

Effect of Ultrasonic Shock on Microstructure and Properties of TC4 Titanium Alloy Repaired by Laser

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Abstract. TC4 titanium alloy is widely used in key load-bearing components of aerospace and other high-end equipment. Laser cladding repair is easy to cause coarse microstructure, high residual stress, and a decline in plasticity and fatigue properties in the repair area. In this paper, ultrasonic shock was used to post-treat TC4 titanium alloy repaired by laser cladding. The microstructure evolution and property regulation were studied by microscopic characterization and a mechanical testing system. The experimental results show that ultrasonic impact can break the coarse columnar crystal, refine the grain and homogenize the microstructure, and effectively relax the residual stress in the surface layer; The tensile strength and yield strength of the repaired parts were increased by 9.3% and 9.2%, respectively, and the elongation after fracture was increased by 68.8%, realizing the synergistic improvement of strength and plasticity; The high cycle fatigue life is significantly increased, and the life in the low stress region is increased by about 14 times, and the fracture mode is changed from quasi cleavage to ductile fracture. Based on the Basquin model, accurate prediction of fatigue life can be achieved, and the error is controlled within 15%. The results show that ultrasonic impact can significantly improve the comprehensive mechanical and fatigue properties of repaired parts, and provide a theoretical basis and technical support for laser remanufacturing of key components of titanium alloy.

Keywords: ultrasonic shock, TC4 titanium alloy, laser cladding repair, microstructure, mechanical properties, fatigue life

1. Introduction

To meet the requirements of life extension and green remanufacturing of key components of aero-engine, China's "made in China 2025" [1] and "the 14th five year plan" for civil aviation development [2] have listed the research and development of key materials of aero-engine, component autonomy and sustainable remanufacturing as the core development direction. With the advantages of high specific strength and stable mechanical properties at medium and low temperatures, TC4 titanium alloy has become a key material for compressor disks, blades and other core components [3]. However, it is prone to fatigue cracks, creep deformation and surface wear under long-term high temperature, high pressure and vibration service environment. This material is difficult to process and has a high cost, and the traditional replacement method seriously affects the operation efficiency of the equipment. Laser cladding has become the most promising

remanufacturing scheme because of its high repair accuracy, small heat-affected zone and good performance recovery. However, it is easy to oxidize and nitride at high temperature, easy to produce pores, and insufficient interface bonding, which restricts its engineering application. Due to the high processing difficulty and high manufacturing cost of TC4 material, it will also prolong the equipment downtime and affect the operation efficiency. At present, the mainstream repair schemes include TIG arc welding (small defects, non-key mechanism) [4], laser cladding [5], electron beam welding [6], and thermal spraying technology [7]. The scheme of laser cladding combined with CT scanning, computer modeling, and automatic repair is the current emerging repair scheme due to the advantages of high repair accuracy, high efficiency, small impact on the workpiece, small heat affected area, good performance after repair, and material saving [8].

At present, ultrasonically coupled laser cladding has become a research hotspot in controlling microstructure and defects. Dongzhe Zhang [9] of Texas Tech University in the United States introduced ultrasonic vibration into directional energy deposition, which significantly refined NiTi alloy grains and increased hardness by about 11.1%; The team of South China University of technology [10] found that ultrasonic vibration can change the morphology of molten pool, refine the grains of GH5188 alloy, and improve the tensile and hardness properties; Chenjian team of Zhejiang University of technology [11] confirmed that ultrasound can optimize the microstructure of laser cladding Inconel 718 Alloy and improve the strength, plasticity and fatigue life. The existing researches focus on nickel-based and superalloy, but there is still a lack of systematic research on the ultrasonic impact control mechanism and multi-field coupling law of TC4 titanium alloy laser cladding.

In order to solve the bottleneck of laser repair of TC4 titanium alloy, such as high porosity, weak interface bonding, and coarse microstructure, an ultrasonic shock-assisted laser cladding repair experiment was carried out in this paper. Through multi-field coupling experiments and multi-scale characterization, the regulation laws of ultrasonic parameters on solidification behavior, grain evolution, and defects were revealed, and the quantitative correlation between process, microstructure, and properties was established to clarify the mechanism of gradient structure strengthening and toughening. The coaxial process device was developed, and the online verification was completed. Finally, the theoretical basis and feasible process path were provided for the high-quality remanufacturing of TC4 titanium alloy components of an aeroengine.

2. Research methods

The tensile property test is the basic method to evaluate the mechanical properties of materials. The key mechanical parameters, such as tensile strength, yield strength, and elongation after fracture, can be obtained through a unidirectional static tensile test. In the research of laser cladding repair, tensile test is used to evaluate the mechanical matching degree between the repair area and the substrate, and analyze the influence of ultrasonic impact treatment on the strength and plasticity collaborative optimization effect of the repaired specimen.

The tensile specimen is designed according to GB/T 228.1-2021, Tensile Testing of metallic materials Part 1: room temperature test method. In consideration of the size of the repair area and the thickness of the plate, the sample is a non-standard proportion sample. The sample cutting method and its geometric dimensions are shown in Figure 1 (a). The repair area in the middle of the specimen is located at the center of the gauge length section to ensure that the failure occurs near the repair area or interface during the tensile process.

The three groups of tensile test samples were taken from the base material (BM), laser cladding (LC), and ultrasonic shock-assisted laser cladding (LC+US) repair metal plate. Five tensile

specimens were prepared for each state to ensure the statistical reliability of the test results. The sample is processed by WEDM, and then the surface is ground on 240 mesh, 600 mesh, and 1000 mesh sandpaper in order to remove the traces of WEDM and surface micro-defects and reduce the interference of surface roughness on the test results. When grinding, pay attention to keeping the thickness of the sample uniform to avoid geometric eccentricity.

The tensile test was completed on the MTS 809.25 electro-hydraulic servo tension torsion fatigue testing machine, as shown in Figure 1 (b). The test was carried out at room temperature and in an atmospheric environment. The loading mode was displacement control mode, and the tensile rate was 1 mm/min. During the test, the computer control system collected the load, displacement, and strain data in real time, and the sampling frequency was 10 Hz. When the sample broke, the loading was stopped immediately, and the complete load displacement curve and stress-strain data were saved.

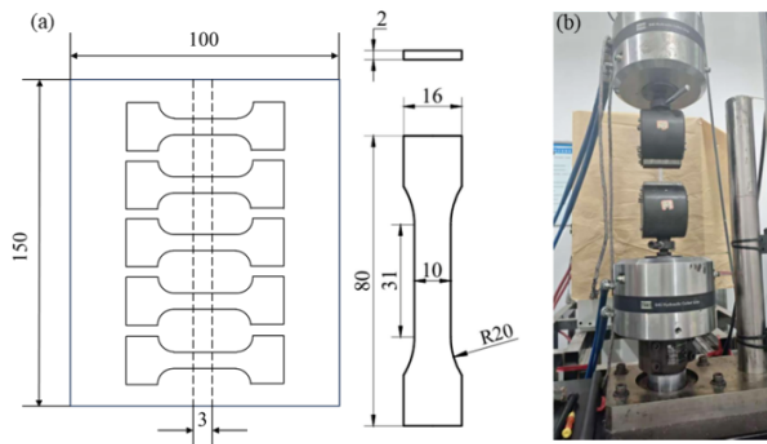


Figure 1. . Tensile property test: (a) schematic diagram of tensile specimen size (mm);(b) site drawing of tensile test

After the test, the mechanical properties of each sample were calculated using data processing software. The tensile strength is calculated according to the maximum load and the original cross-sectional area, the yield strength is determined by 0.2% residual strain method, and the elongation after fracture is obtained by measuring the gauge length change after the fracture sample is assembled. After removing the obviously abnormal data from each group of 5 samples, take the average value, and calculate the standard deviation to evaluate the degree of dispersion of the data. The tensile property data of base metal, laser cladding repair state, and ultrasonic impact treatment state were compared and analyzed to evaluate the influence of repair process on mechanical properties and the improvement effect of ultrasonic impact treatment on strength plasticity matching.

3. Result analysis

To evaluate the effect of ultrasonic shock treatment on the tensile properties of TC4 titanium alloy repaired by laser cladding, quasi-static tensile tests at room temperature were carried out on BM (base metal), LC (laser cladding repair), and LC+US (ultrasonic shock treatment) samples, respectively. Five tensile samples were prepared for each group, and two groups of effective data were taken for processing and analysis. The results of tensile properties were summarized in Table 1, and the corresponding stress-strain curve is shown in Figure 2. It can be seen from Table 1 that the

average tensile strength, average yield strength, and average elongation after fracture of the base metal used as the reference material are 924.1 MPa, 831.7 MPa, and 8.4%, respectively, showing good strength plasticity matching. The stress-strain curve of the base metal shows the typical tensile characteristics of ductile metal. After the elastic deformation stage, it enters the obvious plastic yield stage, and then work hardening occurs until fracture. The surrounding area under the curve is large, which reflects the good plastic deformation ability.

Table 1. Tensile properties at room temperature

Sample No	state	Tensile strength Rm (MPa)	Yield strength Re(MPa)	Elongation after fracture A (%)
1	BM -1	936.9	842.9	7.9
2	BM -2	911.1	820.0	8.9
3	LC-1	938.8	844.9	3.6
4	LC -2	1025.6	923.4	2.7
5	LC+US-1	1076.4	968.8	5.6
6	LC+US -2	1069.8	962.8	5.2
mean value	BM	924.1	831.7	8.4
mean value	LC	982.2	884.0	3.2
mean value	LC+US	1073.1	965.8	5.4

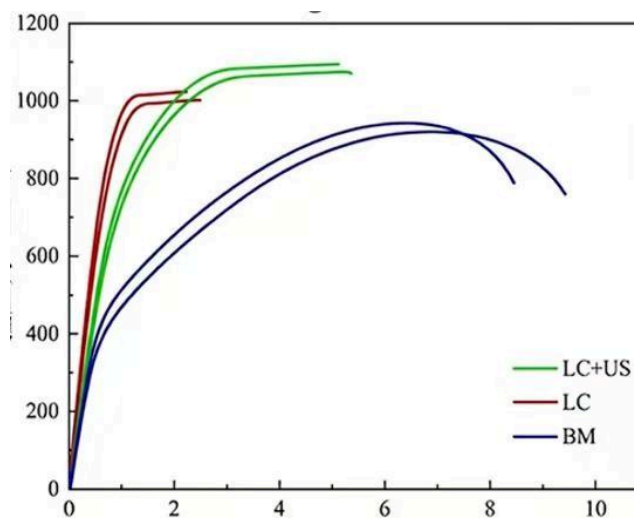


Figure 2. Tensile stress-strain curve

The average tensile strength and yield strength of the samples repaired by laser cladding are 982.2 MPa and 884.0 MPa, which is about 6.3% higher than that of the base metal, but the plasticity decreases sharply, and the elongation after fracture is only 3.2%, which is about 62% lower than that of the base metal, showing the characteristics of "high strength and low plasticity". The stress-strain curve quickly reaches the peak stress and decreases rapidly after the elastic stage, without an obvious plastic yield stage, and the fracture occurs in a small strain range, indicating that although the repaired area has high strength, the plastic deformation ability is seriously insufficient. There are three main reasons for the plastic deterioration of LC specimens: first, coarse columnar crystal structure is formed in the repair zone, the number of grain boundaries is small and the obstacles to dislocation movement are limited, and columnar grain boundaries become the preferred path of

crack propagation; Second, micro defects such as porosity, lack of fusion and oxide inclusions may be introduced during rapid solidification, which become the source of stress concentration in the tensile process; Third, the residual tensile stress introduced by laser cladding is superimposed with the external tensile load to accelerate the local yield and damage accumulation. The tensile strength and yield strength of the samples treated by ultrasonic impact were 1073.1 MPa and 965.8 MPa, which were 9.3% and 9.2% higher than those in the LC state, respectively. The elongation after fracture was restored to 5.4%, which was 68.8% higher than that in the LC state. The stress-strain curve showed an obvious plastic yield stage after the elastic stage, and the surrounding area under the curve increased, indicating that the material experienced sufficient plastic deformation before fracture.

4. Conclusion

On the basis of laser repair, the repair samples with a gradient structure were obtained by adjusting the ultrasonic impact parameters (load, frequency, time). The deformation coordination mechanism, crack initiation and propagation behavior of the interface gradient structure during the loading process were dynamically analyzed through the combination of in-situ tensile and non-in-situ mechanical tests, and the micro mechanism of ultrasonic impact-assisted laser repair to improve the strength and toughness of TC4 titanium alloy was revealed. Ultrasonic shock treatment can effectively realize the synergistic optimization of the strength and plasticity of TC4 titanium alloy specimens repaired by laser cladding. The tensile property test results at room temperature showed that the average tensile strength of the repaired samples after ultrasonic impact treatment reached 1073.1 MPa, which was 9.3% higher than that of the laser cladding repaired samples; The average yield strength increased to 965.8 MPa, an increase of 9.2%; At the same time, the average elongation after fracture was restored from 3.2% to 5.4%, which was significantly increased by 68.8% compared with the laser cladding repair state. Compared with the "high strength and low plasticity" characteristics of laser cladding repair state, ultrasonic shock can effectively increase the number of grain boundaries and improve deformation coordination by refining coarse columnar grains and introducing dynamic recrystallization equiaxed grains; At the same time, the residual stress in the surface layer is relaxed and the local stress concentration is reduced, so that the plastic deformation in the repair area can occur more evenly during the bearing process. Finally, the plasticity is significantly restored under the premise of maintaining the continuous improvement of strength, and the technical bottleneck of strength and plasticity after laser cladding repair is successfully broken.

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