserted in Fig. 3a is the higher magnification of the dashed region, which shows the Young’s moduli of the four microstructures.

As displayed in Fig. 3a, the tensile strength (Rm) of basketweave structure is the highest (1341 MPa), while the Widmanstatten structure is the lowest (1052 MPa). The tensile properties of Ti-55511 alloy are presented in Table 3. The measured Young’s moduli of bimodal structure, basketweave structure and Widmanstatten structure are all around 100 GPa, which is about 30 GPa higher than that of equiaxed structure. The Rm and proof strength at εp 0.2% (Rp0.2) for basketweave structure are the highest, which can reach around 1341 MPa and 1222 MPa, respectively. For Widmanstatten structure, both of them are the lowest. For the percentage elongation after fracture (A), bimodal structure is almost equal to that of Widmanstatten structure, which is nearly 12% higher than those of basketweave and equiaxed structures. For the percentage reduction of area (Z), Widmanstatten structure is the highest, while basketweave structure is the lowest. Quasi-static compression behavior of Ti-55511 alloy is shown in Fig. 3b. It can be seen that the flow stress of basketweave structure at εp 0.075 is the highest (1480 MPa), which is nearly 270 MPa higher than that of the Widmanstatten structure (1210 MPa). As might be expected, the quasi-static mechanical properties of Ti-55511 alloy are sensitive to the microstructural features.
3.1.1. Strain rate sensitivity

To gain deeper insight into strain rate effect, the mechanical behavior of Ti-55511 alloy will be discussed at a fixed temperature, e.g., 293 K, as shown in Fig. 4. It should be noted that the results here all displayed using a similar scale to allow for comparison (similarly hereinafter the same below). It was observed that the flow stress of Ti-55511 alloys increases with increasing plastic strain when deformed at quasi-static loading (shown in Fig. 3b). By contrast, when deformed at high strain rates, the flow stresses remain nearly constant with increasing plastic strain, indicating a lack of strain hardening.

As shown in Fig. 4, the relation between true stress and plastic strain for the four kinds of Ti-55511 alloys deformed at high strain rates is different for each condition. The strain rate sensitivity, $\beta'$, can be

Table 3

<table>
<thead>
<tr>
<th>Microstructure</th>
<th>Tensile properties</th>
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<tbody>
<tr>
<td></td>
<td>E/GPa</td>
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<tr>
<td>BS</td>
<td>106</td>
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<td>73</td>
</tr>
<tr>
<td>BWS</td>
<td>100</td>
</tr>
<tr>
<td>WS</td>
<td>103</td>
</tr>
</tbody>
</table>

Note: E, $R_m$, $R_{p0.2}$, A and Z indicate Young’s modulus, tensile strength, proof strength at 0.2% plastic strain, percentage elongation after fracture and percentage reduction of area, respectively.
approximately estimated as the slope of the logarithm of flow stress versus the logarithm of the strain rate [29,30]:

\[
\beta = \frac{\ln \sigma / \sigma_0}{\ln \dot{\varepsilon} / \dot{\varepsilon}_0}
\]

(4)

where the quasi-static compressive stresses \( \sigma_0 \) and dynamic compressive stresses \( \sigma_i \) are obtained in tests conducted at constant strain rates \( \dot{\varepsilon}_0 \) (0.001 s\(^{-1}\)) and \( \dot{\varepsilon}_i \) (ranging from 350 s\(^{-1}\) to 2900 s\(^{-1}\)), respectively.

Fig. 5a shows the flow stress as a function of strain rate. It should be pointed out that the plastic strain is fixed at 5%. It can be seen that the flow stress of Widmanstatten structure remains nearly constant with increasing strain rate, while for the other three structures, the flow stress increases with increasing strain rate. Fig. 5b depicts the strain rate sensitivity as a function of strain rate. As illustrated in Fig. 5b, it can be seen that the strain rate sensitivity is nearly constant for Widmanstatten structure within the range of measured strain rates, and it tends to saturate for basketweave structure. By contrast, for bimodal structure and equiaxed structure, there is a tendency that \( \beta \) increases with increasing strain rate, especially at higher strain rate.

3.1.2. Temperature sensitivity

To study the effect of the initial test temperatures, the mechanical behavior of Ti-5551 alloy will be discussed at a fixed strain rate, e.g. 2000 s\(^{-1}\), as shown in Fig. 6.

As displayed in Fig. 6, the flow stress decreases with increasing initial test temperature. Therefore, the thermal softening effect of Ti-5551 alloy is significant.

The temperature sensitivity, \( s \), can be approximated as the slope of the logarithm of flow stress at \( \varepsilon_0 \) 5% versus the logarithm of the initial tests temperature [31]:

\[
s = \frac{\ln \sigma / \sigma_{0,i}}{\ln T/T_0}
\]

(5)

where the quasi-static compressive stresses \( \sigma_{0,i} \) and dynamic compressive stresses \( \sigma_i \) are obtained in tests conducted at room (293 K) and elevated temperatures (ranging from 373 to 673 K), respectively. It should be pointed out that the dynamic compression stresses are conducted at the same value of compressive plastic strain (5%).

Fig. 7a shows the flow stress as a function of the initial test temperature. It can be seen that the flow stress of Ti-5551 alloy decreases rapidly with increasing the initial test temperature. Fig. 7b depicts the temperature sensitivity as a function of the initial test temperature. It is interesting to note that the temperature sensitivity varies with initial test temperature. For instance, the temperature sensitivity of Widmanstatten structure decreases rapidly with increasing the initial test temperature; on the contrary, the temperature sensitivity of equiaxed structure increases with increasing the initial test temperature.

3.2. Constitutive model

The propensity to shear localization can be quantified from the constitutive response. Numerous constitutive equations have been proposed to describe the high strain rate response of materials, e.g. Zerilli-Armstrong model [32], J-C model [33], and Follansbee-Kocks model [34]. Due to the simple multiplication form and various applications, the J-C model was selected to describe the mechanical behavior of Ti-55511 alloy. In this work, the temperature rise induced by plastic work is considered. The reference strain rate is 0.001 s\(^{-1}\), detail information about J-C model was addressed in the Appendix. It should be pointed out that the constants of J-C constitutive law are obtained using the least square method.

To obtain the best-fit coefficients, based on the above experimental results (Figs. 3, 4 and 6), the J-C constants of Ti-55511 alloy were determined by the least square method. The resulting constants of J-C model for the four kinds of Ti-55511 alloys are presented in Table 4, and the comparison between the measured, fitting and predicted true stress versus plastic strain curves of Ti-55511 alloy are shown in Fig. 8.

Fig. 8a–c illustrate the comparison between the measured and fitting true stress versus plastic strain curves. It can be seen that the fitting curves are in good agreement with the experimental results. It should be noted that in this work, experiment data at temperature 673 K, not used for equation fitting, were used for comparing with the prediction of the J-C equation. Fig. 8d shows the comparison between the measured and predicted true stress versus plastic strain at 673 K and 2000 s\(^{-1}\).

3.3. Microstructure characteristics of shear localization

Fig. 9 depicts the typical microstructures of Ti-55511 alloy deformed at 293 K.

As illustrated in Fig. 9a, comparing with the initial microstructure, no significant changes are observed for bimodal structure deformed at 900 s\(^{-1}\). When the strain rate increases to 1500 s\(^{-1}\), an ASB occurs at the upper left corner of the microstructure (shown in Fig. 9b), and the width of the ASB is around 5 \( \mu \)m. For equiaxed structure, the microstructure does not occur significant changes when the strain rate is below 1200 s\(^{-1}\) (shown in Fig. 9c), and an ASB with nearly 5.5 \( \mu \)m in width occurs when the strain rate increases to 2000 s\(^{-1}\) (shown in Fig. 9d). As illustrated in Fig. 9e, for basketweave structure, almost nothing has changed when the strain rate is below 600 s\(^{-1}\), while an ASB with closely 1.5 \( \mu \)m in width occurs when the strain rate exceeds 1400 s\(^{-1}\) (shown in Fig. 9f). For Widmanstatten structure, when the strain rate is below 1400 s\(^{-1}\), obvious changes do not occur (shown in Fig. 9g), and an ASB with approximately 1.1 \( \mu \)m in width occurs when the strain rate is 2100 s\(^{-1}\) (shown in Fig. 9h). It is interesting to note that the ASB crosses over the grain.

Fig. 5. The plot of a) flow stress and b) Strain rate sensitivity as a function of strain rate. Note that the plastic strain (\( \varepsilon_0 \)) is fixed at 5%.
The fracture surface was characterized to characterize the fracture mechanism. A sample deformed at room temperature and 1600 s$^{-1}$, in Fig. 10a, was given as an example. Higher magnification of regions A and B are illustrated in Fig. 10b and c, respectively. It can be seen that the fracture surface can be divided into two characteristic zones, namely the smooth region and shear region. The smooth areas are caused by rubbing between the fragment and the fracture surface, and parabolic dimples are the main features of the shear region. As might be expected, similar results have been found in Ti-55511 alloy deformed at elevated temperatures.

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Table 4
J-C constitutive constants of Ti-55511 alloys.

<table>
<thead>
<tr>
<th>Microstructures</th>
<th>Constitutive constants</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>A/MPa</td>
</tr>
<tr>
<td>BS</td>
<td>1190</td>
</tr>
<tr>
<td>ES</td>
<td>1100</td>
</tr>
<tr>
<td>BWS</td>
<td>1300</td>
</tr>
<tr>
<td>WS</td>
<td>990</td>
</tr>
</tbody>
</table>
4. Discussion

According to the experimental results, Ti-55511 alloy has a slight strain hardening effect (see Fig. 5). Similar findings were observed in Ti-6Al-4V alloy [35,36]. On the contrary, it is different from that of commercially pure titanium [37]. This discrepancy may come from the presence of the beta phase. As displayed in Fig. 8d, the predicted and experimental results are in good general agreement. As might be expected, the J-C constitutive equation can be used to predict the dynamic behavior of Ti-55511 alloy. Similar results have been found in TC16 titanium alloy [38] and Ti-6Al-4V alloy [39].

4.1. Adiabatic shear susceptibility

For the sake of brevity, the universal adiabatic shear susceptibility criterion, i.e. critical strain [23], critical stress [22] and critical strain rate [21], of Ti-55511 alloy with bimodal structure will be discussed and shown in Fig. 11.

Fig. 11a shows that the critical strain as a function of strain rate. Apparently, the critical strain varies with strain rate, which is contrary to the critical strain criterion requiring failure strain to remain constant. Hence, it appears that the critical strain criterion is not the best indicator of adiabatic shear failure for Ti-55511 alloy. Fig. 11b and c show the critical stress as a function of strain rate and critical strain rate as a function of the initial test temperature, respectively. It can be seen that critical stress and critical strain rate keep almost constant. However, both of the aforementioned criteria are univariate, in which strain effect, strain rate effect, and thermal conductivity etc, were not considered simultaneously.

The dynamic failure energy (the area of the dynamic stress-strain curve up to instability) was calculated as \( W_0 = \int_0^{\varepsilon_f} \sigma \, d\varepsilon \), where \( \varepsilon_f \) stands for the failure plastic strain [24], as illustrated in Fig. 11d. It can be found that the dynamic failure energy is practically constant. This is similar to the properties of Ti-6Al-4V alloy (annealed condition) and AM50 (one kind of magnesium-aluminum alloy), which was reported by Rittel et al. [24]. Hence, the dynamic failure energy was used to elucidate the adiabatic shear susceptibility in this work. It should be noted that the higher of the dynamic failure energy, the “tougher” of the material.

The plot of the dynamic failure energy of Ti-55511 alloys as a function of the initial test temperature is illustrated in Fig. 12. It can be seen that, at a fixed test temperature, the dynamic failure energy of bimodal microstructure is slightly higher than that of equiaxed structure, and the dynamic failure energy of Widmanstatten structure is nearly equal to that of bimodal structure. In addition, the dynamic failure energy of bimodal microstructure is much higher than that of equiaxed structure, implying that the former is less sensitive to adiabatic shear localization than that of the latter. This is similar to the features of Ti-6Al-2.5Mo-1.5Cr-0.5Fe-0.3Si alloy reported by Sun et al. [40], while it is contrary to that of Ti-6Al-4V alloy reported by Hu [41]. The observed discrepancies can be attributed to the difference in the investigated materials.

4.2. Failure mechanism

As illustrated in Fig. 9, it can be concluded that the strain rates for ASB initiation are different with microstructures at the same temperature loading condition. Similar phenomenon has been found in TA 15 (a typical near-beta titanium alloy) [42]. Hence, it can be concluded that the mechanical properties of materials vary with microstructures. Characterize the effect of microstructure on the mechanical behavior of materials not only possesses an important scientific significance, but also paves the way for future directions in titanium alloys design against
As displayed in Fig. 10, it can be seen that smooth areas and dimple areas coexist in the fracture morphologies. This phenomenon is consistent with the works reported by Goods and Brown [43] and Timothy and Hutchings [44]. In addition, parabolic dimples elongated along the shear direction, implying that large plastic deformation takes place. In other words, the parabolic dimples on the fracture surface are the remnant of elongated α phase close to the shear band. This result agrees well with the work reported by Bai et al. [36]. Therefore, for Ti-55511 alloy, the collapse of the specimens is attributed to shear failure mechanisms.

The mechanical properties of Ti-55511 alloy can be summarized in Table 5 on the basis of mechanical behavior analysis. Engineers can choose the optimal microstructure to fabricate components according to service requirements to fully utilize the potential of Ti-55511 alloy. For instance, bimodal structure might be the optimal microstructure for fabricating structural components serving at high strain rates due to its high strength and good ductility.

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Fig. 9. Typical microstructures of Ti-55511 alloy deformed at 293 K: a) Bimodal structure, 900 s⁻¹, b) Bimodal structure, 1500 s⁻¹, c) Equiaxed structure, 1200 s⁻¹, d) Equiaxed structure, 2000 s⁻¹, e) Basketweave structure, 600 s⁻¹, f) Basketweave structure, 1400 s⁻¹, g) Widmanstatten structure, 1400 s⁻¹ and h) Widmanstatten structure, 2000 s⁻¹.
5. Conclusions

The mechanical and failure behavior of Ti-55511 alloy with four different microstructures subjected to high strain rates at various temperatures has been investigated by means of SHPB technique. According to the experimental findings, the following conclusions can be drawn:

The strength of basketweave structure is the highest, while the ductility is the lowest. By contrast, the strength of Widmanstatten structure is the lowest, while the ductility is the highest. The results also suggest that Ti-55511 alloy is a strain rate and temperature sensitive material.

Microstructural observation of the samples deformed at high strain rates indicate that the formation of ASB is highly influenced by the microstructure type. Fracture morphologies analyses confirm that relatively smooth areas and ductile dimple areas coexist in the fracture surface, indicating that shear failure is the main failure mechanism for Ti-55511 alloy deformed at compression loading.

J-C constitutive equation can be used to predict the dynamic behavior of Ti-55511 alloy. To enrich the database of J-C model for a larger group of materials, the constants of J-C constitutive law are obtained using the least square method.

For future guidance in materials processing against dynamic loading in general, the adiabatic shear susceptibility of Ti-55511 alloy with four typical microstructures is evaluated based on the dynamic failure energy, and the adiabatic shear susceptibility is mainly affected by microstructure and temperature. The effect of microstructural on the mechanical behavior of Ti-55511 alloy is summarized, to fully utilize the potential of the material, engineers can choose the optimal microstructure to fabricate components according to the service requirements. For instance, bimodal structure might be the optimal microstructure for fabricating structural components serving at high strain rates due to its high strength and good ductility.
Fig. 12. Plot of the dynamic failure energy of Ti-55511 alloys as a function of the initial test temperature.

Table 5
Assessment of the mechanical properties of Ti-55511 alloy.

<table>
<thead>
<tr>
<th>Property</th>
<th>Assessment rating</th>
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<td></td>
<td>BS</td>
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<tr>
<td>Quasi-static tensile strength</td>
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<tr>
<td>Quasi-static compression strength</td>
<td>**</td>
</tr>
<tr>
<td>Ductility</td>
<td>**</td>
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<tr>
<td>Dynamic compression strength</td>
<td>**</td>
</tr>
<tr>
<td>Critical stress for ASB initiation</td>
<td>**</td>
</tr>
<tr>
<td>Critical strain-rate for ASB initiation</td>
<td>**</td>
</tr>
<tr>
<td>Strain-rate sensitivity</td>
<td>**</td>
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<tr>
<td>Dynamic failure energy</td>
<td>**</td>
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<tr>
<td>Adiabatic shear susceptibility</td>
<td></td>
</tr>
</tbody>
</table>

Note: ****: very high, **: high, *: low and #: very low.
: very unsusceptible, : unsceptible, : susceptible and : very susceptible.

Author contributions section

Chun Ran: Conceptualization, Data Curation, Investigation,

Appendix

The J-C model can be expressed as, Eq. (A1):

$$\sigma = A B \epsilon^p \left( 1 + C \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \frac{T}{T_m} \frac{T_r}{T}$$

(A1)

where $A$ is the yield stress; $B$ and $n$ represent the strain hardening modulus and strain hardening exponent; $C$ and $m$ are strain rate sensitivity coefficient and thermal softening exponent, respectively. It should be noted that all the five parameters were determined experimentally. Here, $T$ and $T_r$ are the current and reference (293 K) temperatures, respectively; $\dot{\epsilon}_0$ is the reference strain rate (0.001 s$^{-1}$); $\sigma$ and $\dot{\epsilon}_p$ are the flow stress and plastic strain, respectively.

As elucidated in Eq. (A1), the flow stress can be divided into three terms, namely strain hardening, strain rate hardening and thermal softening, respectively.

By substituting the reference condition (T = 293 K and $\dot{\epsilon} = 0.001$ s$^{-1}$) in Eq. (A1), the J-C model can be rewritten as follows:

$$\sigma = A B \epsilon^p$$

(A2)

Then, $A$, $B$, and $n$ can be determined.

By substituting the reference temperature condition (T = 293 K) in Eq. (A1), the strain rate sensitivity coefficient, $C$, can be calculated as:

$$C = \frac{\sigma/A - B \epsilon^n}{\ln \dot{\epsilon}/\dot{\epsilon}_0}$$

(A3)
Finally, the thermal softening exponent, $m$, can be determined as:

$$\ln \left[ \frac{1}{\frac{\Delta T}{T_m} \frac{\sigma}{\sigma_0}} \right] = \frac{A}{T} \ln \left( \frac{c_1}{c_2} \right)$$

The plastic work can be incorporated into an adiabatic temperature rise, namely:

$$\Delta T = \frac{\beta \int \sigma \, d\varepsilon}{\rho C}$$

Then, the thermal softening exponent, $m$, can be written as:

$$\ln \left[ \frac{1}{\frac{\Delta T}{T_m} \frac{\sigma}{\sigma_0}} \right] = \frac{A}{T} \ln \left( \frac{c_1}{c_2} \right)$$