Effect of different micro-arc oxidation coating layer types on fatigue life of 2024-T4 alloy

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Abstract Due the fatigue life of aluminum alloys is strongly sensitive to the environmental effect in the most engineering applications, one of effectively improved methods on the strength and fatigue life of aluminum alloys is generally to take a coating process on the surface of these aluminum alloys. And the micro-arc oxidation ceramics coating method is not only to enhance the fatigue strength but also to avoid the environment corrosion. In this work, a dual-spindle rotating bending environment fatigue tests for two types aluminum alloys were carried out. The effects of differently relative humidity and oxidation ceramics coating types on fatigue life of aluminum alloys were discussed. These results indicated that the fatigue life (N_f>10^6) of 7074-T6 alloy began obviously to degrade when the relative humidity is over than 75% and there is a threshold. At the same time, the fatigue lives of 2024-T4 alloy by using the different oxidation ceramics coating treatments present the different changed tendencies. For example, the effect of micro-arc oxidation ceramics coating with sealing hole technology on fatigue life is positive and the effect of other two oxidation ceramics coating technologies on fatigue life is negative, such as micro-arc oxidation coating and hard oxidation coating.

Keywords Fatigue life, Aluminum alloy, Micro-arc oxidation technology, Coating layer, Relative humidity

1. Introduction

Aluminum alloys have been widely used for making structural parts in transport vehicles such as ships and aircraft for the purpose of reducing their weight. However, these structures are usually exposed to the natural environment throughout their lifetime. In these fields, very often the main requirements for the components include high-cycle fatigue (HCF) and corrosion resistance [1], especially the corrosion fatigue (CF) is defined as the sequential stages of aluminum alloys damage that develops during accumulated load cycling in an aggressive environment [2-4]. In addition, the effect of the relative humidity of over 60% on the HCF life of aluminum alloys can not be ignored. This is because the decrease in fatigue life was mainly the acceleration of crack growth caused by brittle fracture under rotating bending and the transition to shear mode crack accompanied with glide plane decohesion and void formation under ultrasonic loading respectively [5,6]. The first requirement is achieved usually by a proper material selection to enhance the fatigue resistance of aluminum alloy but not to avoid the higher cost. The second requirement for aluminum alloys is achieved by using corrosion resistance coatings [7,8]. Micro-arc oxidation ceramics process is a classical approach to enhance the fatigue properties [9] and to provide one of countermeasures against the fatigue corrosion damage of aluminum alloys. However, the enhanced behavior and effective mechanism to fatigue property of aluminum alloys exists still some arguments and/or there are not enough experimental evidences. In this work, we sum up the effect of the relative humidity on the fatigue life of aluminum alloys then investigate the effects of different micro-arc oxidation ceramics methods on the fatigue life of Al 2024-T4 alloy. The results indicated that the fatigue life (N_f>10^6) decreased obviously when the relative humidity scopes from 50% to 75% and the effect of micro-arc oxidation ceramics coating with sealing hole on the fatigue life of Al 2024-T4 alloy is positive and the effect of other micro-arc oxidation ceramics coating technologies, such as micro-arc oxidation process and hard oxidation process, on the fatigue life of Al 2024-T4 alloy is negative.

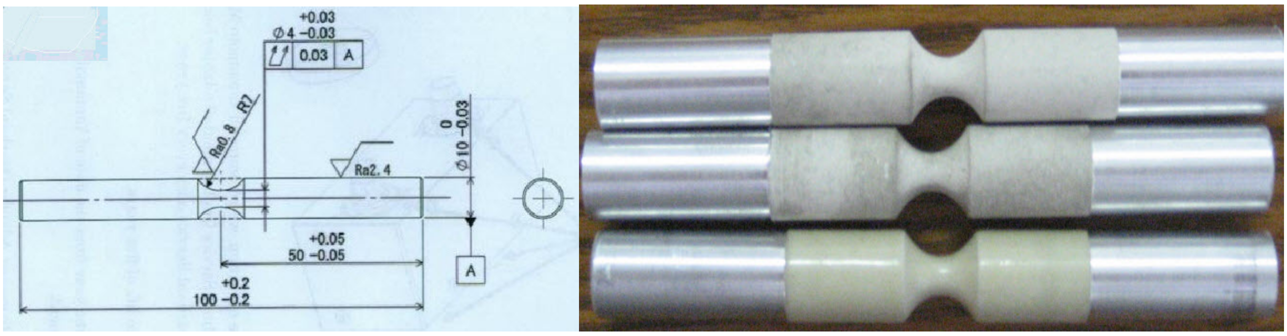
2. Material and Experimental Procedure

Materials used were Al 2024-T4 alloy and Al 7074-T6 alloy. And the size and shape of the experimental specimens is shown in Figure. 1 including the morphology of specimen with the different micro-arc oxidation ceramics coating processes consisting of the different micro-arc oxidation ceramics coating technologies with sealing hole, micro-arc oxidation ceramics coating and hard oxidation ceramics coating surface technologies as shown in Fig. 1b. The oxidation ceramics coating layer of all experimental specimens by the different oxidation ceramics coating surface technologies has the approximate same ceramics coating layer thickness of about 0.15 mm. The center notch in these specimens was fabricated to control the stress concentration factor as about 1.08. The mechanical properties of aluminum alloys are presented in Table 1. All fatigue tests were performed by using the rotating bending machine including the addition relative humidity controlled device and 4-spindle loading device (by Yamamoto Metal Tech Co. LYD, Japan) as shown in Figure 2. The machine provides the cyclic loads at the frequency of 50 Hz and at the stress ratio of R=-1.

Table 1. Mechanical properties

	$\sigma_{0.2}$ (MPa)	σ_B (MPa)	E (GPa)	δ (%)
Al 2024-T4	325	470	70.0	20
Al 7075-T6	527	673	72.2	11

$\sigma_{0.2}$: 0.2% proof stress. σ_B: Tensile strength. E: Young's modulus. δ: Percentage elongation.



(a) (b)

Figure 1 Shape and dimensions of specimens (mm)

Figure 2 Experimental machine

3. Results and discussion

3.1 Effect of the relative humidity on fatigue life of Al 7075-T6 alloy

Figure 3 illustrates the S-N curves under the different relative humidity scopes of Al 7075-T6 alloy. The high-cycle fatigue (HCF) behavior of Al 7075-T6 alloy indicated that the effect of the relative humidity on the fatigue life can not be ignored. Especially when the relative humidity is over than 75% and the fatigue cycles is over than 2×10^6, the effect of the relative humidity on fatigue life of aluminum alloy is very obvious. At the same time, there is a difference about the fatigue behavior in the two relative humidity states of both 75% and 100% (in water), in which with the increasing of relative humidity, the fatigue life of Al 7075-T6 alloy observably decreases no matter what is the relative humidity of over than 75% and the low- or high- cycle fatigue life of aluminum alloy. Of course, the difference of fatigue life is much obvious when the cycles are over than 10^6. However, the decreasing trend of fatigue life was restrained at lower relative humidity scopes from 75% to 50% and low-cycle or $N<10^6$. The effect of the relative humidity on the fatigue life of aluminum alloy can be even ignored. It has previously been reported that the influence mechanism was expressed by the different fatigue fracture models [5,10]. One of main reasons is because the shear stress action occupies more than part in fatigue fracture process although the applied stress is only a compressive and tensile stress at the surface damage point of specimen. The shear stress at the fatigue fracture surface might be caused by the coupling action both stress state and hydrogen or oxygen on the fatigue crack initiation and growth mechanism of aluminum alloys. Therefore, the fatigue crack growth driven force of Al 7075-T6 alloy comes from the interaction both shear and normal stresses. With the corrosion effect of hydrogen or oxygen increasing, the shear stress occupied the proportion to increase. However, the composite damage behavior of humidity effect needs to be carefully discussed in further.

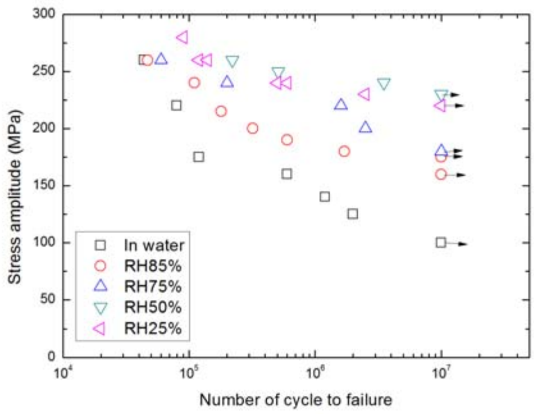


Figure 3 S-N curves under the different relative humidity scopes of Al 7075-T6 alloy

3.2 Effect of different micro-arc oxidation processes on fatigue life of Al 2024-T4 alloy

Considering the countermeasures against the effect of relative humidity on the fatigue life of aluminum alloy, the oxidation ceramics coating layer were carried out on the surface of Al 2024-T4 alloy specimens by using the micro-arc oxidation, micro-arc oxidation plus the sealing hole and hard oxidation technologies, respectively. All coating layers have an approximate same thickness of about 0.15 mm. in addition, to compare with the differently typical coating layer how to influence on the fatigue life of Al 2024-T4 alloy, the fatigue data without coating layer has been also plotted in the S-N curves as shown in Figure 4. These experimental results indicated that the fatigue life (mark Δ) of Al 2024-T4 alloy is seriously injured with the hard oxidation ceramics coating layer, but the effect of micro-arc oxidation plus sealing hole method on the fatigue life of Al 2024-T4 alloy is positive. And the fatigue life (mark ○) of Al 2024-T4 alloy with the micro-arc oxidation ceramics coating layer is approximate same fatigue life (mark ■) of Al 2024-T4 alloy. By means of the fatigue data with and without oxidation ceramics coating layer of Al 2024-T4 alloy compared as shown in Figure 4, we clearly know that the coating layer is able to avoid the effect of humidity or corrosion on the fatigue strength of aluminum alloy but the different coating layer technologies cause the fatigue damage mechanism change of aluminum alloy. Therefore, we should pay close attention to the issue in future to optimize and improve the coating layer technology.

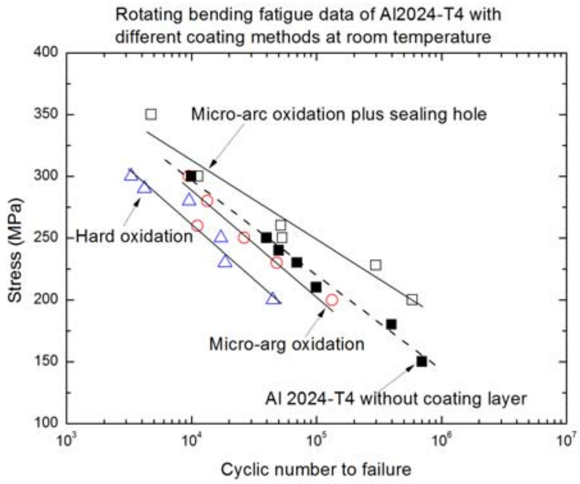
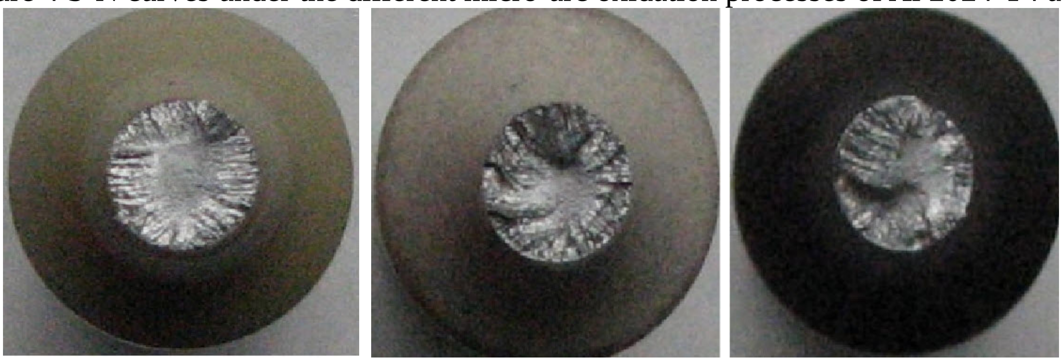


Figure 4 S-N curves under the different micro-arc oxidation processes of Al 2024-T4 alloy



(a) (b) (c)

Figure 5 Fatigue fracture surfaces for differently typical micro-arc oxidation processes of Al 2024-T4 alloy (a) micro-arc oxidation ceramics coating with sealing hole, (b) micro-arc oxidation ceramics coating, (c) hard oxidation ceramics coating.

Figure 5 illustrates the fracture appearances for the different oxidation ceramics coating layer technologies including (a) the micro-arc oxidation ceramics coating layer with sealing hole, (b) the micro-arc oxidation ceramics coating layer and (c) hard oxidation ceramics coating layer. All the applied stress amplitudes are 230 MPa, respectively. These fracture surfaces have much more different flat fracture surface such as the smooth area in the center or concave-convex surface in the marginal zone as shown in Figure 5a and 5b as well as 5c. This is a fact that the different flat fracture surface reflects the different fatigue crack propagation life. That is the fatigue crack propagation life for micro-arc oxidation ceramics coating layer with sealing hole is slower than that for micro-arc oxidation ceramics coating layer. This is because the center area and the fatigue crack propagation area in the marginal zone for the micro-arc oxidation coating ceramics layer with sealing hole are larger and relative smoother than that other two oxidation technologies. It means that the surface quality in the oxidation ceramics coating layer processes plays an important part in fatigue damage of aluminum alloy. In additional, the fracture-resistant of the different fracture appearances is different under the different oxidation ceramics coating layer methods. The different oxidation ceramics coating layer methods cause unavoidably the different surface quality. The oxidation ceramics coating layer with sealing hole can much easily avoid the surface defects such as shrinkage cavity. And the shrinkage cavity causes unavoidably the stress concentration and fatigue life degradation of materials. At the same time, the residual stress affects on the fatigue life of Al 2024-T4 alloy to exist the different results in three oxidation ceramics coating processes.

4. Summary

Fatigue life of aluminum alloys may be either affected by relative higher humidity when the cycle is over than 2×10^6 or improved by the appropriate oxidation ceramics coating layer technology. For example, the effect of micro-arc oxidation with sealing hole process on the fatigue life of Al 2024-T4 alloy is positive and the effect of other micro-arc oxidation processes, such as micro-arc oxidation process and hard oxidation process, on the fatigue life of Al 2024-T4 alloy is negative. Therefore, the micro-arc oxidation ceramics coating layer with sealing hole technology is not only to enhance the fatigue strength but also to avoid the harmful or negative effect of the relative humidity on the fatigue life of Al 2024-T4 alloy.

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