Effect of Different Connection Modes on Bolt Structural Properties of TC4 Alloy in Selective Laser Melting

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Abstract: The bolt structural properties of selective laser melted (SLM) samples produced from TC4 powder metal has been investigated. Two different connection molds relative to single lap joint and bilateral lap joint as well as two different state of surface quality were considered. Samples and test procedures were designed in accordance with HB 5143 and HB 5287 standard. The results show that there is a strong influence of connection molds on the dynamic behavior of SLM produced TC4. The mechanical properties of bilateral lap joint are better than those of the single lap joint. Meanwhile the fatigue performance of the bilateral lap joint is much stronger than that of the single lap joint which it is a symmetrical structure of the two-shear test on both sides of the force evenly, while the single lap joint is a single shear sample of the uneven force. There are two kinds of fracture form most of which are broken in the first row of screw and a small part in the middle of the connecting plate.

1. Introduction

Selective laser melting is an additive fabrication process in which successive layers of powder are selectively melted by the interaction of a high energy density laser beam. Molten and re-solidified material forms parts, while non-melted powder remains in place to support the structure [1-4]. This layer-wise production technique offers some advantages over conventional manufacturing techniques such as high geometrical freedom, short design and manufacturing cycle time and made-to-order components. Titanium alloys have been used widely in various fields due to their good mechanical properties and corrosion resistance [5-7].

In the aerospace industry, much attention has been given to SLM of TC4. Because it shows a great potential compared to subtractive methods concerning the processing of TC4 titanium alloy which has excellent specific tensile and fatigue strengths and corrosion resistance. Forged TC4 has become increasingly popular because of its low cycle fatigue strength and crack propagation resistance, although wrought products, such as forged, extruded, as cast, or rolled materials, are widely used as structural and engine parts in aircrafts[11]. Normally, the conventionally machining of this alloy is characterized by some difficulties through a short life time of the tools and a low cutting speed. These negative aspects can be avoided using additive manufacturing methods.

With the development of aerospace technology, for reducing the mass and improving the performance of equipment effectively, the structurally large metallic components (SLMCs) manufactured by titanium alloys are increasingly applied in aircraft. However, problem of the forming metal material applied on different parts at the same component is more and more difficult [12-15].
Therefore, the new technology of titanium alloy material properties research is particularly important. In aircraft structure, single lap joint bolt connection form has been widely adopted, and the damage form is given priority to with fittings of fatigue fracture. In this paper, TC4 titanium power was melted and formed by laser melted selection, and its structural connections were compared. The performance of bolted connecting structures under different lap forms was compared and analyzed. This study is based on the more advanced 3D printing technology, and it is different from other alloy materials. Titanium alloy is the object of study. It provides effective reference for the application of TC4 alloy unilateral lap joint in the aerospace field data support.

2. Materials and Methods
TC4 (Ti6Al4V) powder is a rich α stable element and α+β dual-phase titanium alloy powder. Table 1 shows the measured element contents of TC4 powder. TC4 alloy has high mechanical strength, good fracture toughness, high hardenability and a wide forging-temperature range. TC4 alloy is usually used in aero engine compressor components. Therefore, a forging TC4 plate is used as the to-be-repaired substrate, which has circular grooves on the surface. The samples were composed by two pieces of SLM TC4 alloy plates and one base metal connecting piece, which the single/bilateral lap joint was adopted with the form of six single screw connection (M6), as shown in figure 1. There were a total of 30 samples, divided into three groups by different connection forms as follows: Group TA, Single lap joint, Ra6.3; Group TB, Single lap joint, Ra1.6; Group TC, bilateral lap joint, Ra1.6. TC4 alloy plate test section width was controlled in 25 mm, thickness in 3 mm, the connecting sheet width in 25 mm, thickness in 7 mm. the increase of the connection piece of geometry size ensured that the connection piece priority failure will not occur.

The static tensile and fatigue tests were conducted at a stress ratio of R=0.1, a sine wave of 6Hz to obtain the stress-life curves, and a constant rate loading of 1 mm/min in UTM9100. Before the test, according to the 40% of tensile failure load did the pre-tension test. During the trial, recording the real-time load and strain data ensured that there were more than 500 sampling points. Static stretching needs to ensure that the alignment is centered and the error is reduced. The load is determined by controlling the fatigue life in 180000~200000 cycle. Collect the strain date under the fixed cycle count. Unload until peak load is arrived. Record the real-time load and strain date, the fatigue cycle, failure modes and failure location. When calculating the experiment data, ensure the Degree of confidence no less than 95%, the effective number of test pieces shall not be less than four.

| Table 1. Chemical compositions of TC4 (wt%) |
|-----|-----|-----|-----|-----|-----|-----|-----|
| Al  | V   | Fe  | C   | N   | H   | O   | Ti  |
| 6.1 | 4.1 | 0.04| 0.01| 0.021| 0.01| 0.12| Bal.|

Figure 1. Shape of samples
3. Results

3.1. Tensile Test

The average, standard deviation and dispersion coefficient of the test results are calculated according to the following formulas (1), (2) and (3), respectively. The calculation results are shown in Table 2. The discrete coefficients of three groups are both relatively small. Group TA and TB samples are based on the same structure and materials. The difference is that group TA samples are blown sand, and group TB samples are machined to enhance the surface quality and then blown sand. Resulting that the surface roughness is not the same which TA is Ra6.3 and TB is Ra1.6. Compared with group TA and TB samples, it can be seen that the fracture strength of TB is slightly higher than that of TA. The structure of group TB and TC samples is different which TB is unilateral lap bolt connection form and TC is bilateral lap bolt connection form. The experimental results show that the mechanical properties of the overlapped lap joint are better than those of the unilateral lap joint.

\[
X = \frac{\sum_{i=1}^{n}X_i}{n}
\]

(1)

\[
S = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n}}
\]

(2)

\[
C_v = \frac{S}{\bar{X}} \times 100\%
\]

(3)

Table 2. The tensile test results of connecting pieces

| Samples | Maximum load F/kN | Average $\bar{X}$ | Standard deviation S | Discrete coefficient $C_v$ |
|---------|-------------------|-------------------|----------------------|---------------------------|
| TA-1    | 38.38             | 37.95             | 0.6151               | 0.0162                    |
| TA-2    | 37.51             | 37.95             |                      |                           |
| TA-3    | 37.90             |                   |                      |                           |
| TB-1    | 40.92             |                   |                      |                           |
| TB-2    | 39.26             | 40.09             | 1.1738               | 0.0293                    |
| TB-3    | 40.00             |                   |                      |                           |
| TC-1    | 49.95             |                   |                      |                           |
| TC-2    | 51.15             | 50.55             | 0.8485               | 0.0168                    |
| TC-3    | 50.50             |                   |                      |                           |

Where $\bar{X}$ is the average, S is the standard deviation, $C_v$ is the discrete coefficient, $X_i$ is the measured value.

3.2. Fatigue Test Result

The first sample of each group was tested with 31% of static test failure load as a peak. Six samples were taken from each group to determine the peak load of the two test samples which strain collection was not necessary. But the last two samples were subjected to strain collection and the strain gauge was attached according to the test scheme to collect the trend of strain in the process of stretching near the nail hole under different cycles.

Repeated reassembly of samples may cause damage to its performance. For the titanium alloy, the crack initiation life occupies the main part of the whole fatigue life. The initial damage is caused in the
vicinity of the nail hole due to the repeated assemble which greatly weaken the titanium alloy crack initiation life. So that the initial damage degree of each sample cannot be observed and quantitative analysis. Therefore, the dispersion of the experimental data is increased, and due to the limitation of the number of samples, the valid data of the group fail to obtain. But the test results still have some reference.

According to the experimental results, it can be seen that the results of TA and TB with the same structure are obviously different. In group TB, the fatigue life is lower than that of group TA under the stress peak of TA. In that case the fatigue performance of group TA is much better. At the same time, the fracture position of TA and TB can be observed, and the fracture area of TA and TB is basically the same. There are two kinds of fracture form most of which are broken in the first row of screw (fig2a) and a small part in the middle of the connecting plate (fig2b), while the fracture of TC is only presented at the first row of screws. Compared with different structures of experimental data, it can be found that the fatigue life of TC is similar to that of TA when the loading peak of TC is higher than that of TA, indicating that the fatigue performance of TC is much stronger than that of TB. TC is a symmetrical structure of the two-shear test, test plate on both sides of the force evenly while the TB is a single shear samples, the test plate on both sides of the uneven force.

**Table 3. The fatigue test results of connecting pieces**

| Group | Number | Percentage of damage load (%) | Peak (kN) | Fatigue life (cycle) | Average (cycle) | Standard deviation | Discrete coefficient |
|-------|--------|-------------------------------|----------|----------------------|-----------------|--------------------|---------------------|
| TA    | 5      | 31                            | 11.763   | 500000               | 248895          | 0.2942             | 0.0545              |
|       |        |                               |          | 227814               |                 |                    |                     |
|       |        |                               |          | 126966               |                 |                    |                     |
|       |        |                               |          | 132092               |                 |                    |                     |
|       |        |                               |          | 211961               |                 |                    |                     |
|       |        |                               |          | 500000               |                 |                    |                     |
| TC    | 6      | 30                            | 15.165   | 500000               | 245910          | 0.4538             | 0.0842              |
|       |        |                               |          | 33910                |                 |                    |                     |
|       |        |                               |          | 246132               |                 |                    |                     |
|       |        |                               |          | 500000               |                 |                    |                     |

Note: 500000 indicates that the number of cycles is greater than 500,000

**Table 4. The fatigue test results of group TB**

| Percentage of damage load (%) | Peak (kN) | Fatigue life (cycle) | Average (cycle) |
|-------------------------------|-----------|----------------------|-----------------|
| 27                            | 10.824    | 299097               |                 |
| 27                            | 299097    |                      |                 |
| 28                            | 10.824    | 92127                | 204364          |
| 28                            | 109631    | 92127                |                 |
| 28                            | 92127     | 204364               |                 |
| 28                            | 11.225    | 97232                | 94680           |
| 31                            | 12.428    | 97232                |                 |
| 31                            | 72772     | 72772                |                 |
| 31                            | 72772     |                      |                 |

The fatigue life of the material has a certain degree of dispersion, it is usually used to meet a certain degree of confidence in the statistical method to determine the fatigue life of a material. However, the fatigue life of the structural parts affected by factors such as the complexity of the sample geometry, the accuracy of the assembly will produce a greater dispersion resulting in more human resources, material and financial needs.
3.3. Fracture Analysis
The fatigue fracture surface is comprised of three morphologically distinct zones: the crack initiation zone, the crack propagation zone and the instant rupture zone. In the LCF, the crack initiation zone and the propagation zone occupy smaller area on the fracture surface. The fatigue fracture of the SLM TC4 titanium alloy typical connection samples can be observed in Fig. 3 in which inevitably the structure of large or small damage are occurred as a consequence of being assembled several times. Moreover the crack initiation life of the titanium alloy is greater than the crack propagation life, so the fatigue life of the samples after the injury will be greatly reduced.

The fatigue cracks mostly initiate from the samples surface or the defects inside of the samples (i.e. pores). As shown in Fig. 3, the fatigue crack nucleates at the corners of the plate samples and fatigue initiation site is obviously observed. This is because the mutual constraints between the grains at the corners and the edges are lower than the other positions. The majority of the injury appears at the edge of the plate (Fig 3a) or the edge of the bolt hole (Fig 3b). The fatigue source which is formed in the damaged surface propagates radially to the inside of the samples.

![Figure 2. Fracture location (a) Broken at the screw (b) Broken at the middle of the connection plate](image)

![Figure 3. Fracture surface morphology (a) Crack initiates at the corner (b) Crack initiates at the bolt hole](image)

4. Conclusions
The tensile properties are much influenced by bilateral lap form to unilateral lap form. The maximum failure load of the bilateral lap samples is much higher than that of the unilateral lap.

The consideration of connection form and surface quality has highlighted the sensitivity of mechanical properties to the microstructural and force distribution effects that arise from different lap modes. Bilateral overlap is a symmetrical double shear samples resulting in uniform force on both sides of the test plate, while the unilateral lap is a single shear samples, leading to uneven test on both sides of the test plate.

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