

The Effects of Surface Texture on Fretting Fatigue between Fastener and Aluminum Structure

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Alcoa Fastening Systems

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ABSTRACT

Multi-fastener lap joints are vulnerable to fretting fatigue when they are subjected to repeated loading. In general the fretting fatigue condition leads to degraded properties of metallic structures due to the presence of the surface stress concentration resulting at the sites of fretting pits. In many cases, fretting can result in premature structure failures therefore a series of counter measures are frequently taken to minimize fretting especially at the fastener holes. One of major factors that affect the fretting phenomena between the fastener and fastener hole is the surface condition of the fasteners.

In this study, the influences of the surface texture and the surface plating of the fastener on the joint life were investigated by conducting double lap shear fatigue testing. It has been found that the joint fretting fatigue resistance is very sensitive to the surface texture of the fastener and as the surface roughness of the fastener is reduced the joint life increases. In addition, the test results presented in this paper indicated that the use of copper plating substantially improves the joint life by reducing the fretting between the fasteners on the aluminum structure.

INTRODUCTION

Mechanically fastened lap joints are extensively used in aircraft frame constructions and they are subjected to vibrations and cyclic loading during the service of the aircraft. Therefore lap jointed structures in aircrafts are susceptible to fretting fatigue occurring at the fastener hole. Fretting fatigue is known to be a major cause of failure in the aircraft industry and leads to high maintenance and inspection costs. Thus, it represents not only durability but it is also safety concern and plays a critical role in the maintenance of aging aircrafts.

Fretting is a combined form of wear, corrosion and fatigue and it is a time dependent process that requires more attention as the aircraft fleet continues to age [1, 2, 3, 4, 5]. The basic

requirements for fretting are relative motions between two contacting surfaces and cyclic loads applied to these surfaces [1, 2, 3]. In the case of fastened lap joints, relative motions can occur between the fastener outer surface and the bore surface of the structure hole. The cycling loading to the joints takes place during take-off and landing and vibratory stresses also occur during flight. In some cases the fretting can also occur between the faying surfaces of the joint plates if there is a loss of some of the preload due to losing of the fasteners resulting in gross slip of the joint [6, 7, 8]. The micro-slip causes damage to the surfaces and eventual failure by means of fretting fatigue (catastrophic failure) or fretting wear [5, 8]. The slip condition in fretting is frequently described as: i) complete stick, ii) partial slip and iii) full (gross) sliding. It is often observed that the most fretting damage takes place at a partial slip region where the slip levels are between 2 to 50 micron [9, 10].

The presence of fretting is often unexpected and causes reduction in fatigue life in comparison to plain fatigue, emphasizing the importance of recognizing and avoiding the phenomenon of fretting during the design stage of the joints. It is recognized that a significant number of variables affect fretting fatigue life. Primary variables are listed as:

- Contact pressure (normal load),
- Coefficient of friction (COF),
- Slip amplitude

Additionally, wear phenomenon plays an important role in the fretting fatigue process. The fretting wear process removes particles from the contacting bodies and produces substantial amount of debris which are predominantly made-up of abrasive oxide particles. The accumulation of wear debris at the interface of the contacting surface modifies contact condition and sub-surface stress state, directly influencing both the crack initiation and nucleation processes. Black debris due to fretting wear is commonly reported with aluminum alloys [12, 13, 14].

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In a fastened lap joint there are at least three possible sites where fretting can occur: 1) between the faying surfaces 2) under the pin head and collar or nut and 3) between the shank of the pin and the structure hole. Previous works conducted by Alcoa researchers examined the methods of improving fretting fatigue resistance of fastened joint through surface treatment techniques such a various types of anodizing, shoot peening, laser peening and low plastic burnishing [13]. Later they also examined the potential of the series of fastener coatings [7]. Their results showed that the best fretting resistance and joint fatigue life were obtained with the use of aluminum pigmented coating. Another earlier work showed that Teflon coating also increases the fretting fatigue life of fastened joints substantially [7]. Despite the fatigue life improvement achieved with use of such fastener coatings these solutions will be less desirable for applications where the electrical conductivity of the joints is critical due to their insulating characteristic. Therefore there is still a need for highly electrically conductive and fretting resistance fastener coatings for lightning critical applications such as fuel tanks. Furthermore, previous work done by Alcoa Fastening Systems demonstrated that the application of soft but highly conductive metal fastener coatings such as silver, nickel or gold provided added protection from lightning in composite components by increased conformity to the carbon fiber structure [11]. The objective of this evaluation was to determine if soft metallic coatings or any surface finish texture help to prevent fretting fatigue failure of the lap shear joints without adversely affecting the electrical conductivity of the joints. Furthermore, an attempt was also made to demonstrate the critical influence of the joint design on fretting fatigue resistance. Although this study primarily focused on the fretting fatigue of aluminum structure jointed by mechanical fasteners, fretting wear which can occur in conjunction with the fretting fatigue was also investigated.

I. Experimental Procedure

1.1. Materials

Test coupons were machined from 2024-T351 plate material in the longitudinal direction (i.e. parallel to grains). The chemical composition of the received alloy is given in [Table I](#). Composition of the test plates was found to be within the designated AMS-QQ-A-250/4. Machined test plates were then chromic acid anodized and painted before drilling.

The room temperature tensile properties obtained from the longitudinal specimens along with the fastener material properties are listed in [Table II](#).

1.2. Drilling and Assembly

A pattern of 9 holes per panel (three rows of three holes) were drilled using conventional TNC coated carbide drills and countersink drills. The top, middle and bottom splices were clamped tightly and drilled simultaneously. All of the drilling was conducted using coolant and a vertical mill center at a constant spindle speed of 2500 rpm and a feed rate of 3 in/min. Chips and debris created during drilling were continually removed using a vacuum system. Drills were visually inspected for any noticeable wear or chipping prior to drilling each panel to make sure not to introduce any micro-cracks along the surface of the drilled holes. After drilling, the fastener holes were carefully reamed to the desired size and cleaned to remove any residual debris. Finally each hole was inspected and measured using a bore gage. Hole dimensions were matched to the nominal interference requirement (0.003" to 0.0035") specified by the fastener manufacturer and kept constant for the all test specimens in order minimize the effects of the interference levels to the fastener/hole fretting.

Table I. Chemical composition of the as received 2024-T351

Elements (Wt. %)	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti
2024 plates	0.10	0.20	4.40	0.55	1.29	0.17	0.01	0.02
AMS-QQ-A-250/4	0.50 max	0.50 max	3.8-4.9	0.3-0.9	1.2-1.8	0.25 max	0.10 max	0.15 max

Table II. Typical mechanical properties of the materials

Alloy/Temper	Elastic modulus Ksi	Yield strength Ksi	Tensile strength Ksi	% Elongation	Hardness
Plates-2024-T351	10.0	47.3	69.8	17.8	63 HRB
Fasteners-A286 cres.	29.1	108	160	24	33 HRC

During assembly of the test coupons, an inter-fay polysulfide sealant was applied between the faying surfaces of the splices. Fasteners were wet assembled by applying sealant to the pin shank and head. The combined stack-up thickness was 1.0" which represents a nominal grip installation condition. The fastening system used for test panel assembly was a threaded sleeved fastener where the pins were made of A-286 corrosion resistance steel and the collars were made of Ti-3.5Al-2V titanium alloy. [Figure 1](#) and [2](#) illustrate the images of the test plate stack-up used to fabricate the lap-shear joint fatigue specimens and assembled test specimens

1.3. Fatigue tests

Fatigue tests were performed using a hydraulic servo-control test system. A constant amplitude sinusoidal cyclic loading of 25,600 lbf at load ratio (R) = -0.1 was applied. Test frequency was kept constant at 8 Hz. All tests were conducted at room temperature and in air with average humidity of 38 %. The test was terminated if no failure occurred after 400,000 cycles.

1.4. Surface Characterization

Scanning electron microscopy (SEM) was used to evaluate fretting damage and surface characteristics, such as topography and roughness. Fretting byproducts collected around the fastener surface including fretting debris were analyzed using an Energy Dispersion Spectroscopy (EDS) linked to the SEM. Topographical characterization of stainless steel fasteners with various surface coatings was performed using a non-contact optical profilometer instrument and a SPIP (Scanning Probe Image Processor).

II. Results and Discussion

2.1. Microstructure

The microstructure of the test plates was characterized using an optical microscope. The metallographic specimens were sectioned parallel to the extrusion direction. These samples were etched with standard Keller's reagent to reveal the grains

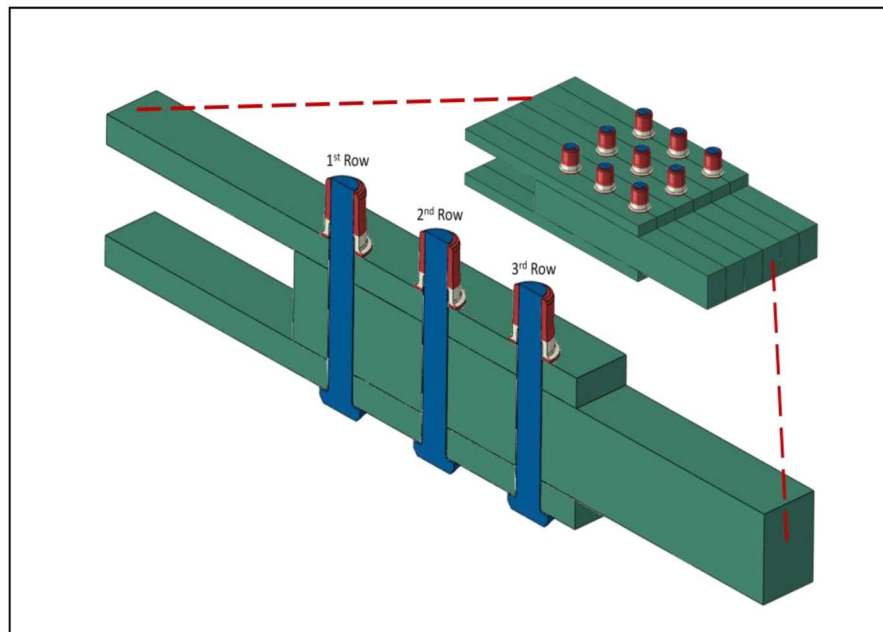


Figure 1. Schematic showing the lap shear fatigue test specimens.

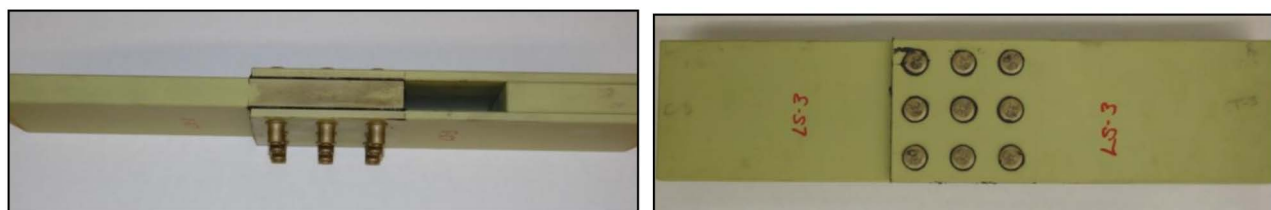


Figure 2. Photo showing the assembled test specimens.

and other microstructure details. The optical micrograph is presented in Figure 3. As can be seen in this figure, the microstructure of 2024 alloys consists of elongated grains and dispersed un-dissolved inter-metallic phases which are typical features of cold finish 2024 plates.

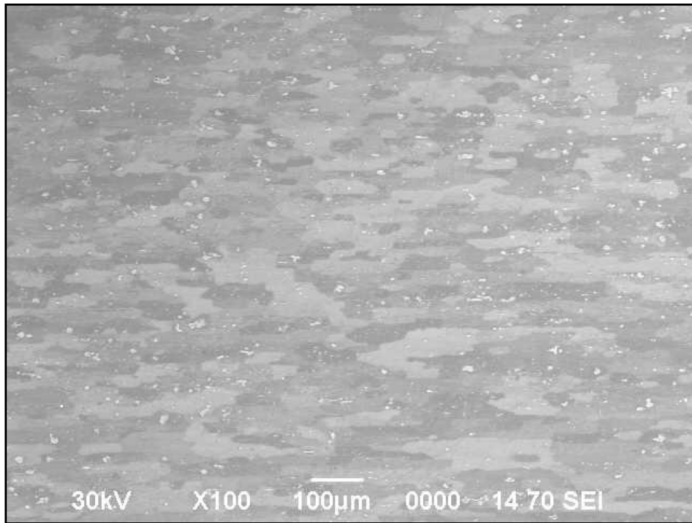


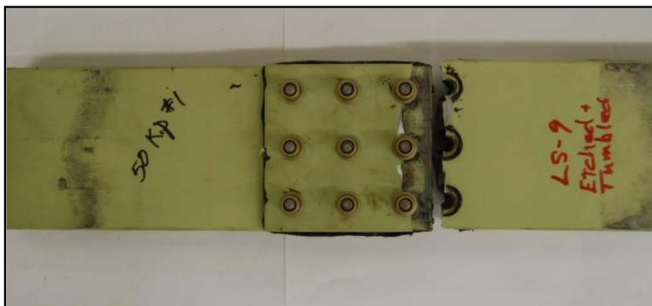
Figure 3. Optical micrograph showing the general microstructure of the test plates.

2.2. Lap shear joint fatigue test results

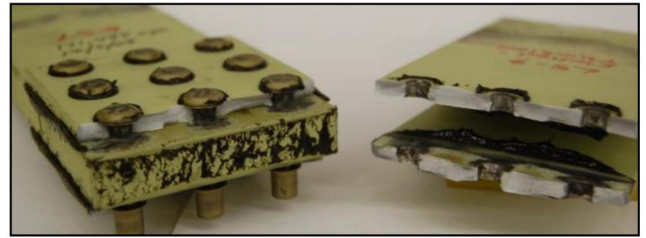
Figure 4 shows the typical failed test plate after lap shear fatigue testing. Table III summarizes the results of fatigue testing of the double lap shear specimens at load ratio of $R=-0.1$.



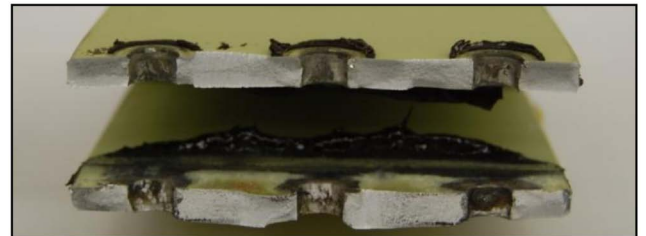
a). Top view



b). bottom view



c). general view



d). broken splice

Figure 4. Typical view of the failed test panels after lap shear fatigue testing

As can be clearly seen in this table, the glass bead finish on the fasteners produced the lowest fatigue life. Copper coating on the fasteners improved the fatigue life noticeably but once the copper layer was stripped the fatigue resistance of the joint decreased. The highest fatigue resistance was obtained with bare but larger size fasteners with different joint design configuration. More detailed discussion of the effects of fastener texture or finish on fretting fatigue behavior of the lap shear joint will be presented in later sections.

2.3. Typical Failure Modes

Failure of each double lap shear sample, without exception, was due to the net section fracture of the aluminum splices and occurred along the first row of the fasteners consistent with the higher percentage of load transferred through this row. The first row carries increasing portion of the load as the end region of the plates exposes higher shear load transfer [15]. No dominant fracture location either on the head side or the collar side of the aluminum splices was present. It has been determined that the failure mode of the tested specimens is the fretting fatigue which occurred at hole/fastener interface. It was observed that the multiple fatigue cracks initiated primarily at or near the hole wall corners and grew in the region of the net section. Figure 5 provides low-magnification stereoscope images of representative specimens and possible fatigue crack initiation points of the fracture were also marked in these images.

To understand the stress level distribution throughout the lap joint during the fatigue testing, finite element analysis (FAE) corresponding to the actual test parameters was also carried out. The variations of the Von-Misses stresses across the joint