Short Communication

Study on Mechanical Properties of Anodized Films on 5052 Aluminum Alloy

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5052 aluminum alloy as the material for mechanical arm components was chosen as the research object, and its surface was modified by anodization. The single factor method was used for studying the effect of current density during the anodization process on the microstructure and mechanical properties including hardness, friction and wear property, tensile property and elastic-plastic property of the anodized films. The results show that when the current density is 2 A/dm^2, the compactness and crystallinity of the anodized film are good and the hardness reaches 432.6 HV, which is 2.7 times higher than that of 5052 aluminum alloy. Moreover, the tensile strength and yield strength reach 426.4 MPa and 280.8 MPa, which are respectively 0.9 time and 1.5 times higher than that of 5052 aluminum alloy. The anodized film has strong bearing capacity and resistance to local plastic deformation, a wear rate of only 6.4×10^{-4} mm^3/(N·m) and its elastic recovery coefficient reaches 28.3%, which demonstrates excellent wear resistance. However, when the current density is too high, the hardness of the anodized film will decrease as a result of the decrease in compactness, resistance to local plastic deformation and the decrease in wear resistance, which results in a decrease in tensile property and elastic-plastic property.

1. INTRODUCTION

5052 aluminum alloy is generally used for manufacturing high-strength structural parts, including mechanical arm components, pressure vessels and supports for a variety of structural forms [1-5]. Due to the relatively high magnesium content that is found in 5052 aluminum alloy, its weight is lower than that of many other aluminum alloys. However, at the same time, the strength, hardness and plasticity of 5052 aluminum alloy are poor compared with other aluminum alloys. Therefore, taking measures to improve the mechanical properties (including strength, hardness, elastic-plastic properties, etc.) of 5052 aluminum alloy is of particular importance.

Many studies have shown that the anodization process is an effective way to improve the surface properties of aluminum alloy, due to the formation of an anodized film on the surface of aluminum alloy [6-10]. At present, research reports on anodization of aluminum alloy mainly focus on the optimization of electrolyte composition, process conditions, structure, corrosion resistance and mechanical properties of anodized films [11-14]. Meanwhile, mechanical property is an important performance indicator for anodized film. At present, some scholars have studied the effect of anodization process conditions on the mechanical properties of aluminum alloy. For example, Aerts et al. [15] studied the influence of electrolyte temperature on the hardness and wear performance of anodized film on pure aluminum surface, and they found that electrolyte temperature could affect the microstructure of anodized film and thus affect its mechanical properties. Yoshimoto et al. [16] prepared an anodized film with a thickness of 100 μm and high hardness (500 HV) on the surface of pure aluminum plate by optimizing the anodization process conditions. Bensalah et al. [17] studied the failure mechanism of mechanical properties of anodized film. Moreover, Hagelsieb et al. [18] also studied the mechanical properties of anodized film and its application in micro-electromechanical system devices (such as cantilevers, pressure and flow sensors, etc.). Cheng et al. [19] found that voltage is a key anodization process parameter affecting the mechanical properties of anodized film.

According to some reports from the literatures, many scholars mainly use pure sulfuric acid electrolyte through optimizing anodization process conditions to improve the mechanical properties of aluminum alloy. In addition, numerous literatures about the mechanical properties of anodized film on aluminum alloy mainly focus on the wear resistance and hardness. In fact, tensile property and elastic-plastic property are also important mechanical properties of anodized film. Therefore, an anodized film with excellent mechanical properties on 5052 aluminum alloy used for mechanical arm components was prepared from the mixed electrolyte with sulfuric acid and tartaric acid in the paper. Through analysis and testing of the comprehensive mechanical properties (including hardness, wear resistance, tensile property and elastic-plastic property) of anodized film, the inner relationship between the current density, structure of anodized film and comprehensive mechanical properties of anodized film is further revealed, which has a certain significance and innovation.

2. EXPERIMENTAL

2.1 Materials

The experimental material is 5052 aluminum alloy, and its chemical composition is shown in Table 1. Multiple samples of 70 mm × 30 mm were cut by wire cutting, and after grinding, polishing, degreasing, activation, cleaning and drying in sequence, they were immersed in electrolyte for anodization.

Table 1. Chemical composition of 5052 aluminum alloy

Element	Mg	Cr	Cu	Si	Zn	Mn	Al
Mass fraction/%	2.2~2.8	0.15~0.35	0.1	0.25	0.1	0.1	Balance

2.2 Anodization of 5052 aluminum alloy

Figure 1 shows schematic diagram of anodization of 5052 aluminum alloy. The pretreated 5052 aluminum alloy sample was used as the anode, and the pure aluminum plate was used as the cathode. The power supply is a DC regulated power supply with an output voltage of 0~100 V. Analytical pure sulfuric acid (98%) and tartaric acid were mixed to prepare electrolyte. The composition of the electrolyte is sulfuric acid (98%) 200 g/L, tartaric acid 60 g/L. The addition of tartaric acid can reduce the corrosion and dissolution of the electrolyte to anodized film, and is conducive to the formation of a dense anodized film. A precise temperature controller was used to maintain the temperature of the electrolyte at about 10°C. During the anodization process, the electrolyte was magnetically stirred, and the current density was set to 0.5~3.5 A/dm^2 while the oxidation time was 50 min.
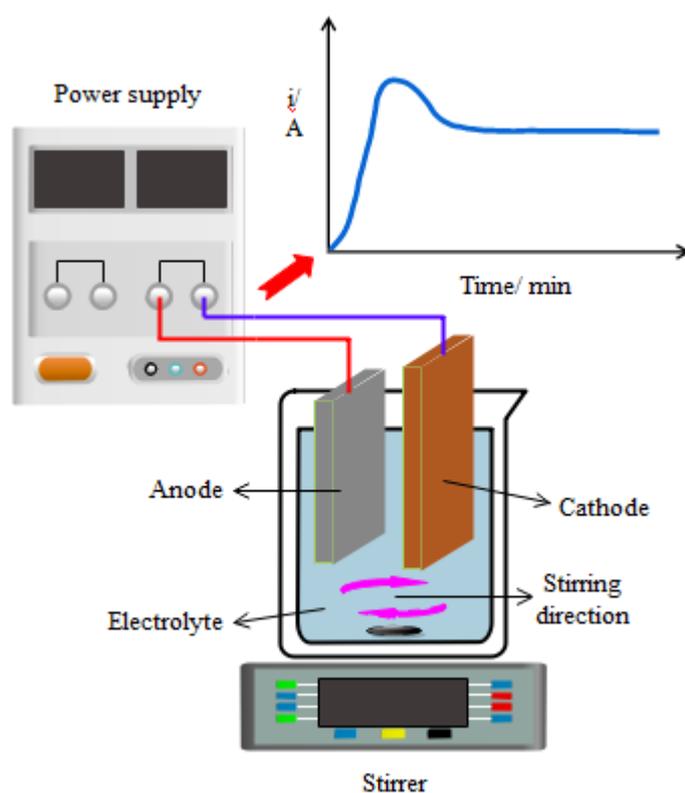
Figure 1. Schematic diagram of anodization of 5052 aluminum alloy

2.3 Microstructure and mechanical properties of different anodized films

2.3.1 Microstructure characterization

The microstructure of different anodized films on the surface of 5052 aluminum alloy were characterized by MERLIN Compact scanning electron microscope. The accelerating voltage of the scanning electron microscope was set at 10 kV, and the magnification was 12000 times.

D8 Advance X-ray diffractometer was used for characterizing the phase structure of different anodized films on the surface of 5052 aluminum alloy. The voltage and current were set at 40 kV and 40 mA, respectively, and the step scan range was between 15° and 95°, and the scan rate was 4°/min.

2.3.2 Hardness testing

MV-TEST1000 Vickers hardness tester was used for testing the hardness of different anodized films on the surface of 5052 aluminum alloy. The load was 0.98 N, and it was unloaded uniformly after 15 s. In addition, five points on the surface of each sample were chosen at random and the test results were averaged as a means of reducing errors.

2.3.3 Friction and wear property testing

The friction and wear property of different anodized films on the surface of 5052 aluminum alloy were tested by using UMT-2 friction testing machine in a reciprocating friction mode at room temperature without lubrication. The normal load was 5 N, the reciprocating frequency was 5 Hz, and the stroke was 12 mm. After the experiment was conducted, the wear debris on the surface of each sample was cleaned, and the wear scar morphology on the surface of 5052 aluminum alloy was observed with VHX-5000 3D microscope. The wear scar area was measured so that the wear rate could be calculated.

2.3.4 Tensile property testing

The test samples were prepared according to ASTM E8M-04 standard, and Shimadzuag-100kN universal testing machine was used for tensile property testing. The tensile rate was set at 1 mm/min, and the tensile strength and yield strength of different anodized films on the surface of 5052 aluminum alloy were obtained. Prior to the experiment, sand paper was used to polish each samples, and any visible defects on the surface of each sample were removed in order to minimise their influence on the test results.

2.3.5 Elastic-plastic property testing

The load-displacement curves of diffferent anodized films were obtained using NHT2 nanoindentor which automatically controlled the change of the applied load, and the maximum load did not exceeding 150 mN. The maximum load and elastic recovery coefficients were obtained through analysis of the load-displacement curves, which were used as the basis for evaluating the elastic-plastic property of different anodized films on the surface of 5052 aluminum alloy.

3. RESULTS AND DISCUSSION

3.1 Microstructure of different anodized films on 5052 Aluminum Alloy

Figure 2 shows the surface morphology of different anodized films on the surface of 5052 aluminum alloy. They are many regular pores can be seen on the surface of anodized films. The anodized film on aluminum alloy is composed of many regular pores which are circular or hexagonal due to different process parameters [20-23]. In comparison, it can be seen that current density significantly influences the flatness and compactness of the anodized films. As can be seen in Figure 2(b), when the current density is 0.5 A/dm^2, the pores on the anodized film are smaller and appear to be flatter and denser. This is because the growth rate of the anodized film being slow when the current density is low. Relatively little heat is generated during the anodization process and this can be dissipated in time and without accumulating in the electrolyte. As the current density increases to 2 A/dm^2, the pore size on the anodized film increases. This is because the amount of heat that is generated during the anodization process increases. The heat accumulated in the electrolyte increases the temperature near the anodization surface and the dissolution ability of the anodized film is enhanced. At the same time, the growth rate of the anodized film is obviously accelerated, which slows down the dissolution of the anodized film to a certain extent, resulting in flatness and compactness of the anodized film. However, when the current density reaches 3.5 A/dm^2, the surface of the anodized film becomes rough and loose, some pores of different sizes and depths are formed and some particles are attached. This is because the difficulty in dissipating the large amount of heat that is generated during the anodization process is difficult to dissipate in time as a result of the current density being too high, and the heat accumulated in the electrolyte causes serious dissolution of the anodized film. Although the growth rate of the anodized film is faster, the increased degree of dissolution causes the surface structure becoming loose.
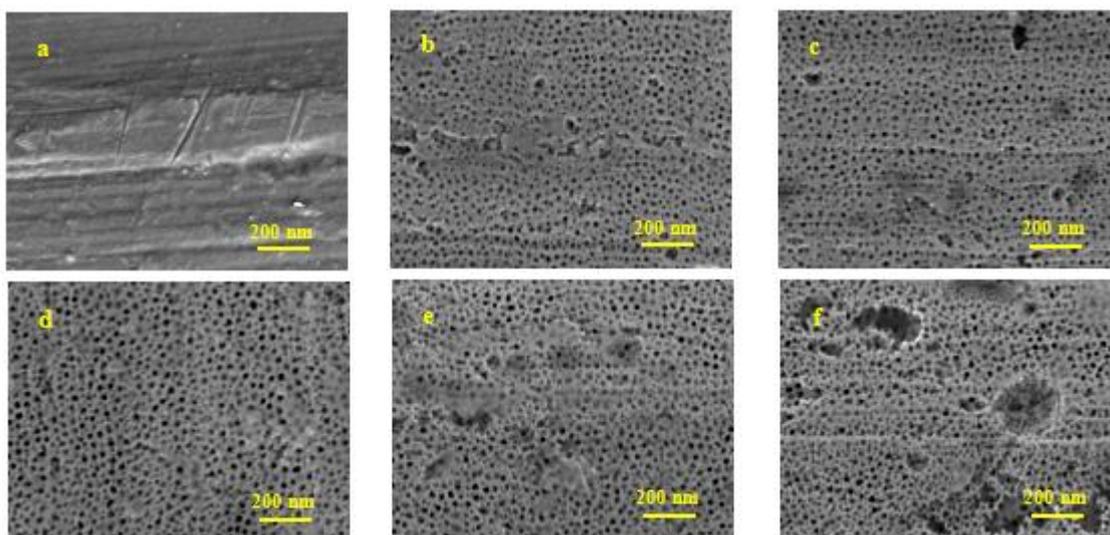
Figure 2. Microstructure of different anodized films on 5052 aluminum alloy: a-5052 aluminum alloy; b-anodized film (current density 0.5 A/dm^2); c-anodized film (current density 1 A/dm^2); d-anodized film (current density 2 A/dm^2); e-anodized film (current density 2.5 A/dm^2); f-anodized film (current density 3.5 A/dm^2); (accelerating voltage is 10 kV, and magnification is 12000 times)
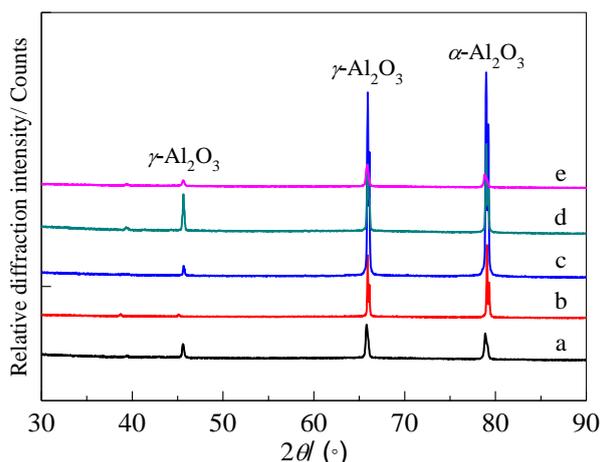
Figure 3. XRD spectra of different anodized films on 5052 aluminum alloy: a-anodized film (current density 0.5 A/dm^2); b-anodized film (current density 1 A/dm^2); c-anodized film (current density 2 A/dm^2); d-anodized film (current density 2.5 A/dm^2); e-anodized film (current density 3.5 A/dm^2); (voltage and current is set at 40 kV and 40 mA, step scan range is between 15° and 95° and scan rate is 4°/min)

Figure 3 shows the XRD spectra of different anodized films on the surface of 5052 aluminum alloy. According to the analysis of XRD spectra, it is known that the current density has little effect on the phase structure of the anodized film. Anodized films contain α-Al$_2$O$_3$ and γ-Al$_2$O$_3$ phases which is also verified in some literatures [24-25]. It can be seen from Figure 3 that there are three sharp diffraction peaks in different anodized films and the positions basically overlap, and each diffraction peak corresponds to the same phase. However, when the current density is 2 A/dm^2, the diffraction peak intensity corresponding to α-Al$_2$O$_3$ and γ-Al$_2$O$_3$ are relatively high, indicating that the phase of the anodized film is complete and the crystallinity is good.

3.2 Hardness and wear resistance property of different anodized films on 5052 Aluminum Alloy

Figure 4 shows the hardness of different anodized films on the surface of 5052 aluminum alloy. It can be seen from Figure 4 that when the current density is 0.5 A/dm^2, the hardness of the anodized film is approximately 2.1 times higher than that of 5052 aluminum alloy. As the current density increases to 2 A/dm^2, the hardness of the anodized film gradually increases to 432.6 HV, which is 2.7 times higher than that of 5052 aluminum alloy. The reason is that the increase in the current density is beneficial to increase the growth rate and thickness of the anodized film, resulting in a dense surface structure that contributes to enhancing the resistance to local plastic deformation [26]. However, when the current density reaches 3.5 A/dm^2, due to the severe dissolution of the anodized film, the surface structure becomes loose and the compactness decreases, resulting in a decrease in its resistance to local plastic deformation and there is a significant decrease in hardness. The relationship between current density and

wear resistance of materials prepared by electrochemical methods is also investigated in some papers [27-30].
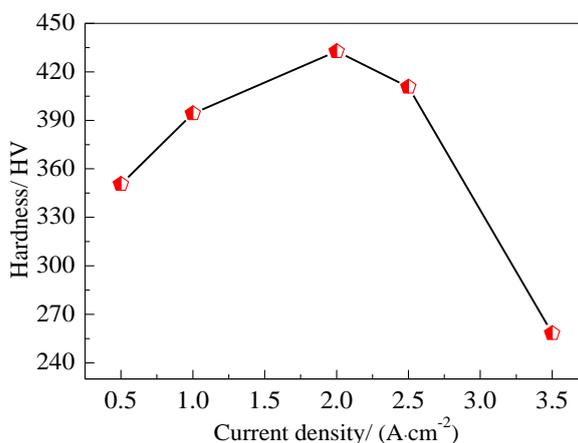
Figure 4. Hardness of different anodized films on 5052 aluminum alloy (loading force is 0.98 N for 15 s at constant load mode; testing results of five positions are averaged)

Figure 5 shows the wear scar morphology of different anodized films on the surface of 5052 aluminum alloy. It can be seen from Figure 5 that there are wear characteristics including local peelings on the surface of 5052 aluminum alloy and different anodized films. This is due to adhesive wear and abrasive wear occurring easily during the friction process. However, obvious differences can be seen in the width of wear scar and the degree of local peelings formed on the surface of 5052 aluminum alloy and different anodized films. Generally, the narrower the wear scars, the better the wear resistance of the material will be.

The wear scar formed on the surface of 5052 aluminum alloy is the widest, which indicates a serious degree of wear. As the current density increases from 0.5 A/dm^2 to 2 A/dm^2, the wear scar formed on the surface of the anodized films becomes significantly narrower. This is because the anodized film gradually thickening and the surface structure having a tendency to be dense, which plays a role in surface modification and reduces the degree of surface wear of 5052 aluminum alloy and improves the wear resistance. When the current density is 2 A/dm^2, the wear scar formed on the surface of the anodized film is the narrowest, indicating that its wear resistance performance is the best. The reason is that the surface structure of the anodized film is relatively dense and has high hardness, enabling it to resist the wear degree caused by the normal load and abrasive particles during the friction process. In addition, the anodized film also has strong resistance to local plastic deformation, thereby hindering the degree of extrusion and damage caused by mechanical shearing force in the friction process and reducing the local peeling phenomenon. However, when the current density reaches 3.5 A/dm^2, the wear scar formed on the surface of the anodized film becomes wider and the local peeling degree also increases, indicating that the wear degree of the anodized film surface is aggravated and the wear resistance performance is declined. This is because when the current density is too high, the surface structure of the anodized film

becomes loose, the density decreases, and the bearing capacity and resistance to local plastic deformation decrease, resulting in poor mechanical property.
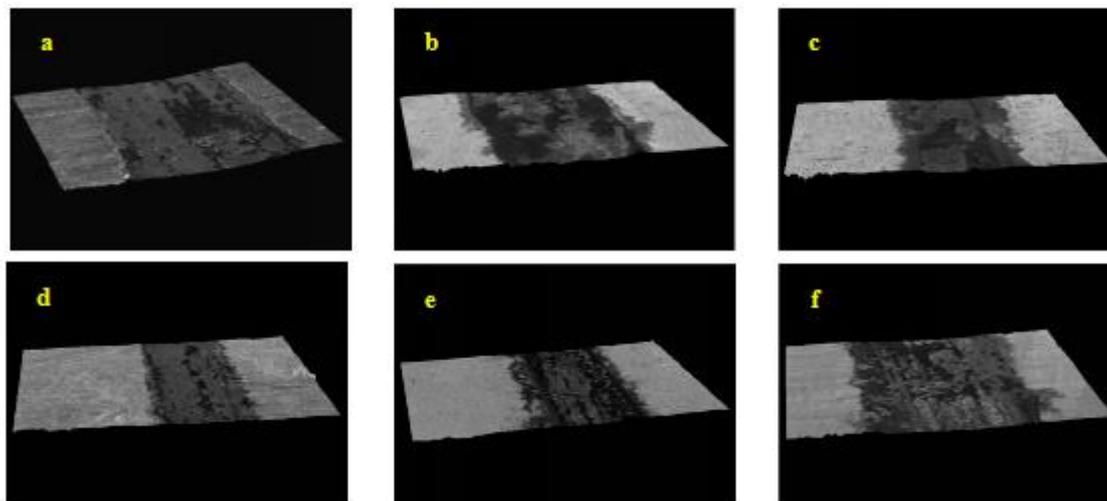
Figure 5. Wear scar morphology of different anodized films on 5052 aluminum alloy: a-5052 aluminum alloy; b-anodized film (current density 0.5 A/dm^2); c-anodized film (current density 1 A/dm^2); d-anodized film (current density 2 A/dm^2); e-anodized film (current density 2.5 A/dm^2); f-anodized film (current density 3.5 A/dm^2)

Figure 6 shows the wear rate of different anodized films on the surface of 5052 aluminum alloy. It can be seen from Figure 6 that with the increase of the current density from 0.5 A/dm^2 to 2 A/dm^2, the wear rate of the anodized film shows a decreasing trend, and the corresponding decrease is from 9.7×10^{-4} mm^3/(N·m) to 6.4×10^{-4} mm^3/(N·m). This further indicates that the increase in current density increases the hardness of the anodized film and enhances the resistance to local plastic deformation and damage, which is manifested as improved wear resistance. When the current density is 2 A/dm^2, the wear rate of the anodized film is only 6.4×10^{-4} mm^3/(N·m), and its wear resistance performance is the best, which is consistent with the above analysis results. However, as the current density increases from 2 A/dm^2 to 3.5 A/dm^2, the wear rate of the anodized film increases, correspondingly from 6.4×10^{-4} mm^3/(N·m) to 1.2×10^{-3} mm^3/(N·m). This further indicates that the high current density leads to a decrease in the hardness of the anodized film, and the resistance to both local plastic deformation decreases, thus showing poor wear resistance.
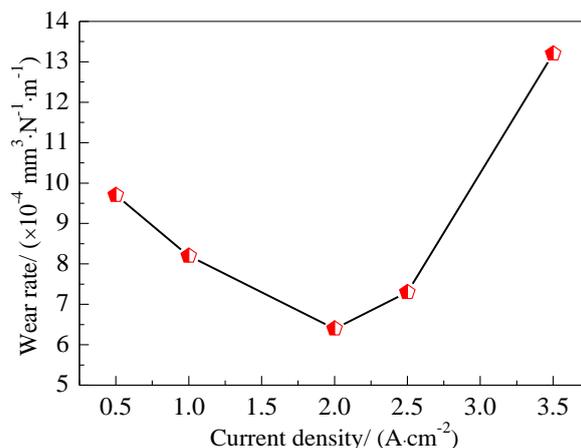
Figure 6. Wear rate of different anodized films on 5052 aluminum alloy (load force is 5 N, reciprocating frequency is 5 Hz, and stroke is 12 mm; reciprocating friction mode is used at room temperature without lubrication)

3.3 Tensile and elastic-plastic property of different anodized films on 5052 aluminum alloy

Figure 7 shows the tensile strength and yield strength of different anodized films on the surface of 5052 aluminum alloy. It can be seen from Figure 7 that as the current density increases from 0.5 A/dm^2 to 3.5 A/dm^2, the tensile strength and yield strength of the anodized film both increase first and then decrease. During the anodization process, the dissolution of 5052 aluminum alloy and the anodized film occur simultaneously, resulting in the surface structure of 5052 aluminum alloy changing. The anodic oxidation process of aluminum alloy is accompanied by the formation and dissolution of alumina [31-33]. Only when the formation rate of anodized film is greater than the dissolution rate, it is beneficial to get the compact anodized film. The anodized film acts as a surface modification for improving the tensile property of 5052 aluminum alloy. When the current density is 2 A/dm^2, the tensile strength and yield strength of the anodized film reach 426.4 MPa and 280.8 MPa, which are about 0.9 times and 1.5 times higher than that of 5052 aluminum alloy, respectively. The mechanical property such as tensile, fatigue and yield strength of anodized aluminum alloy has also been investigated by several researchers [34-36]. Because the surface structure of the anodized film is relatively dense and high in hardness, it has great resistance to local plastic deformation, meaning that its tensile property are the best. However, when the current density reaches 3.5 A/dm^2, the surface structure of the anodized film becomes loose and the density decreases, resulting in a decrease in its tensile property.
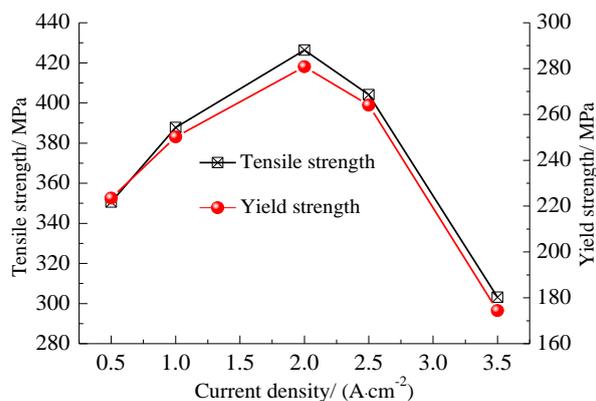
Figure 7. Tensile strength and yield strength of different anodized films on 5052 aluminum alloy (specimens are prepared according to ASTM E8M-04 standard; testing is at room temperature with a tensile rate of 1 mm/min)

Figure 8 shows the load-displacement curves of different anodized films on the surface of 5052 aluminum alloy. It can be seen from Figure 8 that the load-displacement curves of 5052 aluminum alloy and different anodized films are relatively smooth, and each curve can be divided into two parts: loading stage and unloading stage. In the loading stage, when the indentation depth is the same, the load applied by the anodized film is larger than that of 5052 aluminum alloy, indicating that the anodized film has a strong resistance to external loads. However, with the current density increasing from 0.5 A/dm^2 to 3.5 A/dm^2, the load applied by the anodized film shows a trend of increasing first and then decreasing under the same indentation depth.
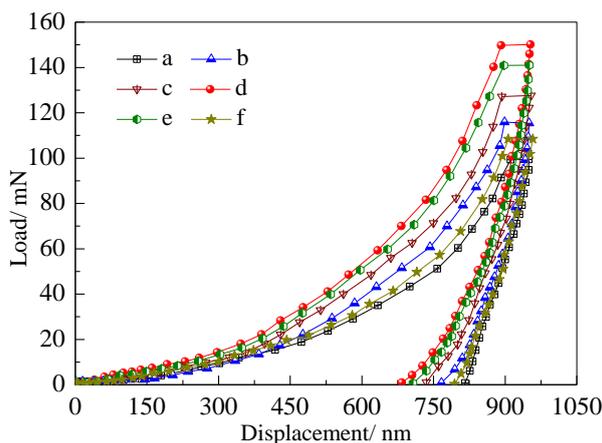
Figure 8. Load-displacement curves of different anodized films on 5052 aluminum alloy: a-5052 aluminum alloy; b-anodized film (current density 0.5 A/dm^2); c-anodized film (current density 1 A/dm^2); d-anodized film (current density 2 A/dm^2); e-anodized film (current density 2.5 A/dm^2); f-anodized film (current density 3.5 A/dm^2)

This is related to the obvious difference in the density and hardness of different anodized films, which leads to differences in their resistance to loading. In the unloading stage, due to the recovery of elastic deformation to a certain extent, the indentation of 5052 aluminum alloy and different anodized

films all retracts, but the depth of indentation left on the surface of the sample is different. Since 5052 aluminum alloy produces severe plastic deformation during the loading-unloading process, its indentation recovery is less.

When the current density is 2 A/dm^2, the surface structure of the anodized film is dense, the hardness is the highest, and it shows strong resistance to local plastic deformation, so it can better resist external loads. During the loading-unloading process, it has the lightest plastic deformation and the largest indentation recovery.

According to the maximum indentation depth during the loading stage and the indentation depth left on the surface of the sample after unloading, the elastic recovery coefficients of 5052 aluminum alloy and different anodized films were calculated, as shown in Figure 9. It can be seen from Figure 9 that the elastic recovery coefficient of 5052 aluminum alloy is the smallest, just 14%, indicating that its poor elastic-plastic property. The elastic-plastic property of the anodized film are improved compared with 5052 aluminum alloy. When the current density is 2 A/dm^2, the elastic recovery coefficient of the anodized film is the highest, reaching 28.3%, providing further indication that the anodized film has excellent elastic property. However, when the current density is too high, the elastic recovery coefficient of the anodized film exhibits a significant decrease due to the surface structure of the anodized film becoming loose and the compactness decreasing, which results in a reduction in its elastic-plastic deformation resistance.
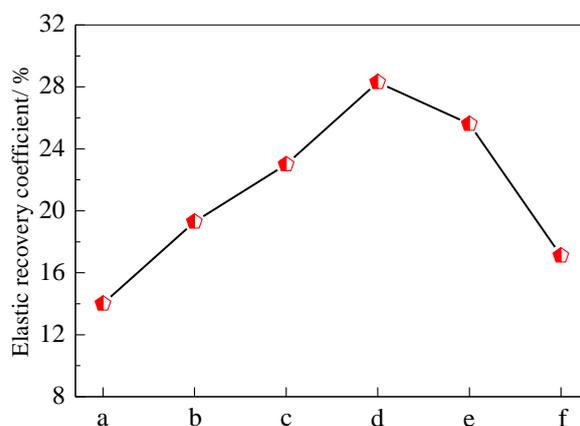
Figure 9. Elastic recovery coefficient of different anodized films on 5052 aluminum alloy: a-5052 aluminum alloy; b-anodized film (current density 0.5 A/dm^2); c-anodized film (current density 1 A/dm^2); d-anodized film (current density 2 A/dm^2); e-anodized film (current density 2.5 A/dm^2); f-anodized film (current density 3.5 A/dm^2)

4. CONCLUSIONS

In this paper, 5052 aluminum alloy as the materials for mechanical arm components was chosen as the research object, and its surface was modified by anodization. The following conclusions were obtained through research:

　　　(1) Current density during the anodization process has basically no effect on the phase structure of the anodized film. Anodized films contain α-Al_2O_3 and γ-Al_2O_3 phases. When the current density is 2 A/dm^2, the compactness and crystallinity of the anodized film are both good. The hardness, tensile strength and yield strength reach approximately 432.6 HV, 426.4 MPa and 280.8 MPa respectively. The wear rate is just 6.4×10^{-4} mm^3/(N·m) while the elastic recovery coefficient reaches 28.3%. However, when the current density is too high, the hardness of the anodized film decreases due to the decrease in the compactness of the anodized film and the decline in the resistance to local plastic deformation. The tensile property and elastic-plastic property are also decreased.

　　　(2) The increase of current density makes the anodized film thicker and the surface structure has a tendency to be dense, thereby enhancing the ability to resist local plastic deformation and fracture. The degree of extrusion and damage caused by shear forces is reduced, resulting in high hardness, excellent wear resistance and good elastic-plastic property.

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