Research and test of electrochemical corrosion in NC machining of 7 series aluminum alloy aircraft structure parts

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Abstract. In order to avoid the corrosion of 7 series aircraft aluminum alloy structural parts in the process of NC machining. For GB6144 and JB7453, in the process of 7 series alloy aluminum aircraft structural parts NC machining, the evaluation of the anti-corrosion performance of the water-based cutting fluid used in the evaluation of the material pertinence is not strong, the time length index is insufficient, and the galvanic corrosion performance is lack. Based on the analysis of the mechanism of corrosion by combining the processing conditions and processing environment of 7 series alloy aluminum aircraft structural parts, a semi immersion corrosion test was designed to compare the electrochemical corrosion resistance of four water-based synthetic cutting fluids. The test can evaluate and compare the anti-corrosion performance of different cutting fluids for 7 series alloy aluminum aircraft structure, and provide guidance for the optimization and management of 7 series alloy aluminum aircraft structure.

1. Introduction

The aircraft structure made of 7 series alloy aluminum is an important part of the aircraft frame and aerodynamic shape[1]. In order to improve the efficiency and machining quality of 7 series alloy aluminum aircraft structural parts in NC machining. In the current stage, many of them adopt the process plan of large allowance and high-speed cutting fluid for the numerical control machining of 7 series alloy aluminum aircraft structural parts. In this processing mode, a lot of cutting heat will be produced. In order to take away a lot of cutting heat and avoid sticking the cutter, 7 series alloy aluminum aircraft structural parts are usually processed with water-based cutting fluid with better cooling performance.

The commonly used water-based cutting fluid mainly includes emulsion, semi-synthetic cutting fluid, and fully synthetic cutting fluid[2]. Emulsion refers to the water-soluble cutting fluid, which only uses mineral oil as the base oil. It is made of oil emulsified oil and water. The content of mineral oil is between 50% - 80%. It has good lubricity and corrosion resistance. However, the disadvantages of emulsion are its poor stability, short service life, easy to stink, and the use of employees' skin is prone to allergic reactions, which are harmful to the environment and personnel[3]. Semi-synthetic cutting fluid is a kind of water-soluble cutting fluid which contains both mineral oil and chemical synthetic base oil, and contains a small amount of mineral oil (5% - 30%) in its concentrate. For semi-synthetic cutting fluid, it has better cooling, lubricity, and corrosion resistance[4]. The all synthetic cutting fluid is a kind of water-soluble cutting fluid that uses the chemical composition to synthesize the base oil completely. Its thermal conductivity is the best of the three kinds of water-based cutting fluid, but its corrosion resistance is poor because it does not contain mineral oil[5]. From the perspective of green manufacturing, in the current aviation enterprises, the use of electromagnetic has been gradually limited.
At present, semi-synthetic and synthetic cutting fluid is the main auxiliary media in the machining of 7 series alloy aluminum aircraft structural parts.

However, semi-synthetic cutting fluid and full synthetic cutting fluid have worse anti-corrosion performance than emulsion, and 7 series alloy aluminum itself has poor anti-corrosion performance. Therefore, in the processing of 7 series alloy aluminum aircraft structural parts with semi-synthetic cutting fluid or full synthetic cutting fluid as an auxiliary medium, there are often problems such as discoloration and blackening of parts, which will lead to the failure of the surface quality of parts. Therefore, this phenomenon may cause corresponding product quality problems or add additional manufacturing processes and affect the delivery nodes of products. Therefore, in the numerical control machining of 7 series alloy aluminum aircraft structural parts, it is necessary to focus on the corrosion resistance of cutting fluid.

2. The evaluation standard of cutting fluid at home and abroad and the characteristics of cutting fluid evaluation for Aeronautical Structural Parts

At this stage, the current domestic standards for water-based cutting fluid evaluation of the corrosion resistance of aluminum alloys are mainly GB/T 6144-2010 "Synthetic Cutting Fluid" and JB/T 7453-2013 "Semi-Synthetic Cutting Fluid". In these standards, the investigation of aluminum alloy materials in the corrosion test is through the use of 2 series aluminum alloys LY12, 2A12. Among them, the corrosion test method in JB/T 7453-2013 refers to the test method in GB/T 6144-2010. The method used in the test is to immerse the test piece in a capped beaker filled with diluent under the condition of 55 °C ± 2 °C and observe it after continuous placing for a specified time. First of all, in the two standards, the corrosion test is to select the 2-Series aluminum alloy from the aluminum alloy test piece material, its alloy composition is less than 7 series alloy aluminum, so its corrosion resistance is stronger than 7 series alloy aluminum. Based on this way to evaluate the corrosion resistance of 7 series alloy aluminum structural parts, there are some deficiencies in material pertinence. Secondly, in these two standards, the inspection time of the corrosion test is at most 8 hours, while for large-scale aluminum alloy aircraft structural parts, many CNC machining processes take more than 24 hours, and the longest is even 120 hours. Therefore, there is a certain lack of inspection time to evaluate the anti-corrosion performance of cutting fluid in the processing of 7 series alloy aluminum structural parts. Third, in GB/T 6144-2010 "Synthetic Cutting Fluid," the corrosion test of aluminum alloys only provides single metal test schemes. However, at present, the contact of dissimilar metals often occurs in the processing of aluminum alloy aircraft structural parts, the situation and galvanic corrosion also often occurs. Therefore, it is not enough to evaluate the corrosion resistance of cutting fluid only through the single metal corrosion test to fully reflect the real performance of cutting fluid in the 7 series alloy aluminum aircraft structural parts NC machining.

According to the performance evaluation of cutting fluid used in the machining of 7 series alloy aluminum aircraft structural parts, the Boeing Company puts forward a more strict process plan. In the process specification bac5008 of Boeing Company, they provide test process and evaluation indexes for performance evaluation of various production auxiliary media involved in aircraft manufacturing. Among them, they put forward the performance requirements of cutting fluid with resistance to galvanic corrosion. The test materials are 7075-T7451 bare aluminum, cadmium plated alloy steel bolt, cadmium plated steel gasket, cadmium plated steel nut, etc. In their test methods, aluminum, steel, and titanium laminations are used for drilling and reaming. During the drilling process, use the diluent of the cutting fluid to be measured, then insert the fastener and clamp it, and place it for 28 days under the condition of 60 °C temperature, 50% relative humidity, and contact with air. Then, take out and check the corrosion around the hole. The standard requires no evidence of corrosion in any alloy. Boeing's cutting fluid anti-corrosion testing technology focuses on the period after the completion of machining, rather than the process cycle of NC machining of aircraft structural parts. Therefore, in order to investigate the corrosion resistance of 7 series of aviation aluminum alloy structural parts in NC machining, in this paper, combined with the process conditions and corrosion occurrence of 7 series alloy aluminum
aircraft structural parts in NC machining, the relevant analysis was carried out. The corrosion test of 7 series alloy aluminum in different cutting fluids was carried out.

3. Electrochemical corrosion of aluminum alloy and anti-corrosion mechanism
Galvanic corrosion refers to the corrosion caused by the electrochemical reaction of metals in the electrolyte solution. Because the electrolyte solution is mostly aqueous, it is also called "wet corrosion"[2]. Aluminum is a chemically active metal. In both acidic and alkaline solutions, aluminum both dissolves at the anode and releases hydrogen at the cathode. The aluminum metal dissolves in the anode (oxidation reaction), enters into the solution in the form of aluminum ion. Then the electrons flowing from the anode through external circuit are absorbed by oxygen from electrolyte solution and adsorbed on the cathode surface, and the cathode process (reduction reaction) occurs.

Anode reaction: \[4\text{Al} - 12e^- = 4\text{Al}^{3+}\]
Cathode reaction: \[3\text{O}_2 + 6\text{H}_2\text{O} + 12e^- = 12\text{OH}^-\]
Total reaction: \[3\text{O}_2 + 6\text{H}_2\text{O} + 4\text{Al} = 4\text{Al}^3+ + 12\text{OH}^-\]

This electrochemical reaction causes the corrosion of aluminum and its alloys. In the process of NC machining, the passivation film on the surface of aluminum alloy will be destroyed. In the presence of an anionic and alkaline environment, it will promote the occurrence of corrosion. If the anti-corrosion performance of cutting fluid is insufficient, it will lead to discoloration and blackening caused by electrochemical corrosion on long cycle parts.

3.1. Electrochemical corrosion of single alloy
In most industrial metals, there will be a certain amount of impurities, and there is a certain potential difference between the impurities and the parent metal. Therefore, when the metal is immersed in the electrolyte solution or contacted with it for a long time, many corrosion micro batteries with metal as anode and impurity as cathode will be formed on its surface, which will make the metal produce anode dissolution and suffer corrosion. In the process of machining, the excessive amount of anions or high pH in the water-based cutting fluid may cause corrosion on the surface of parts. The electrochemical corrosion of aluminum alloy in the water-based cutting fluid is caused by the formation of many corrosion micro batteries during the processing period of aluminum alloy on equipment. When the reaction of these corrosion micro cells reaches a certain scale and lasts for a certain period of time, the electrochemical corrosion phenomenon of products will be formed. For 7 series alloy aluminum aircraft structural parts, there is no discoloration and blackening phenomenon when dissimilar metals contact in the processing scheme, which is often caused by this reason. As shown in Figure 1, aluminum alloy thin-walled cavity parts are loaded by aluminum alloy tooling and fixed by vacuum adsorption. In this case, because the anti-corrosion performance of water-based cutting fluid can not meet the requirements, when the thin-walled parts are immersed in water-based cutting fluid, they may appear discoloration and blackening.

![Figure 1. Process plan easy to produce electrochemical corrosion of single alloy.](image_url)

3.2. Galvanic corrosion
When aluminum alloy contacts with other high potential metals, galvanic corrosion will occur. In some process conditions, if the parts are directly clamped on the machine tool workbench (as shown in Figure 2a) or the steel screws, pressing plates and steel tooling (as shown in Figure 2b) are used, the aluminum alloy material contacts with the steel material, forming a primary battery with water-based cutting fluid as an electrolyte solution, resulting in electrochemical corrosion. This kind of corrosion usually occurs at the contact surface or around the contact surface of two kinds of alloys and spreads out continuously.
3.3. **Galvanic corrosion**

In the process of machining, because the oxide layer on the surface of aluminum alloy is removed, it will lead to electrochemical corrosion more easily. Therefore, the anti-corrosion problem should be considered in the formulation of water-based cutting fluid. The anti-corrosion additive generally realizes the anti-corrosion of water-based cutting fluid in the cutting fluid. The commonly used antitrust agents are mainly divided into three types: anode antitrust agent, cathode antitrust agent, and mixed antitrust agent. Their working mechanism is to increase anode passivation, cathode passivation, or at the same time increase anode and cathode passivation so that a layer of passivation film can be formed on the surface of the aluminum alloy after machining to inhibit the generation of blocking electrochemical reaction. Among the commonly used corrosion inhibitors for aluminum alloy, there are mainly phosphorus-containing type antitrustives, heterocyclic type antitrustives, siliceous type antitrustives, and fatty acid derivative antitrustives. In order to improve the corrosion resistance of cutting fluid for aluminum alloy, the material properties, the aluminum inhibition effect of corrosion inhibitor, and the compatibility of corrosion inhibitor should be considered in the formulation.

For an excellent aluminum alloy cutting fluid, it must have good corrosion resistance. For the two standards of GB/T 6144-2010 and JB/T 7453-2013, they are insufficiency in the material targeting, evaluation time, and environmental factors of the cutting fluid evaluation in the CNC machining of 7 series alloy aluminum aircraft structural parts. And the problem of the Boeing BAC5008 process file deviating from the processing environment in the corrosion test. In this paper, an aluminum alloy semi-immersion corrosion test is proposed for the process conditions and environment in the CNC machining of 7 series alloy aluminum aircraft structural parts.

4. **Test part**

4.1. **Galvanic corrosion**

7 series alloy 7050-T7451, which is widely used in the aeronautical structure, is selected as the test material, and the single metal corrosion and bimetal corrosion tests are designed respectively for the single metal electrochemical corrosion and galvanic corrosion which occur more in the NC machining of 7 series alloy aluminum. In order to better simulate the real corrosion situation in the field, the 7050-T7451 aluminum alloy was used in the 7 series alloy aluminum aircraft structure. According to the structural form and processing characteristics of 7 series alloy aluminum aircraft structural parts, the size of the test piece is determined to be 50mmx25mmx3mm. Before the test, 240 mesh or finer sandpaper is used to polish the surface of the test piece to remove the original passivation film on the surface. After grinding, clean the surface with industrial alcohol. Two kinds of semi-synthetic cutting fluid and two kinds of fully synthetic cutting fluid (diluent with a concentration ratio of 6%) were selected for semi immersion test. In order to accelerate the test process, the test was carried out at a constant temperature of 55°C.
4.2. Single metal corrosion test

4.2.1. Test materials.

Table 1. Single metal corrosion test materials.

| Material name                  | Model / description   | Quantities |
|--------------------------------|-----------------------|------------|
| Cutting fluid                  | Semi-synthetic/A      | 100ml      |
| Cutting fluid                  | Semi-synthetic/B      | 100ml      |
| Cutting fluid                  | Total synthetic/C     | 100ml      |
| Cutting fluid                  | Total synthetic/D     | 100ml      |
| Aluminum alloy test piece      | 7050-T7451            | 4          |
| Measuring glass                |                       | 200ml      |

4.2.2. Test method. There are 4 pieces for the test. They are placed in 4 200ml-measuring cups numbered A, B, C and D respectively. The same volume of the above-mentioned 6% concentration diluent of A, B, C, D cutting fluid are poured into the measuring cups. The diluent shall be submerged in half of the test block (as shown in Figure 3), and placed in a constant temperature oven set at 55°C for 24 hours. Finally, the test pieces are taken out and checked for corrosion.

![Figure 3. Electrochemical corrosion test of single metal.](image)

4.3. Bimetallic corrosion test

4.3.1. Test materials.

Table 2. Bimetal corrosion test materials.

| Material name                  | Model / description   | Quantities |
|--------------------------------|-----------------------|------------|
| Cutting fluid                  | Semi-synthetic/A      | 100ml      |
| Cutting fluid                  | Semi-synthetic/B      | 100ml      |
| Cutting fluid                  | Total synthetic/C     | 100ml      |
| Cutting fluid                  | Total synthetic/D     | 100ml      |
| Aluminum alloy test piece      | 7050-T7451            | 4          |
| Bolt                           | Cadmium plated alloy steel | 4          |
| Nut                            | Cadmium plated alloy steel | 4          |
| Washer                         | Cadmium plated alloy steel | 4          |
| Measuring glass                | 200ml                 | 4          |

4.3.2. Test method. There are 4 pieces for the test. The washers and screws are installed in the holes of each test piece, and locked by nuts. Then 4 test pieces are placed in 4 200ml-measuring cups numbered A, B, C and D respectively (as shown in Figure 4). The same volume of the above-mentioned 6% concentration diluent of A, B, C, D cutting fluid are poured into the measuring cups. The diluent needs to be submerged to half of test pieces and placed in a thermostat set at 55°C for 24 hours. Finally, the test pieces are taken out and checked for corrosion.
5. Test results and analysis

Figure 5 shows the state of the test piece after the single metal corrosion test. Among them, the test piece A had a serious discoloration below the liquid surface, the test pieces B and D had a moderate darkening below the liquid surface, and the gloss of the test piece C was the same as the new one. Figure 6 shows the state of the test piece after the galvanic corrosion test. Discoloration and blackening of specimen A occurred more severely than the single metal corrosion test below the liquid surface, specimen B slightly darkened below the liquid surface, and specimen C remained the same gloss as the new one. D is moderately darkened. According to two groups of experiments, for 7 series alloy aluminum, total synthetic cutting fluid has the worst corrosion resistance among the four cutting fluids. In contrast, semi-synthetic cutting fluid C has the best corrosion resistance among the four cutting fluids. According to the test results of full synthetic cutting fluid B, for 7 series alloy aluminum, the same cutting fluid will have different performance in single metal corrosion resistance and galvanic corrosion resistance.

In order to determine the influence of electrochemical corrosion on the surface of 7 series alloy aluminum aircraft structure parts in NC machining, the surface observation and roughness analysis of
the two groups of specimens at the boundary of discoloration and blackening was carried out under the shape analysis laser microscope. As shown in Figure 7 and Figure 8, although there are discoloration and blackening on the surface of the test piece after the corrosion test, there is no obvious change in the surface shape. From the roughness analysis results in Figure 9 and Figure 10, it can be seen that the discoloration and blackening on the surface of the test piece have no obvious effect on the surface roughness.

Therefore, it can be considered that during the process of NC machining, the corrosion of parts caused by cutting fluid has no obvious influence on the roughness and surface morphology of parts. However, the presence of metal compounds on the surface may affect the chemical properties of the workpiece surface, such as the subsequent anti-corrosion performance, anti-fracture performance.

6. Conclusion

- Single metal corrosion test and bimetal corrosion test can well evaluate the corrosion resistance of cutting fluid used in the NC machining of 7 series alloy aluminum aircraft structural parts.
- For the same kind of cutting fluid, the corrosion resistance may have different performance when contacting single metal and bimetal. In general, bimetallic will be more serious.
- The surface discoloration and blackening of parts in the NC machining of 7 series alloy aluminum aircraft structural parts have no obvious influence on the surface roughness of parts.

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