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Statistical Analysis of Titanium Alloy Surface Processing on Aerospace Components Strength

Wesley Zeng[1] and Donald Buckley[#]

[1] Woodbridge High School, Irvine, CA
[#]Advisor

ABSTRACT

In the aerospace and space industry, Titanium alloys such as Ti-6Al-4V and their surface processing are widely used due to their excellent strength and lightweight characteristics such as their high strength-to-weight ratio, excellent corrosion resistance, and many factors. It is well known that the tested strength of aerospace components, such as fasteners, depends on both intrinsic material properties and surface processing. However, no detailed research has been done on the aerospace Ti-6Al-4V component tensile and double shear strength variation due to conducted surface processing on the component. Thus, the objective of this evaluation is to systematically evaluate the effect of various surface processings on the typical aerospace component, Ti-6Al-4V, including its fastener's mechanical properties of both tensile and double shear strength. The three most common fastener surface processings were selected, including bare, aluminum organic coating, and dry film lubrication. Detailed statistical analyses, including Tukey's HSD (honestly significant difference), were conducted to identify the relationship between the surface interactions and tested strength. Experimental results confirmed that fastener tested tensile and shear values dropped when surface processing was applied by up to 3.7%. This reduction was likely due to an elimination of localized seizing or galling from the additional lubrication instead of the intrinsic material degradation due to surface processing.

Introduction

Fasteners are an integral part of aircraft hardware which is used to assemble and hold various parts of an aircraft together. The aerospace and space industry are always keen to adopt parts which can reduce the aircraft's overall weight, thereby leading to an improvement in fuel economy and reducing emissions. Titanium alloy fasteners offer significant weight reduction compared to traditional steel and aluminum fasteners, which led to a huge interest to the aerospace and space industry players to switch towards titanium fasteners despite their high cost. Another factor driving the demand for titanium alloy fasteners is the compatibility of titanium with carbon composites. Carbon composites have been gaining shares in the structural sections of the aircraft as most of the next-generation aircraft programs including Boeing 787 are incorporated with carbon composites of up to 53% of their structural weight (Boeing 787). This further assures the demand for titanium fasteners. Therefore, titanium alloy fasteners are increasingly and widely used in aerospace aircrafts and military fighters such as the Boeing 787, F-15, C- 17, etc. and have achieved great results. For example, titanium alloy fasteners used in F-15 fighters account for 73% of the fasteners used in the whole airplane (Titaniuminfogroup).

In the aerospace titanium fastener industry, Ti-6Al-4V is used almost exclusively due to its excellent strength, ductility and corrosion resistance combinations. The main route for manufacturing titanium alloy fasteners generally starts with forging, rough machining, and heat treatment, before undergoing in-process testing, fine machining, and additional forming operations such as grinding and rolling, followed by non-destructive testing and surface processing such as coatings, and is completed by a final mechanical testing stage and inspections. Surface coating is used to eliminate Ti-6Al-4V galling with desired lubrications and corrosion protection purposes (Wiklund 2001). Two common coating methods are dry film lubrication and aluminum pigment coating. The dry film lubrication are materials that reduce friction between surfaces. It is based on a sacrificial transfer of lubricant between the two mating surfaces, which helps to minimize friction and prevent seizing and galling, especially in extreme applications such as titanium alloy fasteners (AS5272). In dry film, a MoS_2 based lubrication is commonly used in applications where load carrying capacity, operating temperature, and coefficient of friction, are primary concerns (AS5272). The aluminum pigment coating is phenolic resin-based coatings filled with anti-corrosion pigments, aluminum pigments, plus lubrication pigments. It provides lubrication for fastener thread friction and prevents galvanic corrosion in aluminum alloy airframe structures (NAS4006).

To guarantee performance, all Ti-6Al-4V alloy fasteners must meet specified minimum ultimate tensile strength and a minimum ultimate shear strength value. Fastener tensile strength is the maximum amount of axial stress that a titanium alloy can take before fracture and is measured via the testing fixture (Figure 1a). In contrast, shear force is the load that causes two contiguous parts of the fastener body to slide relative to each other in a direction parallel to their plane of contact. Double shear strength is commonly defined as the maximum load typically applied normally to a fastener's axis that can be supported prior to fracture. Shear strength is tested by applying shear load in two planes that would result in the fastener to be cut into three pieces (Figure 1b).

(a) (b)

Figure 1. Typical images of Ti-6Al-4V alloy fastener (a) tensile (b) shear testing fixtures.

Although extensive tensile and shear testing has been conducted on Ti-6Al-4V fasteners across the industry (Fastener tensile & double shear testing), many key questions remain unanswered. First, it is expected that the tested tensile and shear strength of fastener values should solely depend on the titanium alloy's intrinsic property values. However, this is not the case. It has been widely observed that there are considerable reductions in results between in-process and fully finished conditions for both tensile and shear strength (Fastenal). It is well known in the aerospace titanium fastener industry that typical surface processing methods such as dry film lubrication and aluminum pigment coatings that are processed at very low temperatures of less than 205°C and minimum fastener diameter increment by as little as 5~12.5 µm (AS5272 & NAS4006). However, various strength drops were observed (Internal test report). This seems beyond the normal explanation of purely dimensional changes (Fastenal). Secondly, fastener testing inherently involves a few components and variables such as test nuts and fixtures. The component surface tribology, including friction coefficient, roughness, etc, could have significant effects on the final tested fastener strength values. More importantly, to compensate for the strength drop due to surface coatings, all fasteners had to be heat treated to a higher strength level, leading to, in some cases, excessively high strength and low ductility that could cause manufacturing issues and customer rejections. Thus, a thorough understanding of the impact of fastener coating is crucial for titanium alloy fastener manufacturing.

Despite the known in-process and finished titanium alloy fastener strength dependencies, no detailed open literature on the impact of surface coating on fastener strength has been available. Little or no systematic comparison on the effect of surface finish, including coating types, on strength values have been reported for titanium alloys fasteners. Although fastener tensile and double shear testing seem relatively simple, fast, and inexpensive to implement, there is no open literature about the in-depth statistical knowledge of the fastener failure via different surface treatments. Therefore, the aim of this study was to achieve a better understanding analytically of the relationship between titanium alloy fastener testing values and surface processing.

In this study, detailed characterization of fastener coatings impact on tensile and double shear strength are evaluated. Although no Ti-6Al-4V material intrinsic properties changes expected after both dry film and aluminum pigment coatings, we do expect both tensile and double shear strength changes statistically. This study shall provide valuable information about differences in coatings of titanium alloy fasteners in the aerospace industry.

Methods

Components

The Ti-6Al-4V fasteners with part number NAS6803A22 and diameter of 4.81 mm (0.189 inch) in this investigation were provided by Fastener Innovation Technology (19300 S Susana Rd, Compton, CA 90221). These fasteners were processed per standard processing procedures, starting from wire forging, machining, heat treatment, grinding, thread rolling, followed by different surface coatings (Fastenal). The aluminum pigment and dry film coatings processes have been well established and as dictated by industry standards (NAS4004), details below. To eliminate possible fastener lot variations and expedite the investigation, all fasteners used for this evaluation were obtained from the same batch, followed by random splitting into 3 surface processing groups of 25 fasteners. All 25 fasteners of each group were carefully labeled and measured before treatments were applied.

Various Surface Coatings

In this investigation, three different surface coating groups were selected and compared, bare or uncoated, aluminum phenolic coating and Molybdenum disulfide (MoS_2) dry film lubrication. Fasteners were placed at random into each group with 25 fastener parts at minimum in each group. All three surface finishes selected are widely used for Ti-6Al-4V fasteners in the aerospace industry and our processing followed industry standards (NAS4004). Aluminum phenolic based coating has excellent corrosion and high temperature resistance of up to 232°C (450°F). It is a solvent-based material that is applied by spraying it on and is then oven cured for one hour at 204°C (400°F) (NAS4006). Dry film lubrication was applied by the standard industry specification AS5272. For fasteners receiving dry film coating, initial soap cleaning, and multi-stage of dipping fasteners into lubricant, which is then followed by elevated temperature baking performed at 204°C.

Measurements and Testing

Before testing, each Ti-6Al-4V fastener was carefully labeled, following detailed thickness measurements. Two strength tests were performed in this study: fastener tensile strength and double shear strength properties were conducted in accordance with industry standards with MIL-STD-1312-8 and MIL-STD-1312-20, respectively (Fastener tensile & double shear testing). Each fastener was tested using the same test fixture/equipment (shown in Figure 1) to eliminate impact of other testing fixtures.

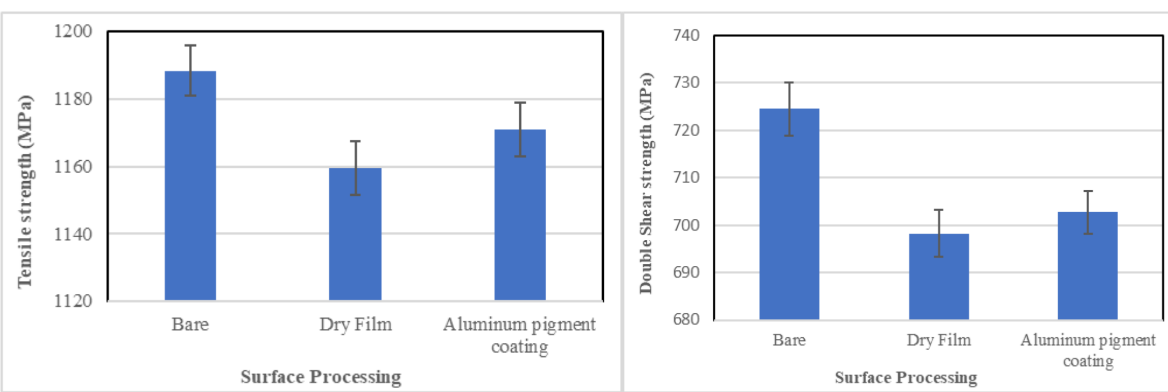
The tensile testing was conducted by fixturing the fastener into test fixture and nuts, then following applying a longitude force was applied to the fastener by separating the testing machine crossheads. The maximum load for each fastener was recorded as the ultimate tensile failure load that fastener can be sustained without fracture (Figure 1a). For double shear testing, a high strength hardened tool steel blade, having an accurate cutout of the diameter of the fastener to be tested, is inserted in a fastener support fork. These two components are mounted in a steel holder for stability (Figure 1b). The Ti-6Al-4V fastener to be tested rests on the fork and a compressive force is applied directly to the top of the blade to shear the fastener. Once compressive load drop reaches above 1%, the test shall stop, and shear strength will be calculated.

Statistical Analysis

After tensile and double shear testing, all test data was grouped, and statistically analyzed. Statistical software Minitab was used to assist the analysis. Groups were then statistically compared using the one-way ANOVA test for independent measures designed to compare the means of all three groups of samples simultaneously. Tukey's HSD (honestly significant difference) procedure was used. The Tukey's HSD procedure was used to facilitate pairwise comparisons within ANOVA data (Tukey's HSD test). The F statistic shall determine whether there is an overall difference between all three-surface processing group averages. Tukey's HSD test allows us to determine the difference between each of the various pairs of all three-surface processing groups and the significant difference (if any). Furthermore, a 95% confidence interval was calculated and evaluated.

Results

The objective of this project was to systematically evaluate the effect of surface processing on Ti-6Al-4V fastener properties via tensile and double shear testing. Three fastener groups were tested, including: bare (uncoated), aluminum pigment, and dry film coatings. Each of these groups of Ti-6Al-4V fasteners were carefully tested for tensile and shear strength, values measured, and statistically analyzed. Tensile strength of fasteners after application of aluminum pigment coatings or dry film lube surface finishes was shown in figure 2a with error bars representing 95% confidence interval per each treatment. With additional surface treatment, the mean values of tested tensile strength dropped. The one-way ANOVA calculated f & p values are 13.3 and <0.05, respectively, indicating a statistically significant impact of the processing on tested tensile strength. Further comparison analysis via Tukey's HSD test, shown in Table 1, indicated significant changes for fasteners after both treatments with a p-value of less than 0.05 and with a mean value drop of 1.5~2.4%, respectively.



(a) (b)

Figure 2. Tensile Strength and double shear strength for Ti-6Al-4V fasteners with bare, or dry Film, or Aluminum pigment coating. Tensile (a) and double shear strength (b) of fasteners after either Bare, Dry Film, or

Aluminum pigment coating. The error bars represent the standard 95% confidence interval for each processing group. n = 25 for each surface treatment group.

Similarly, double shear strength of Ti-6Al-4V fasteners after application of aluminum pigment coating and dry film lube surface finishes shown in figure 2b. Apparently, with additional surface treatment, the mean values of tested shear strength dropped. The one-way ANOVA calculated *f* & *p* values are 30.1 and less than 0.05, respectively, indicating statistically significant impact of processing on double shear strength. Further comparison analysis via Tukey's HSD test indicated significant changes for fasteners after both treatments with *p*-value of less than 0.05, as shown in Table 1. As expected, both aluminum pigment coating and dry film lube lowered tested shear strength wih an average drop of 3.0 and 3.6% respectively.

Table 1. Statistically calculated F & p-values for processing group comparison. p-values compared between different processing groups, for both tensile strength and double shear strength testing groups. Statistical analysis was completed via one-way ANOVA and Tukey HSD Test were performed to confirm our results and calculate the above p-values. n = 25 for each surface treatment group.

Processing Group Comparison	F-value (Tensile strength)	*p*-value (Tensile strength)	F-value (Tensile strength)	*p*-value (Double Shear strength)
Bare: Aluminum pigment coated	4.1	<0.05	3.8	<0.05
Bare: Dry film lube coated	2.5	<0.05	3.2	<0.05
Aluminum pigment coated: Dry film lube coated	1.7	0.11	0.7	0.4

Discussion

The goal of this study was to evaluate the effect of surface coatings on tested Ti-6Al-4V fastener strength. Consistent with our expectations, these results demonstrated that both aluminum pigment and dry film surface coating dramatically affected both tensile and shear strength. We did not expect such a dramatic drop in both tensile and double shear strength from both surface coatings.

The tested tensile and double shear strength drop after both coatings were quite surprising because we did not expect material degradation during the surface processing. First, the NAS6803A22 fasteners were made from Ti-6Al-4V material from AMS4967 (Aerospace material specification AMS4967). It has a stabilized microstructure with final heat treating at elevated temperature between 510-593°C for four hours, which is much higher than both aluminum pigment and dry film lube baking temperatures performed at 204°C (AS5272 & NAS4006). Thus, it was not expected to have any microstructural or mechanical property changes or degradation due to surface coatings of any aluminum pigment and dry film processing.

Another possible explanation, however, is that both coatings tend to increase the overall fastener diameter. Even under the same maximum tensile or double shear testing fracture load, the calculated tensile and shear strength would be lower due to an increased diameter as demonstrated by the equation below:

Tensile strength = Ultimate Tensile Failure Load ÷ (0.25 X π X Fastener Diameter^2) (Fastener tensile testing).

Double shear strength = Ultimate Shear Failure Load ÷ (0.125 X π X Fastener Diameter^2) (Fastener double shear testing).

This change, however, estimated to be 5~12.5 µm (0.0004-0.0010 inch) dimensional increase cannot explain the magnitude of both tensile and shear strength drop. For example, for a bare fastener with diameter

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maximum incremental of 12.5 μm (0.0010 inch), the re-calculated double shear strength drop should be maximum at 0.6% which is way below the experimental tested results of 3-3.7% fasteners (Figure 2). Thus, it is expected that the tested strength drop may have a different root cause.

If the tested strength drop is not due to material degradation or dimensional changes, we next expected that an additional factor would cause the tested strength dropping. With coating applied, the interaction between the test fixture and fasteners changed. With bare or uncoated Ti-6Al-4V fasteners, close and direct pressure contact between test fixture and fasteners was expected. It is well known that for dry surfaces and low surface pressures the friction is directly proportional to the pressure between the surfaces. As the pressure rises the friction factor rises slightly. At very high pressure the friction factor then quickly increases to seizing or galling (Lovell 1999). During bare or uncoated Ti-6Al-4V fasteners testing, localized seizing or galling is expected since Ti-6Al-4V is well known for its galling characteristics due to surface activities.

However, with additional coatings, it is expected that the coating be compressed to minimum thickness but not be completely removed or stripped off. There is no direct contact between the Ti-6Al-4V and tooling fixture. The friction resistance is almost independent of the specific pressure between the surfaces. It is unlikely localized seizing or galling occurred due to high pressure contact during testing with coating or lubrication between. Thus, the interaction between fastener and test fixture would be different due to the presence of coating or lubrication which has lower friction coefficient. One main advantage of both aluminum pigment coating and dry film lube is the extremely low friction coefficient, 0.05, which is significantly lower than the typical bare Ti-6Al-4V surface friction coefficient of 0.3-0.5 (AS5272 & NAS4006). With a lower friction coefficient, a Ti-6Al-4V fastener tends to slide and bend easier and less likely seizing or galling, leading to lower tested tensile and shear values (Lovell 1999). This is consistent with previous studies that show surface friction coefficients can affect tested strength values (Haylock 2006). Therefore, surface friction coefficient modification via surface treatment can dramatically change the tested strength values.

Conclusion

This evaluation has been devoted to the study of the effects of surface coating on Ti-6Al-4V fastener tensile and double shear strength. The three most common fastener surface processings were selected, including bare, aluminum pigment coating, and MoS_2 dry film lubrication. Prior to testing, each individual Ti-6Al-4V fastener and diameter was measured. Our experimental results showed that both tensile and shear values statistically dropped after both aluminum pigment coating and dry film lube.

Our experimental results and statistical analysis indicate that surface friction modification might be the root cause of the drop in tested strength, rather than the intrinsic material degradation. With additional coating or lubrication, it is unlikely to have localized seizing or galling during Ti-6Al-4V fastener testing. This study has yielded important insights into the field of Ti-6Al-4V fastener testing values. Tested Ti-6Al-4V fastener strength depends not only on the intrinsic material strength, but also the surface friction coefficient that ultimately affects the interactions between fastener and test fixtures. Thus, the tested strength may not fully represent the intrinsic Ti-6Al-4V material properties. Ideally, the compensation factor should be adopted based on the fastener's material and surface processing types. For example, many aerospace Ti-6Al-4V fasteners require 655 MPa minimum double shear strength with dry film lubrication coating applied. To compensate for the decrease due to applying coating, the in-process double shear strength in bare should be 682 MPa minimum using 4% compensation factor. Therefore, this evaluation shall provide a solid foundation to develop the right compensation factor to improve aerospace fastener processing.

Limitations

This evaluation provided insightful information of tested Ti-6Al-4V fastener strength. However, no statistical or quantitative model was built due to the limited number of coating types. It would be ideal to expand the evaluation with the design of experiments with more coatings that have a wide variety of friction coefficients. Furthermore, no stress model was developed to simulate the local stress evolution. Thus, future studies could focus on the impact of surface friction on tested strength quantitatively. Furthermore, finite element analysis could be used to simulate the effects to confirm the experimental results.

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