Mechanical Properties and Fracture Mechanism of Laser Solid Formed TC4 Titanium Alloy under Dynamic Compression

Ping Zhou, Baojun Liu, Fengshan Sun
Aviation Maintenance NCO Academy
Air Force Engineering University
Xinyang, China
zhouping79@outlook.com

Abstract—The mechanical properties and fracture mechanism of laser solid formed TC4 titanium alloy under different temperatures and strain rates were investigated experimentally. The results show that there is no obvious anisotropy in compression property, and the susceptibility to adiabatic shear deformation is nearly the same. The microscopic analysis shows that the adiabatic shear bands (ASBs) can be formed easily under the dynamic compression loading, and the high experimental temperature may suppress the formation of ASBs. With the Johnson-Cook constitutive mode, the critical strain of ASB was calculated. By means of microscopic observation and mechanical analysis, the formation mechanism of fracture surface was explained, that is, voids and cracks form in shear zone and propagation of cracks along the interface of α/β forms fracture surface.

1. INTRODUCTION
As medium-strength α-β titanium alloy, TC4 titanium alloy is widely used in the manufacture process of fuselage, wing part and engine blade of aircraft due to its good overall performance. However, titanium alloy has high melting point, high melting state activity and large deformation resistance. There are some disadvantages such as high cost, low material utilization in the traditional manufacture process. Laser Solid Forming (LSF) technology, which combines the characteristics of rapid prototyping technology and laser cladding technology, is a fast, mold-free, near-net-shape manufacturing technology. This technology can be used in manufacturing high-performance metal parts with complex structural.

Current research on titanium alloys (LSFed) is mainly focused on the forming process, microstructure, as well as compression, tension, and fatigue properties under room temperatures and low strain rates. There are few reports on the mechanical behaviour, deformation mechanism, and failure mechanism of TC4 titanium alloy (LSFed) under extreme conditions such as high temperatures and/or high strain rates. In the present study, the compressive mechanical properties of TC4 titanium alloy (LSFed) at different temperatures (173~1073 K) and strain rates (0.001~5000 s⁻¹) were studied. The micro-characteristics of this material before and after loading were analysed, the critical strain at the onset of the adiabatic shear band (ASB) was calculated, and the fracture mechanism under dynamic compression was explored. This work provided a reference framework for the use of this material in engineering applications.
2. EXPERIMENTAL MATERIAL AND METHOD

2.1 Experimental Material

The experimental material was prepared on a laser solid forming system at the State Key Laboratory of Solidification Processing, Northwestern Polytechnical University (Xi'an, China). This forming system consisted of a transverse-flow CO₂ laser, a four-axis numerical control working table, a box filled with inert gas, a high precision powder feeder, and a side powder feeding nozzle. The raw material used in this study included pure titanium substrates and 100~150 µm TC4 titanium alloy spherical powder. The mass fraction (%) of the powder was 6.02 Al, 4.00 V, 0.098 Fe, 0.033 Si, 0.025 C, 0.04 N, 0.008 H, and 0.16 O, with the remainder being Ti. The entire forming process was carried out in a box filled with inert gas to prevent the titanium alloy from being contaminated by impurity elements such as O, N, and H. The shielding gas for the side powder feeding nozzle and the powder carrier gas were pure Ar. The main processing parameters are shown in Table I.

| Parameter | Value |
|-----------|-------|
| Laser power /kW | 7 |
| Scanning velocity /mm·s⁻¹ | 10~15 |
| Powder feed rate /g·min⁻¹ | 15~30 |
| Carrier gas flow /L·h⁻¹ | 9~12 |
| Laser spot diameter /mm | 6 |
| Increment of Z axis /mm | 0.8~1.5 |

The LSF technology was used to produce a cuboid block of Ti-6Al-4V alloy. Samples were sliced from the block along the Y-direction and Z-direction, respectively. The Y-direction represents the laser scanning direction, while the Z-direction represents the depositing direction. Then the samples were stress relief annealed at 500 °C for 4 h and were cooled in furnace.

2.2 Experimental Method

The static compression test was carried out with the strain rate of 0.001 s⁻¹ by a servohydraulic testing machine. The initial temperatures for the static compression test were selected to be 293 K, 573 K, 873 K and 1173 K, respectively. The dynamic compression test was carried out with the respective strain rates of 1000 s⁻¹ and 5000 s⁻¹ by enhanced split Hopkinson pressure bar system [1]. The initial temperatures for the dynamic compression test were selected to be 173 K, 293 K, 573 K, 873 K and 1173 K, respectively. The required high temperatures for samples were attained by a radiant-heating furnace. The cylindrical samples of Ti-6Al-4V alloy (LSFed) for static and dynamic compression tests were prepared with the nominal dimensions of 5 mm in diameter and 4 mm in length, i.e., Φ5 mm × 4 mm.

3. RESULTS

3.1 Mechanical response

The principal compressive stress-strain curves of the LSFed TC4 alloy with the temperatures of 173~1073 K and the strain rates of 0.001, 1000, and 5000 s⁻¹ are shown in Fig. 2. There is no obvious anisotropy in the compressive mechanical properties despite of different loading directions due to the 7 kW working power laser, which is the high-power laser. During the forming process, the re-melting rate was high, the cladding layer became thinner, the stay time of the heat-affected zone at high temperatures was short, and the cooling rate was high. All the above factors make the β grains in this alloy not prone to rapid deformation and growth due to overheating. As a result, the layer bands become thinner and the microstructure becomes finer and more homogeneous, thus the anisotropy is not obvious.
TC4 titanium alloy is sensitive to adiabatic shearing. It tends to form adiabatic shear bands under high strain rate loading conditions [2-3]. Grady [4] derived the expression of the dissipation energy per unit area ($\Gamma_s$) during the expansion of the shear band:

$$\Gamma_s = \frac{\rho C_p}{\alpha} \left(\frac{9D^3C_p\chi}{\tau_y^2\alpha^2\gamma}\right)^{1/4}$$  \hspace{1cm} (1)

where $\rho$ is the density, $\chi$ is the thermal diffusion coefficient, $\alpha$ is the thermal softening coefficient, $C_p$ is the specific heat, and $\tau_y$ is the flow stress at strain rate $\dot{\gamma}$. The laser solid formed TC4 titanium alloy samples with two different loading directions had the same density, thermal diffusion coefficient, and thermal softening coefficient. Figure 1 shows that their flow stresses were almost equal, so the dissipation energies of the shear bands were also almost the same. Thus, the adiabatic shear deformation sensitivities of samples under two different loading directions were basically the same.

Figure 1. Stress-strain response along Y-direction and Z-direction at selected initial temperatures

3.2 Microstructure characteristics

Figure 2 shows the microstructure of the longitudinal cross section of sample at 298 K and 5000 s$^{-1}$. It can be seen that the failure mode of this sample is adiabatic shear failure. The shear cracks occurred on the plane, which is at an angle of 45° to the direction of the compressive load axis. In the uniaxial compression experiment with isotropic samples, the ASBs appear on this plane. The strain, strain rate, and shear stress magnitudes on this plane are the maximum [5]. A void with radius of approximately 4 μm is observed in front of the shear crack. The ASB is very narrow, whose width is approximately 8 μm. Under the high strain rate loading condition, the severe plastic deformation of sample causes extreme temperature increasing, which in turn causes thermal softening and the formation of ASB. The ASB itself is not a failure mode, but it can cause the material to lose its energy absorption capacity and load capacity [6], so it is often considered as a portent of material failure. Fractures often occur after ASBs appear in the materials.
Figure 2. SEM micrograph of the sample tested under the temperature of 298 K and strain rate of 5000 s\(^{-1}\).

Figure 3 shows the microstructure of the longitudinal cross section of sample at 1173 K and 5000 s\(^{-1}\). Compared with the sample obtained at the same strain rate (5000 s\(^{-1}\)) and a lower temperature (273 K), there are smaller and thinner \(\alpha\) plates in the sample at 1173 K. In addition, the most obvious difference was the absence of ASBs in the sample at 1173 K. There are two main reasons why titanium alloys tend to form adiabatic shear bands: few slip planes and poor thermal conductivity. High temperatures can inhibit the adiabatic shear localization of Titanium alloys. The main reasons are as follows. First, at high temperatures, the flow stress of the material reduces, the power of plastic work is lower, and the converted heat per unit time reduces; these changes are not beneficial to the local accumulation of heat at the beginning of the shear band formation, so shear localization can be delayed. Second, approaching the phase transition temperature (995 °C for TC4), the titanium alloy undergoes a partial phase transition from the hexagonal close packed (HCP) structure to the body centered cubic (BCC) structure. The BCC structure has more slip systems and is more prone to uniform plastic deformation \(^7\), which is not beneficial to deformation localization. Therefore, although thermal softening is the main cause of adiabatic shear localization under dynamic loading, the raising of environmental temperature will inhibit the formation of ASBs.

Figure 3. SEM micrograph of the sample tested under the temperature of 1173 K and strain rate of 5000 s\(^{-1}\).
4. DISCUSSION

4.1 Critical strain at the onset of the adiabatic shear band

In this paper, the Johnson-Cook model was used to describe the plastic flow behavior of TC4 titanium alloy (LSFed). The Johnson-Cook model is a commonly used ideal rigid-plastic strength model for metal materials, which can reflect the strain strengthening, strain rate strengthening and temperature softening. In this constitutive model, the expression of flow stress $\sigma$ is as follows:

$$\sigma = (A + B\dot{\varepsilon}^n)(1 + C \ln \dot{\varepsilon}^*)(1 - T^m), \quad \dot{\varepsilon}^* = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}, \quad T^* = \frac{T - T_r}{T_m - T_r},$$

(2)

where $\sigma$ is the Von Mises flow stress; $\varepsilon$ is the equivalent plastic strain; $\dot{\varepsilon}^*$ is the dimensionless relative equivalent plastic strain rate; $\dot{\varepsilon}$ is the actual strain rate; $\dot{\varepsilon}_0$ is the reference strain rate; $T^*$ is the dimensionless Temperature, $T$ is the actual temperature, $T_r$ is the room temperature (293K), $T_m$ is the melting temperature of this material; $A$, $B$, $n$, $C$ and $m$ are material constants, which need to be fitted according to the stress-strain relationship experiment curve. Using the parameter identification method, the least square method, and the uniaxial compression experiment results described above, the material constants of TC4 titanium alloy (LSFed) are fitted, as shown in Table II.

| A (MPa) | B (MPa) | C   | m    | n    |
|---------|---------|-----|------|------|
| 800     | 832     | 0.046 | 1.06 | 0.42 |

| $\dot{\varepsilon}_0$ (s$^{-1}$) | $T_m$ (K) | $T_r$ (K) | $\rho$ (kg/m$^3$) | $C_p$ (J/kg·K) |
|-------------------------------|-----------|-----------|-----------------|----------------|
| 0.001                         | 1926      | 293       | 4428            | 580            |

When the slope of the stress-strain curve is zero, the corresponding strain is the critical strain at the beginning of the adiabatic shear zone [8]:

$$\frac{\partial \sigma}{\partial \varepsilon} = 0$$

(3)

During the loading process, part of the plastic work is converted into heat energy, and the temperature rise can be expressed as:

$$dT = \frac{0.9}{\rho C_p} \sigma d\varepsilon$$

(4)

Combined with the Johnson-Cook model, the dimensionless temperature $T^*$ can be expressed by plastic strain as follows:

$$\int_{0}^{T_{cr}} \frac{dT^*}{1 - T^m} \frac{0.9(1+C \ln \dot{\varepsilon}^*)}{\rho C_p} = \int_0^{\dot{\varepsilon}_{cr}} (A + B\varepsilon^n) d\varepsilon$$

(5)

Since $m \approx 1$, $m = 1$ can be made for simple calculation, then the solution of equation (5) is:

$$T^* = 1 - \exp \left[ - \frac{0.9(1+C \ln \dot{\varepsilon}^*)}{\rho C_p(T_m - T_r)} \left( A\varepsilon_{cr} + \frac{B\varepsilon_{cr}^{n+1}}{n+1} \right) \right]$$

(6)

Substituting into the Johnson-Cook model, we can get:

$$\sigma = (A + B\varepsilon^n)(1 + C \ln \dot{\varepsilon}^*) \exp \left[ - \frac{0.9(1+C \ln \dot{\varepsilon}^*)}{\rho C_p(T_m - T_r)} \left( A\varepsilon_{cr} + \frac{B\varepsilon_{cr}^{n+1}}{n+1} \right) \right]$$

(7)

Differentiating formula (7), and letting the differential result equal to zero according to formula (3), we can get:
After substituting relevant material parameters into equation (8), the critical strain value can be obtained. For 5000 s\(^{-1}\), \(\varepsilon_{cr} \approx 0.343\). If the critical strain value and other material parameters are substituted into equation (6), the corresponding temperature value \(T \approx 517\) K can be obtained. Since the actual value of \(m\) is greater than 1, the predicted critical strain value and temperature value are a bit higher.

### 4.2 Fracture mechanism

If there is no friction between the sample and the pressure bar, the axial stress is compressive, while the radial and circumferential stresses are zero. If interfacial friction exists between the sample and the pressure bar, tensile circumferential stress will appear in the middle of the cylindrical surface of sample, and the sample will undergo bulging deformation \([9-10]\). As the axial strain and/or the interfacial friction increase, the circumferential stress in the middle of the cylindrical surface also increases \([10]\). From the middle to the two ends of sample, the tensile circumferential stress gradually decreases, while the compressive radial and shear stresses gradually increase.

The temperature of ASB is high, which reduces the flow stress in the shear band. For the same sample under the same initial experimental temperature, the narrower the shear band is, the higher the temperature inside the band, and the lower the stress. Because of the low flow stress in the shear band and the high circumferential tension in the middle of the cylindrical surface of sample, the middle part of sample may fracture along the ASB.

Figure 4 shows the microstructure at the longitudinal cross section of sample at the temperature of 873 K and strain rate of 5000 s\(^{-1}\). The shear cracks were all located in the middle of sample. A void was observed in front of the crack and was closer to the middle of sample than the crack. The result showed that the void was first formed in the middle of sample (high tensile stress area) and continued to form in front of the crack as the crack grew.

Figure 4. SEM micrograph of the sample tested under the temperature of 873 K and strain rate of 5000 s\(^{-1}\).

Based on the above analysis, the fracture process of sample is proposed in Figure 5. During the high strain rate loading, when the internal stress of sample reaches the maximum value, an ASB is formed at the direction of 45\(^{\circ}\) to the compression load (Figure 5(a)). The thermal softening effect caused by the high temperature in the shear band and/or the microvoids caused by the severe shear deformation of the non-uniform microstructures (such as phase boundaries) may lead to the nucleation of voids during the formation of the shear band \([11]\). In the middle of sample, the tensile stress is the largest. The combined
effect of tensile stress and shear stress results in the formation of voids, which in turn leads to the formation of cracks (Figure 5(b)). For α/β-type titanium alloys, the voids are preferably formed at the phase interface [12]. Once the crack appears, it will propagate along the shear band under tensile stress and shear stresses (Figure 5(c)), while the effect of tensile stress gradually decreases. An interfacial phase exists at the α/β phase interface of TC4 alloy (LSFed). The interfacial phase is easy transformed and can seriously affect the mechanical properties of the titanium alloys [13]. In addition, the difference in strength between the α phase and β phase results in poor mechanical properties at the interface, which causes the cracks to propagate rapidly at the α/β phase interface in the shear band. At the ends of sample, the tensile stress is low, and the shear stress is high, which leads to a small number of void nuclei. As a result, the material undergoes strong shear deformation in this area (Figure 5(d)).

Figure 5. Proposed model for the formation of the fracture surface

5. CONCLUSIONS

(1) Although stratification existed along the growth direction, no obvious anisotropy in the compressive mechanical properties was observed, and the adiabatic shear deformation sensitivity was basically the same.

(2) Under the dynamic compressive load, this material is prone to the formation of ASBs at 45° to the compressive load axis. Elevated temperatures could inhibit the formation of ASBs due to factors such as the microstructure characteristics.

(3) By combining with Johnson-Cook constitutive model, the critical strain at the onset of ASB was calculated.

(4) During the dynamic compression, voids and cracks are formed in ASBs because of tensile stress and shear stresses in the middle of sample; the cracks propagate rapidly along the α/β phase interface in the shear band and eventually resulting in the fracture of the sample.

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