Comparison Study on Machined Surface Integrity and Corrosion Resistance of 2024 Aluminum Alloy

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Abstract—2024 aluminum alloy is an engineering equipment material with broad application prospects, which can be used in space flight and shipbuilding industry. However, the lack of corrosion resistance hinders its further application. The effects of milling and further shot peening processes on the surface integrity of 2024 aluminum alloy were investigated. Electrochemical polarization measurements were performed in 3.5wt% NaCl solution to characterize the corrosion resistance of milling alone surfaces and the further shot-peening process surfaces after milling. Experimental results reveal that the surface residual stress and microhardness of the shot-peened surfaces are much higher than those of the only milling surfaces owing to the severer plastic deformation induced by further shot peening process. While the shot-peened surfaces are roughened with the higher surface roughness. Under the synergic effects of three terms mentioned above, the corrosion potential of shot-peened surfaces is much positive than that of milled ones, meaning the corrosion resistance after shot peening is better. The comparison test gives a way to enhance the corrosion behavior of 2024 aluminum alloy milled surfaces.

1. Introduction
As a kind of high strength duralumin, 2024 aluminum alloy is a popular material in space flight and marine [¹,²]. However, due to the influence of corrosive medium in the atmospheric environment, aluminum alloy could be corroded in different corrosion types [³,⁴]. Corrosion brings great harm to equipment safety and personal safety. Therefore, improving the corrosion resistance of aluminum alloy is an urgent problem to be solved.

Great efforts have been made to meet this challenge. Choi et al. [⁵] studied the electrochemical polarization test of Al-Mg (6.5%) alloy after homogenization heat treatment. According to the experimental results, so a concluded that with the extension of homogenization duration, the corrosion resistance increases steadily and reaches saturation after 24 h. Dmitry et al. [⁶] used plasma electrolytic oxidation (PEO) technology to generate a layer of alumina film on the surface of 6061 aluminum alloy, and characterized its corrosion resistance. The experimental results can effectively prove that the alloy treated by PEO process has better corrosion resistance than the untreated matrix. The corrosion behavior of materials is not only related to their own element composition, but also related to the surface condition in direct contact with the corrosive medium in the service environment. Niu et al. [⁷] compared the corrosion resistance of milling surface and polished surface of 2A97 Al-Li alloy in 3.5 wt% NaCl...
solution with polarization tests. Experimental results can fully prove that the corrosion resistance of milled surface is better than that of polished surface. Jebaraj et al. [8] used shot peening process to strengthen the surface of 5083 aluminum alloy, and then measured its corrosion resistance. The results of corrosion test in simulated marine solution show that the corrosion resistance of further shot-peened process surface has been significantly improved.

Shot peening process is a very mature surface strengthening process, which is very common in the field of improving the corrosion properties of alloys. With a large number of highspeed shots repeatedly impacting, the variation within the surface layer mainly includes surface grains refinement, residual compressive stress generation and surface microhardness enlargement [9]. In addition, shot peening can also produce a side effect, that is, surface roughness. As a factor of surface integrity, surface roughness has a great influence on surface corrosion. It is reported that as the surface roughness value increases, the corrosion resistance of the material decreases [10,11].

The aim of this paper is to study the surface integrity of 2024 aluminum alloy after milling and further shot peening process. Electrochemical polarization measurement was performed in 3.5 wt% NaCl solution to characterize the corrosion resistance of shot-peened surfaces.

2. Experimental

2.1. Material preparation

2024 aluminum alloy block (50 x 40 x 20 mm) is used in this paper as experimental material. The alloy composition is shown in Table 1.

| Element | Cu | Mn | Mg | Cr | Si | Zn | Al |
|---------|----|----|----|----|----|----|----|
| % Weight| 3.8-4.9 | 0.3-1.0 | 1.2-1.8 | 0.1 | 0.5 | 0.25 | Bal. |

Two different surfaces were used in this research, one is milling surface and the other is shot peening process surface. Due to the different preparation methods of the two surfaces, the whole preparation process falls into two kinds.

First, the milling surface is prepared, as shown in Fig.1. The symmetrical milling experiment was carried out on the YCM-V116B vertical machining tool. Meanwhile, the SECO R220.53-0100-15-5A milling cutter with diameter of 100 millimetres and matching blade SEEX1505 AFN-E10 H25 were selected. According to the results from our previous experiment, the selected parameters are shown in Table 2. After milling process, the sample is cut into six small samples of equal size (10 x 10 x 6 mm) by wire electric discharge machining. Three of the six specimens were randomly selected for the subsequent shot peening process.

![Fig.1 Scheme of symmetric milling.](image)

| Variable | $a_x$/mm | $a_y$/mm | $v_c$/($m\,min^{-1}$) | $f_c$/($mm\,z^{-1}$) |
|----------|--------|--------|---------------|-------------|
| Magnitude | 2 | 40 | 1000 | 0.1 |

The preparation of three samples with shot-peened surfaces is shown in Fig.2. An HWH-5200 air compressor and a nozzle with the diameter of 5 millimetres were used for shot peening process. The steel shots S-110 with the diameter of 0.3 millimetres that utilized in our operations was purchased from
Shandong Kaitai Shot Blasting Machinery Co., Ltd. The shot peening process parameters combination is shown in Table 3.

![Fig.2 Scheme of shot peening process.](image)

| Variable |
|----------|
| Pressure/MPa |
| $d$/mm |
| $\theta$/° |
| Duration/s |
| Coverage |
| Magnitude | 0.7 | 100 | 90 | 60 | 100% |

2.2. Characterization of samples
After the preparation of the two kinds of samples, an ultrasonic cleaning is carried out immediately in ethanol for 5 min to remove impurities. Then the surface roughness, residual stress and microhardness were measured. Surface roughness was measured using a Mitutoyo SJ-410 surface profilometer. Residual stresses on machined surfaces were measured by an IXRD-MG40 residual stress analyser equipped with CrKβ radiation. The surface microhardness is measured by 402MVD Vickers hardness tester. Every measurement mentioned above was repeatedly at least three times for the repeatability of data, and then the mean values were obtained.

2.3. Electrochemical polarisation
In 3.5wt% NaCl solution, the electrochemical polarization was measured at normal atmospheric temperature with CHI604E electrochemical workstation. In this experiment, we used a three-electrode system, in which the working electrode is the processed specimen, the reference electrode is saturated calomel, and the auxiliary electrode is platinum sheet. Each specimen is connected with copper core wire and sealed with acrylic resin to expose a 10 mm × 10 mm machined (i.e., milling or shot peening process) surface as the working electrode. After the test is powered on, each specimen shall be immersed in corrosive solution for 45 minutes to meet the test conditions of stable open circuit potential. The corrosion solution of each sample needs to be replaced after polarization measurement to avoid the test error caused by solution factors.

3. Test Results and Discussions

3.1. Machined surface roughness
Milling and further shot peening process have different effects on the surface roughness of 2024 aluminum alloy. After further shot peening process, the sample surface darkened, as shown in Fig.3. Compared to milling surface, the further shot peening process increases obviously the surface roughness. After measurement, the surface roughness after milling was Sa 0.19 μm, while the shot-peened surface roughness was Sa 4.82 μm, which is 25 times of that after milled surface. The three-dimensional (3D) morphology of the processed samples was further characterized with the white light interferometer for the visual difference, as shown in Fig.4. The upper and lower limit depth of the shot-peened surface was more obvious. Indentation is introduced during shot peening, which is the main factor responsible for the increase in surface roughness.
Fig. 3 Samples under different treatments.

Fig. 4 3D morphology under different processing.

(a) milled surface  (b) shot-peened surface

3.2. Surface residual stresses
Both machining and strengthening process will produce residual stress, while surface residual compressive stress helps to improve the corrosion resistance of parts, while tensile stress weakens the corrosion resistance of parts \(^{[12]}\). For better comparison, the magnitude of residual compressive stress after multiple measurements of the milling and peening surfaces is shown in Fig. 5. The stress magnitude on the milled surface was small, only \(-56.72\) MPa. While the magnitude on the shot-peened surface was up to \(-402.65\) MPa, which is quite higher than that on the milled surface. The comparison indicates that the larger residual compressive stress can be effectively introduced by the further shot peening process.

Fig. 5 Surface residual stress after different processes.

3.3. Surface microhardness
Microhardness is one of the important characteristics of machined surface integrity, which has significant influence on the corrosion resistance. The microhardness values measured on the milled surface and shot-peened surface were both greater than those on untreated surface, as shown in Fig. 6. It shows that work hardening occurred during milling process and shot peening process. However, the microhardness after further shot peening process is \(285.4\) HV, which is much higher than that of milled surface. This is mainly due to the significant increase of dislocation density caused by severe plastic deformation introduced by further shot peening process.
3.4. **Electrochemical polarisation measurements results**

Fig.7 shows the polarization curves of 2024 aluminum alloy milled surface and further shot peened surface in 3.5 wt% NaCl solution. Derived from the curve, the corrosion potential of the further shot-peened sample is -1.0437 V, and the corrosion potential after milled sample -1.1895 V. The results showed that the surface treated by further shot peening process after milling has higher corrosion resistance. This is mainly due to the improvement of surface microhardness and residual compressive stress after further shot peening process, and the defects caused by surface roughness enlargement can be effectively overcome under the combined effects of microhardness and stresses.

![Fig.6 Surface microhardness after different processes.](image)

**Fig.6** Surface microhardness after different processes.

![Fig.7 Potentiodynamic polarization curves of the milled and shot-peened specimens in 3.5 wt % NaCl solution.](image)

**Fig.7** Potentiodynamic polarization curves of the milled and shot-peened specimens in 3.5 wt % NaCl solution.

4. **Conclusion**

This research, the machined surface integrity and corrosion behavior of 2024 aluminum alloy after milling process and further shot peening process were characterized and compared. The conclusions are as follows:

1. Compared with the milled surface, significant differences in the surface integrity are present after further shot peening process. The surface roughness after milling process is much smaller than that after further shot peening process. Further shot peening process treatment will cause large plastic deformation, resulting in large surface residual stress and surface microhardness on the shot peened surface.

2. Compared with milling process alone, the 2024 aluminum alloy surface with further shot peening process has better corrosion resistance. The surface roughness that has an adverse impact on corrosion protection will be offset by the beneficial effects of amplified surface residual compressive stress and microhardness.

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