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A Method for Obtaining More Stable Compressive Residual Stresses

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Abstract. Compressive residual stress (CRS) is a favourable factor for improving the fatigue and fretting fatigue (FF) properties of metallic materials. In this study, an ultrasonic surface rolling process (USRP) in a high temperature environment was proposed to obtain a more stable CRS field. The surface integrities of ultrasonic rolled titanium alloys at room temperature (25 °C) and at elevated temperature (182 °C), including surface roughness, surface hardness, compressive residual stress and microstructure, were measured and compared. The results showed that a deeper plastic deformation layer with more stable CRS was obtained with laser assistance. The fretting fatigue test results showed that the laser-assist USRP (Laser-USRP) achieved higher fretting fatigue resistance than that of the room-temperature USRP, which showed good prospects for industrial anti-fatigue applications.

In this research, TC11 titanium alloy rolled bar was selected as the research object.TC11 titanium alloy is α+β dual-phase titanium alloy, which is mainly used in the aerospace industry for the manufacture of engine compressor blades. The yield strength and tensile strength of the TC11 titanium alloy are 1000MPa and 1110MPa, respectively.

In this study, the treatment parameters selected for USRP were: static pressure 600 N, ultrasonic amplitude 10 μm, vibration frequency 20 kHz, specimen rotational speed 76 rev/min, and feed rate 0.12 mm/rev. The Laser-USRP was performed using a continuous laser as the heating source. The laser power is 10 W, and the heating temperature is up to 182℃. A GPS-100 high frequency fatigue tester was used for fretting fatigue life test, and the fretting fatigue loading were: maximum stress σ_{max} =750 MPa, the stress ratio R=0.1 and the contact stress 196 MPa. Scanning electron microscopy (SEM) was used to observe the fracture morphology, TEM and HRTEM were used to observe the microstructure morphology. a HV-1000 microhardness tester was used to measure the distribution of the hardness along the depth. An X-ray residual stress tester was used to measure the distribution of the CRS.

After the USRP treatment, the surface integrity of the specimen was significantly improved and machining defects were eliminated. With the assistance of laser heating, the Laser-USRP specimens achieved a more refined surface, and the R_a roughness was reduced from 0.65 μm to 0.41 μm after the USRP treatment, and that of the Laser-USRP was further reduced to 0.32 μm. This is due to the fact that the laser heating has increased the plastic deformation capability of the TC11 titanium alloy, and therefore it is easier to eliminate machining defects during the plastic deformation process. The microhardness of the BM at the top surface was 423 $HK_{0.245N}$, which was increased to 560 $HK_{0.245N}$ and 562 $HK_{0.245N}$ by USRP and Laser-USRP, respectively, with is an enhancement of around 32.4%. The microhardness decreases with depth, and the maximum depth is 600 μm. USRP also introduces CRS into the surface of TC11 titanium alloy. The CRS can significantly inhibit crack initiation and propagation. The maximum value of CRS introduced by USRP was -732 MPa with a maximum depth of more than 800 μm. The values of CRS at depths from 0 to 400 μm were further increased after Laser-USRP, with the maximum value increasing to -787 MPa. Previous studies have shown that the CRS introduced by USRP are the main reason for improving the fretting fatigue resistance of titanium alloys[1–3].

The FF life test results showed that the FF life of the BM specimen was 19314 cycles, the FF life of the USRP was 73,545 cycles, which was improved to 3.8 times, and the FF life of Laser-USRP

was 123,935 cycles, which was improved to 6.4 times, showing more significant improvement of the FF life in comparison with the USRP.

CRS dominates in the resistance to fretting fatigue life. The maximum value of CRS was further improved after Laser-USRP. In order to fully evaluate the effect of laser heating on the CRS stability, CRS relaxation experiments were performed on USRP and Laser-USRP under cyclic loading and high temperature environment. And the results showed that the CRS of Laser-USRP was more stable than that of USRP after 500 cycles under cyclic loading with σ_{max} = 950 MPa and stress ratio R = -1. The CRS of Laser-USRP was also more stable than that of USRP after annealing treatment at 500 °C for 20 hours. The formation of CRS is a result of the accumulation and movement of dislocations, and the stability of the CRS depends on the stability of the dislocations [4,5]. To explain the better stability of the CRS of Laser-USRP, double-beam diffraction TEM was performed on USRP and Laser-USRP specimens. The results showed that the <c> dislocation density introduced in the equiaxial α grains by Laser-USRP is much higher than that induced by USRP. This explains why the CRS of Laser-USPR showed better stability under cyclic loading and high temperature environment.

In summary, the laser-USRP further enhanced the FF life comparing to USRP for the following reasons: firstly, the laser heating-assisted enhances the plastic deformation capability of the TC11 titanium alloy, which results in a smoother surface. At the same time, laser heating promoted surface oxidation and increased the content of surface ceramic oxides. The formation of surface ceramic oxides has a positive effect on the improvement of FF life, which can reduce the coefficient of friction, thus decreasing the stress concentration caused by shear stress and the degree of fretting wear [6]. Meanwhile, the reduction of the friction coefficient can increase the slip amplitude, and according to previous studies, increasing the relative slip amplitude within a certain range can improve the FF life [2]. Compared with USRP, Laser-USRP can prepare more stable microstructures and CRS fields on the surface of TC11 titanium alloy. The high temperature field induces the formation of more stable dislocations, which hinders crack initiation and expansion. Meanwhile, the more stable dislocations can form a more stable CRS field, which reduces the relaxation under cyclic loading stress and high temperature. In conclusion, laser heating can significantly improve the performance of USPR and extend the FF life of TC11 titanium alloy. Laser heating can significantly improve the stability of CRS and microstructure. Therefore, this method has a great potential to improve the fatigue, wear and fretting fatigue resistance of titanium alloys and other metallic materials.

References

[1] Fan K, Liu D, Zhang X, Liu D, Zhao W, Yang J, et al. Effect of residual stress induced by ultrasonic surface rolling on fretting fatigue behaviors of Ti-6Al-4V alloy. Engineering Fracture Mechanics 2022;259.

[2] Fan K, Liu D, Wang C, Yang J, Liu Y, Zhang X, et al. Effect of contact stress and slip amplitude on fretting fatigue behaviour of ultrasonic surface nanocrystallized TC11 titanium alloy. Journal of Materials Research and Technology 2024;28:4052–64.

[3] Liu C, Liu D, Zhang X, Liu D, Ma A, Ao N, et al. Improving fatigue performance of Ti-6Al-4V alloy via ultrasonic surface rolling process. Journal of Materials Science & Technology 2019;35:1555–62.

[4] Chin KS, Idapalapati S, Ardi DT. Thermal stress relaxation in shot peened and laser peened nickel-based superalloy. Journal of Materials Science & Technology 2020;59:100–6.

[5] Yu L, Saida K, Araki H, Sugita K, Mizuno M, Nishimoto K, et al. Mechanism for stress relaxation behavior of the residual stress improving treatments with water jet peening and buffing. Materials Science and Engineering: A 2020;796:140221.

[6] Attia MH, De Pannemaecker A, Williams G. Effect of temperature on tribo-oxide formation and the fretting wear and friction behavior of zirconium and nickel-based alloys. Wear 2021;476:203722..