Effects of Temperature and Strain Rate on Mechanical Behaviour of Laser Rapid Forming Ti-6Al-4V Alloy

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Abstract. Using the electronic universal test machine, the high temperature split Hopkinson bar and the gleeble-1500 thermal simulator, the room temperature quasi-static compression experiment, room temperature dynamic compression experiment, high temperature dynamic compression experiment and the high temperature quasi-static compression experiment on corresponding cylindrical samples of Laser Rapid Forming Ti-6Al-4V (LRF TC4) titanium alloy have been conducted, respectively. And effects of the temperature and strain rate on mechanical behavior of LRF TC4 alloy have been investigated. It is showed that, whether quasi-static compression or high strain rate compression, the strength of LRF TC4 decreases and the plasticity increases at the high temperature. Under the high temperature quasi-static compression, LRF TC4 still has the strain strengthening effects at 400°C, the flow stress changes steadily in the stage of the plastic deformation at 500°C and the strength of LRF TC4 dropped drastically when the temperature goes beyond 500°C. Under the high temperature and high strain rate, the flow stress changes steadily in the plastic deformation stage due to dual function of both strain rate strengthening and temperature softening and adiabatic temperature rise within the sample reduced with the increase of the deforming temperature. Under the coupling function of high temperature and high strain rate, the effect of strain-rate strengthening is weaker than the effect of temperature softening.

1. Introduction

TC4 titanium alloy is widely used due to its excellent properties such as high melting point, strong mechanical strength, low density, strong specific strength, high corrosion resistance, and high-temperature mechanical properties, especially in the aerospace field. Due to its excellent comprehensive mechanical properties, it has become one of the essential materials for the manufacture of aircraft [1 ~ 4]. Traditionally, titanium alloy is produced by forging. However, due to the production cost and the difficulty in processing large-scale structural parts, the advanced laser rapid forming (LRF) technology developed in the past three decades has become the fabrication method for metal materials including titanium alloys. In addition, it has also become an alternative method for the fabrication of rare materials with complex-shaped parts, such as tungsten alloy, nickel alloy [5, 6], H13 tool steel [7, 8] and titanium alloy [9].

The application environment of titanium alloy materials in aerospace and defense weaponry often involves extreme environment with high temperature, high strain rate, and the combination of the two caused by high-speed impact, penetration and explosion. Titanium alloy is a strain rate-sensitive material [10~13], and temperature has a great influence on its mechanical properties [14~19]. Thus the mechanical behavior of titanium alloy in high-temperature environment has been the research focus in recent years. However, there is very little research involved in this area so far, and the study
of the influence of temperature and strain rate on the mechanical behavior of LRF Ti-6Al-4V (LRF TC4) has high academic impact and engineering application value.

2. Experimental Materials and Methods

2.1. Experimental Materials and Treatment methods
The LRF TC4 alloy used in this experiment was purchased from Xi'an Platinum Laser Forming Technology Co., Ltd., and the forming material was TC4 spherical powder with particle size of -100--+150 mesh. The composition is listed in Table 1. The powder is dried before forming under vacuum at about 120 °C to remove moisture to reduce the influence of water on the rapid laser deposition process. The rapid prototyping laser system is Rofin-Sinar CO2, including the following functions/parameters: The laser power was 7 KW, the scanning speed was 10-15 mm/s, the powder rate was 15-30 g/min, the protection gas flow was 9-12 L/h and the spot diameter was 6 mm. The scanning was zigzag along the direction of 45°with the X-axis (the direction of the red line arrow in Figure 1), and the Z-axis direction was the deposition direction. The size of the forming material was 110 mm×110 mm×40 mm, as shown in Figure 1. The microscopic morphology is shown in Figure 2. Figure 2(a) shows the low-magnification metallographic micromorphology, forming coarse columnar crystals almost parallel to the deposition direction. Figure 2(b) shows the morphology of scanning electron microscopy (SEM). The parallel α bundles in the coarse columnar crystals form a mixture of the Weiss structure and the basket structure. There are also defects such as holes left by the escape of bubbles and incomplete melting of the powder during the TC4 material rapidly formed by laser.

![Figure 1. Schematic diagram of LRF TC4 formed and direction of the LRF TC4 sample](image1)

**Table 1. Chemical Constitution of TC4 powder (ω/%)**

| Element | Al | V | C | Si | Fe | H | N | O | Ti |
|---------|----|---|---|----|----|---|---|---|----|
|         | 6.02 | 4.00 | 0.056 | 0.039 | 0.15 | 0.005 | 0.033 | 0.14 | Bal. |

![Figure 2. Microstructure of the LRF TC4 sample. (a) Optical microscope (OM) image with low-magnification; (b). SEM image shows the microstructure in better detail.](image2)
2.2. Experimental Methods

The deposited TC4 alloy after laser rapid prototyping, without any subsequent treatment, was wire-cut to form the cylindrical sample along the direction that is 45° away from the laser scanning direction (as shown in Figure 1). The quasi-static compression test at room temperature was conducted on 7 mm ×10 mm cylindrical sample with MTS universal material testing machine, and the strain rate was 0.01 s⁻¹. The high temperature separated Hopkinson bar with diameter of 14 was used to conduct dynamic compression tests on the cylinder samples with the size of 5 mm × 5 mm at different temperatures. The test temperatures were 25 °C, 400 °C - 800 °C respectively, and the strain rate was 3000 s⁻¹. The gleeble-1500 thermal simulation machine was used to conduct quasi-static compression test on the cylinder sample with the size 8 mm × 12 mm at the temperature of 400°C-800°C, and the strain rate was 0.01 s⁻¹.

The original samples were cut along the axis by a wire cutting method. After sandpaper grinding with different particle sizes, they were mechanically polished to the mirror surface and corroded with klinkt reagent (5% HF, 20% HNO₃, 75% H₂O). The samples were observed for microscopic morphology using a LEICA DMI5000 M metallographic microscope (OM) and a Quanta 200 scanning electron microscope (SEM).

3. Experimental Results and Analysis

3.1. Effect of Temperature on the Mechanical Behavior of LRF TC4

Figure 3 shows the quasi-static compressive stress-strain curve of LRF TC4 alloy at the strain rate of 0.01s⁻¹ and the temperature of 400 °C -800 °C. Under quasi-static compression, the material strength decreases with the increase of temperature, while the plasticity increases. Meanwhile, it can be seen that the material strength is about 850MPa, showing a certain strain strengthening effect when the material is quasi-static compressed at 400°C. This shows that the material has a high softening resistance at 400°C although it is fabricated by laser in a rapid three-dimensional manner. At 500°C, the strain-strengthening effect of the material disappears, and the flow stress almost shows a plateau steady state change. This indicates that the strengthening effect caused by dislocation multiplication and dislocation interaction due to deformation counteract the softening effect caused by temperature rise, which makes the flow stress of the material present steady-state change in the plastic deformation stage. When the deformation temperature exceeds 500°C, the material shows an obvious softening effect and the material strength decreases significantly. Especially when the temperature exceeds 700°C, the material strength decreases more remarkably, because the recrystallization temperature of TC4 alloy is about 700°C (0.4 Tm ~0.5Tm≈671~839°C), and the formation of recrystallization grains accelerates the weakening of the material deformation resistance.

Figure 4 shows the dynamic compressive stress-strain curve of LRF TC4 alloy at the strain rate of about 3000 s⁻¹ and the temperature of 400°C-800°C. Similar to quasi-static compression, the strength of the material decreases with the increase of temperature, while the plasticity increases. It can be seen from the results that there is no obvious strain strengthening effect, nor obvious softening phenomenon, but the plastic deformation shows steady change. when the LRF TC4 alloy is deformed at high temperature and high strain rate. When the dynamic compression temperature is 400°C, the rheological stress of LRF TC4 alloy is about 850 MPa, which is similar to the strength under quasi-static condition. It seems to have nothing to do with the high strain rate, but in fact it does. Because the thermal energy converted by the plastic work during the deformation process can not be conducted out, and the material temperature rises at a high strain rate, fast deformation speed and short time. The raised temperature can be calculated by the following formula[20]:

$$\Delta T = T - T_0 = \frac{\eta}{\rho C_p} \int_0^\varepsilon \sigma d\varepsilon$$
In the formula, \( \eta \) is the thermal conversion coefficient of 0.9; \( \rho \) is the material density, 4500 kg/m\(^3\), \( C_v \) is the material specific heat capacity of 520 J/kg.°C, \( \sigma \) is the flow stress, and \( \varepsilon_p \) is the plastic strain of the sample. According to the above formula, the temperature rise of the material under dynamic deformation at 400°C-800°C is listed in Table 2.

It can be seen from Table 2 that the strength of the test material under quasi-static compression at 400°C is equivalent to the dynamic compressive strength at 500.1°C, indicating that the strain rate during deformation at high temperature still has a significant impact on the mechanical behavior of the material.

According to the temperature rise data of the materials listed in Table 2 under dynamic deformation at various temperatures, it can be seen that with the increase of deformation temperature, the temperature rise in the material gradually decreases. Because the dislocation in the material is easier to move with the increase of deformation temperature, this results in a decrease in the plastic work of the material and a gradual decrease in temperature rise.

| 400°C | 500°C | 600°C | 700°C | 800°C |
|-------|-------|-------|-------|-------|
| \( \Delta T \) | 100.1 | 99 | 85.8 | 73 | 63 |

### 3.2. Effect of Strain Rate and Temperature Coupling on the Mechanical Behavior of LRF TC4

Figure 5 shows the compressive stress-strain curves of the LRF TC4 titanium alloy specimen at strains of 0.001 s\(^{-1}\) and 3000 s\(^{-1}\), at temperatures of 25°C and 400°C, respectively. Since the stress changes with the strain, in order to qualitatively explain the comprehensive effect of strain rate and temperature coupling on the mechanical behavior of LRF TC4, we study the situation when the strain is 0.15. When the temperature is 25°C, the compression strength of the test material at the strain rate of 0.01 s\(^{-1}\) and 3000 s\(^{-1}\) is 980 MPa and 1298 MPa, respectively. It can be seen that when the strain rate is considered solely, the strength of the material with the higher strain rate (3000 s\(^{-1}\)) is increased 318 MPa, and the strain rate strengthening effect is obvious. When the strain rate is 0.01 s\(^{-1}\), the quasi-static compression strength of the test material at the temperature of 25°C and 400°C is 980 MPa and 727 MPa, respectively. It can be seen that when the temperature is considered solely, the strength of the material with the higher temperature (400°C) is reduced 318 MPa, and the temperature softening...
effect is evident. When the temperature is 400°C and the strain rate is 3000 s⁻¹, the strength is 823 MPa, compared with the one at 25°C and 0.01 s⁻¹, the strength is reduced by 157 MPa, and compared with the one at 400°C and 0.01 s⁻¹, the strength is increased by 96 MPa, indicating that the temperature and strain rate have a significant influence on the mechanical behavior of the material.

The strain-rate effect increases the dislocation density of the material in a short time, making the dislocation interacting, which makes the movement of the dislocation difficult and increases the strength of the material. Dislocations are easier to reach the corresponding activation energy and easier to start, and reducing the material strength. The above data shows that the strain-rate strengthening effect seems to be weaker than the temperature-softening effect at 400°C and the strain rate of 3000 s⁻¹, which may be intensified by the temperature rise in the material during the high strain rate analysis analyzed in Section 2.1. Due to the effect, the stress-strain curve under high temperature and high strain rate loading is between the room temperature quasi-static compression and the high temperature quasi-static compressive stress-strain curve. Comparing Figure 3 and Figure 4, it can be seen that when the temperature is higher than 600°C, the strength of LRF TC4 quasi-static compression is much larger than that of high strain rate compression, indicating that the strain-rate effect is stronger than the temperature-softening effect for such case. The material strength is maintained under high temperature and high strain rate.

![Figure 5. The compression stress-strain curves of LRF TC4 samples under the condition of different strains rate and different temperatures.](image)

4. Conclusions

1. At high temperature, no matter the quasi-static or high strain rate compression, the material strength decreases and the plasticity increases;

2. Under the quasi-static condition at high temperature, the material still has strain-strengthening effect at 400°C, and the rheological stress changes steadily at 500°C during the plastic deformation stage. When the temperature is higher than 500°C, the material strength decreases significantly;

3. Under the condition of high temperature and high strain rate, due to the double effects of strain strengthening and temperature softening, the flow stress of the material in the plastic deformation stage presents a steady change.

4. As the deformation temperature increases, the dislocations in the material are easier to move, resulting in a reduction in plastic work. Under the condition of high temperature and high strain rate, the adiabatic temperature rise in the material also decreases gradually.
When the high temperature and high strain rate simultaneously are both applied for the deformation of the material, the strain-rate strengthening effect is weaker than the temperature-softening effect, which makes the material strength decreases.

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6. References
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