Fatigue Fracture Behavior of TA15 Alloy after Laser Marking

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Abstract. In order to study the effect of laser marking on the fatigue properties of TA15 titanium alloy, the alloy was marked at two depths respectively, and the low-cycle fatigue properties and fracture mechanism of TA15 titanium alloy after marking were analyzed and discussed. The results show that different degrees of marking pits appear on the surface of the alloy after laser marking, which is easy to cause local stress concentration. With the increase of power, the cross section shape of the bottom end of laser marking changes from a semi-arc shape to a sharp cone shape, resulting in high stress concentration phenomenon. The low cycle fatigue life of laser shallow marking specimens decreases by 62.7%, and that of laser deep marking specimens decreases by 86.4%. With the increase of the marking depth, the fatigue source area gradually becomes rough from smooth at the beginning, the divergence degree of cracks increases, the spacing of each crack in the initiation area increases, and the morphology becomes rough. The deeper the marking area is, the more driving force is provided for the initiation of cracks, and finally the fatigue performance deteriorates significantly.

Keywords: TA15 alloy; Fatigue fracture; Laser marking; Fracture mechanism; mechanical strength.

1. Introduction

TA15 alloy is a titanium alloy with high strength commonly used in the aviation field. It has excellent mechanical properties and good thermal stability and welding performance. It has medium strength in room temperature and high temperature and can be used in complex environments for a long time, and has strong process plasticity [1]. TA15 titanium alloy is a near-alpha type titanium alloy with high Al equivalent, which is strengthened by solid solution of α-stable element Al, and can be used in the production of thin sheets, forgings, profiles, etc. It is often used in the production of engine structural parts or key components, and is also one of the main materials of aircraft body structure, which has important application scenarios in the aviation field [2-4]. TA15 titanium alloy is prone to fatigue damage in complex service environment, and the main damage form is fatigue fracture [5], which affects the safe service of aircraft.

Metal marking process is a commonly used marking method in the aviation manufacturing industry, which can play a role in the transmission and recording of information such as rapid information identification, parts classification and storage in the digital manufacturing production line [6]. Laser marking is a marking process that uses laser equipment to quickly leave marks on the surface of parts. High-energy laser makes the material on the metal surface melt and fall off, leaving pits on the surface of the workpiece. This non-contact marking method has high efficiency and good precision, and the damage caused to the metal can be maximized. It has been widely used in practical applications [7-9].

Because the high density laser is processed on the surface of the workpiece during laser marking, leaving defects on the metal surface, the microstructure near the laser marking may undergo changes such as remelting, so it is necessary to conduct in-depth observation of the marking morphology and analyze its influence on the fatigue properties. At present, there has been a certain amount of research at home and abroad on the influence of defects and surface quality on mechanical properties of titanium alloys. Deng Wujing, Wang Jihang et al. [10-11] prefabricated test pieces containing defects, and carried out relevant high cycle fatigue test and tensile test at room temperature, and found the rule of influence of different defect types and sizes on fatigue life and tensile properties. Aiming at the corrosion problem of 921A steel in service environment, Liu Dehong [12] studied the stress distribution of corrosion defect depth and width on 621A steel shell under stress and strain. The research showed that the greater the corrosion defect depth or the smaller the defect width, the more obvious the stress concentration at the corrosion defect. Wang Y [13] studied the influence of initial defect morphology on fatigue crack growth rate, and the results showed that under the joint action of fatigue load and corrosive medium, the larger the depth and the smaller the width, the sharper the initial defect morphology, the faster the crack growth rate, and the shorter the life of the chipped steel wire specimen. Ni Y [14] used TB6 titanium alloys with different cyclic stress amplitudes and different defect sizes to carry out high-cycle fatigue tests on TB6 titanium alloys with impact pits and scratched surface defects. The results show that surface defects such as impact pit and scratch will decrease the fatigue life of TB6 alloy with the increase of defect depth, and the decline of fatigue resistance will be aggravated. It is determined that fatigue crack initiation is located at the edge of the impact pit and the bottom of the scratch defect. In summary, there have been researches on the defects and surface quality of titanium alloys at home and abroad, but there are few researches on the defects caused by marking process. In the actual production process of the aviation field, laser marking technology has been applied in a relatively mature way, and relevant parameters have been studied on the marking effect, but there are few studies on the mechanical properties decline caused by marking and its mechanism. In the actual use process, it has been found that some parts have deformation at marking or even fatigue fracture during service. In this paper, the effect of laser marking technology on the fatigue properties of TA15 titanium alloy was studied, and the fracture mechanism was analyzed, which provided a theoretical basis for the better application of laser marking technology.

2. Materials and methods

The main chemical composition of forged TA15 titanium alloy selected in this experiment is: Al≥6.60%, Zr≥2.10%, Mo≥1.72%, V≥2.23%, Ti margin. After mechanical processing and polishing, the material was processed into a plate-like sample as shown in Figure 1 with a thickness of 2 mm. Laser marking process and parameters in accordance with the relevant standards for marking, marking depth selected industry has been formed two common marking depth test, laser marking machine parameters set as: speed: 500 mm/s, laser output power: 10~40W, frequency: 20 kHz. The marking content is commonly used complex characters and characters that are easy to cause damage, such as: M, 9, S, P and other characters. There are 6 unmarked, laser marked (shallow) and laser marked (deep) plate specimens in each group. The cross section microstructure at the marking point was observed by optical microscope (OM), and the effect of laser marking on the alloy microstructure was analyzed. The fatigue test was carried out on the MTS 810 electro-hydraulic servo fatigue test machine, and the test parts were loaded. The stress level of the test was 1010 MPa, the stress ratio was 0.06, and the frequency was 5 Hz. The fatigue fracture was observed by SEM and its fracture mechanism was analyzed.

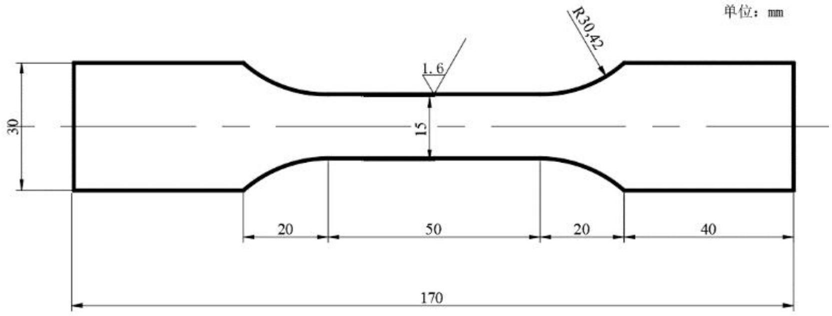

Fig. 1 Schematic diagram of fatigue specimen

3. Results and Discussion

3.1 Microstructure analysis

Fig. 2 shows the side microstructure of the forged TA15 titanium alloy after laser marking at two depths. It can be seen that the microstructure of the forged TA15 titanium alloy selected in the test is a typical two-state structure, consisting of an equiaxed α phase and a layered β phase. After metallographic microscope observation, it can be seen from Fig.2 (a) that the average depth of laser marking (shallow) is about 7μm, the maximum width of the notch is about 28μm, and the depth-to-width ratio is 0.286. The bottom of the cross-section topography is semicircular, the gap is concave downward, but the deepest bottom is relatively smooth and there is stress concentration. The original surface quality of TA15 titanium alloy is affected. Fig.2 (b) shows the side micro-morphology after laser marking (deep). The measured average depth of marking is about 12μm, the maximum notch width is about 14μm, and the depth-to-width ratio is 0.857. This is because in order to present a deeper text marking, the laser power and energy density is relatively high, the bottom end of the score is more sharp, and the depth to width ratio is higher. In laser marking, the marking speed of the two marking processes is the same. The deeper the alloy structure is from the alloy surface, the more affected by the thermal conductivity of TA15 titanium alloy itself, the narrower the surface morphology of the notched side becomes. When higher power laser is applied on the metal surface, the marking morphology gradually changes into a cone shape with the increase of the notched depth. The depth to width ratio increases gradually, and the bottom end becomes sharper, which tends to cause higher stress concentration phenomenon.

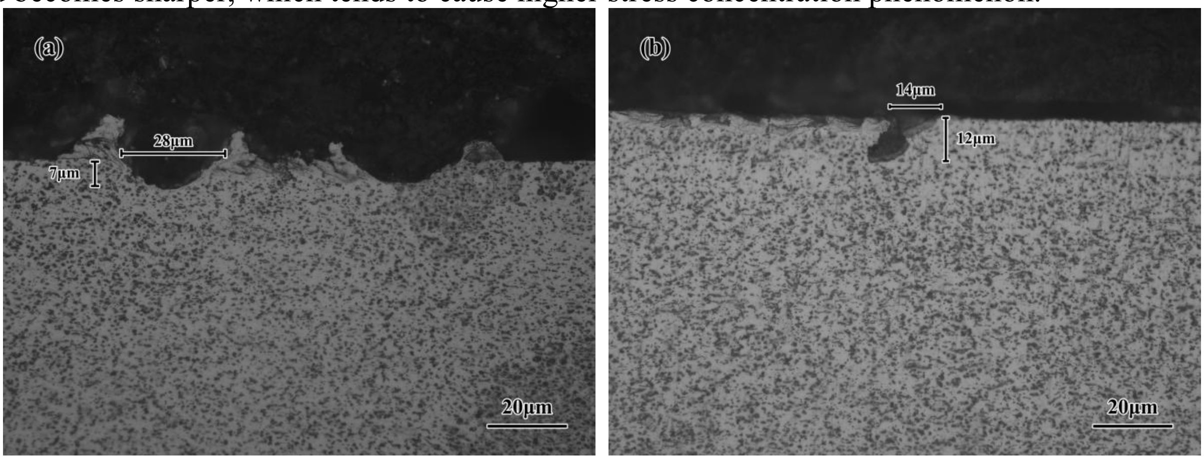

Fig. 2 OM image of the laser marking after : shallow (a) and deep (b)

3.2 Fatigue test result

Fatigue tests were carried out on the alloys after laser marking, and the test results and data statistics were shown in Table 1. The median fatigue life of unmarked TA15 titanium alloy sample was 10143 cyc, that of laser marking (shallow) was 3761 cyc, and that of laser marking (deep) was 1379 cyc. The fatigue life of laser marking (shallow) sample decreased by 62.9% compared with that of unmarked sample. The laser marking (deep) sample decreased by about 86.4%, compared to the laser marking (shallow) by about 63.3%. The fatigue test results show that TA15 titanium alloy is sensitive to laser marking process, and the fatigue life of TA15 titanium alloy has different degrees of decline, and the decline degree of laser deep marking is more obvious.

Table 1. Statistics of fatigue test Results of TA15 alloy

Sample label	Marking technology	Standard deviation /cyc	Median fatigue life/cyc
B0.1G~6	unmarked	1557	10143
B3.1G~6	Laser marking (shallow)	701	3761
B4.1G~6	Laser marking (deep)	222	1379

3.3 Analysis and discussion of crack initiation mechanism

After the fatigue test is completed, the fatigue fracture sample is cut by wire cutting equipment, and the corresponding fatigue fracture observation sample is prepared. The fatigue fracture is characterized by SEM. When a metal is fatigued, cracks generally start from the surface, and the surface quality has a significant impact on the overall life of the alloy. In this paper, 3 groups of samples are selected and fatigue test is conducted. The manufacturing process of the 3 groups of samples is identical except for marking technique. Therefore, the fatigue life of the samples is mainly affected by the surface quality in addition to the material properties of the samples themselves. Therefore, the marking process can reduce the fatigue life by affecting the surface quality of TA15 titanium alloy. In the process of service, the fatigue life of the alloy mainly depends on the crack initiation period. In the fatigue crack initiation of TA15 titanium alloy, the crack initiation will be preferently at the high stress concentration point on the surface. Cracks in unmarked specimens generally start from surface machining defects. Since laser marking is equivalent to the introduction of defects on the surface of the specimen, fatigue cracks will be prefered to start at the text mark of the specimen after laser marking, resulting in early crack initiation, shorter crack initiation period, and lower life compared with unmarked specimens.

Figure 3 shows the fracture morphology in the fatigue crack source region of the unmarked, laser marked (shallow) and laser marked (deep) samples after the test. As shown in Fig 3 (a), the crack initiation of the unmarked specimen occurs at the surface. As shown in Fig 3 (b), cracks in the laser marking (shallow) sample originated in the marking depression of the sample, and then began to diverged in the direction of crack propagation. Finally, the overall topography of the initiation zone showed a fan shape. The overall topography of the initiation zone was relatively smooth and the spacing between adjacent stripes was small, which proved that the initiation of cracks experienced more initiation cycles and a slower rate here. After the crack passes through the initiation zone, it goes through the expansion zone and the transient fracture zone to complete the whole process of fatigue fracture. The crack of the laser marking (deep) sample also originates in the marking depression, because the stress concentration here is the largest, the crack initiation is easier here, and the driving force is greater, so that the crack initiation can expand faster with less energy. As can be seen from Fig 3 (c), due to high-power laser marking and low-cycle fatigue test, cracks start to sprout at multiple laser-made gaps at the surface. In the initial stage of initiation, cracks expand strongly, extrusion ridges are more frequent, and the initiation form is complex, resulting in rough appearance of the fatigue source area at the initial stage of initiation. The crack initiation showed a more divergent crack initiation state, and the spacing between each crack was larger, showing an obvious divergent crack. The source region topography was rougher than that of the laser marking (deep) specimen, and the α phase and β phase could be cut quickly, which accelerated the crack initiation and growth rate, and the crack growth tended to be stable after a period of cycle.

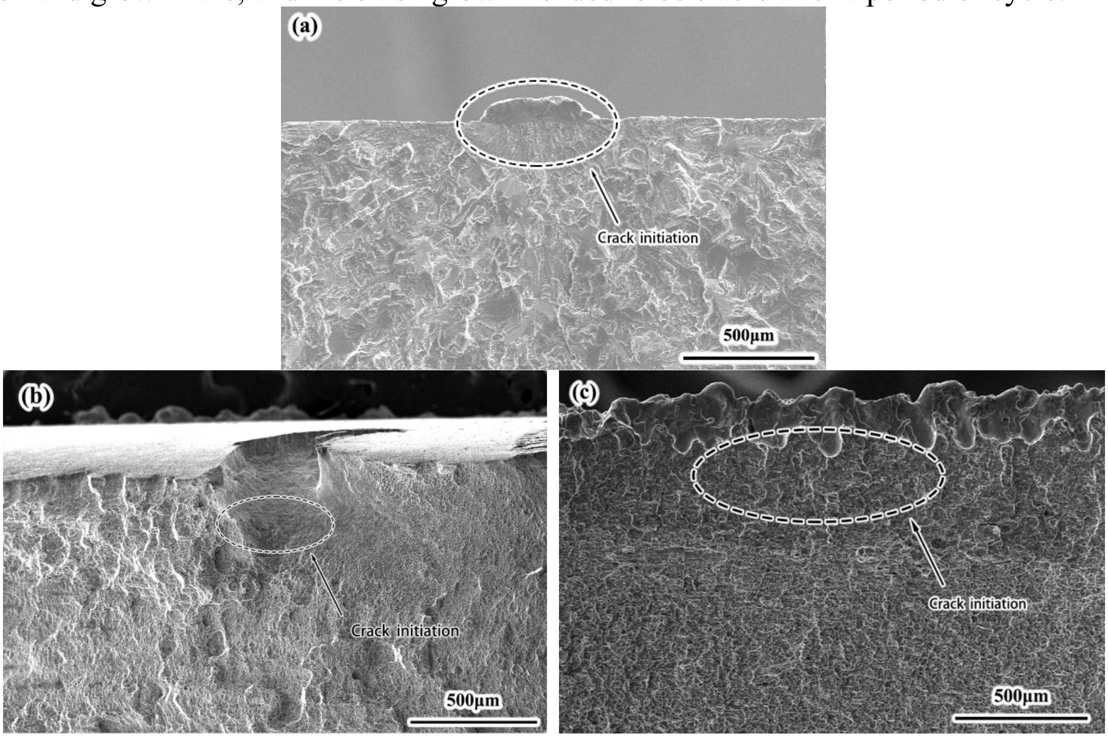

Fig. 3 Fatigue fracture of TA15 titanium alloy after laser marking :
unmarked (a)、shallow (b) and deep (c)

4. Summary

(1) After shallow laser marking of TA15 titanium alloy, the shape of the bottom end of the notch section is mainly semi-circular arc, resulting in local stress concentration. When the laser power is increased for deep laser marking, the shape of the bottom end of the notch section mainly presents a sharp conical shape, which makes the stress concentration phenomenon more obvious.

(2) Laser marking has an effect on the fatigue properties of TA15 titanium alloy. The fatigue life of laser marking (shallow) sample is reduced by 62.7% and that of laser marking (deep) sample is reduced by 86.4% compared with that of unmarked sample. The crack initiation of unmarked specimen is from the surface, and the fatigue crack initiation after laser marking is mainly from the marking place. With the increase of depth, the coarser the topography of the source region, the more obvious the crack divergence state in the initiation zone, the more complicated the crack initiation state in the initial stage of initiation, and the fatigue life decreases rapidly.

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