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Article

Statistical evaluation of the effects of surface processing on aerospace fastener tested strength

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SUMMARY

In the aerospace industry, various surface processing or coatings are widely used. It is known that surface processing can affect tested strength values. However, no detailed research on the aerospace fastener tensile and double shear strength variation due to surface processing has been conducted. Thus, the purpose of this study was to systematically evaluate the effect of surface processing on the standard aerospace fastener's tensile and shear properties. We selected three of the most common fastener finishes, including bare, passivation, and dry film processing. We conducted statistical analyses to identify the relationship between surface friction and tested strength. Our results showed that fastener tensile and double shear strength decreased in the groups that received surface processing compared to the bare group. This decrease was likely due to a change in surface characteristics, such as the friction coefficient instead of intrinsic material degradation due to surface processing. This evaluation may provide a solid foundation to gauge the true strength to improve aerospace fastener processing.

INTRODUCTION

Fasteners play a crucial role in the aerospace industry when manufacturing aircrafts by connecting all the different structural components together in primary and secondary structural areas, as well as pressurized, non-pressurized, and load-transferring applications. Given that fasteners account for a significant amount of the parts numbers (roughly 50% of all airplane part numbers), they directly affect the structural weight, strength, and integrity of each type of commercial and military aircraft (1). Thus, aerospace fasteners such as bolts, blindbolts, screws, and lockbolts are among the most critical components used in aircraft manufacturing. For example, a large commercial aircraft can use up to 1 million fasteners in total, with structural bolts comprising about 25% of the total (2).

Fasteners often undergo special surface processing to improve lubrication or obtain cosmetic and/or corrosion protection. Two common processing methods are passivation and dry film (3). The passivation process is the final treatment process used to remove iron from the surface of steel parts such that a more uniform surface is obtained and corrosion resistance is enhanced (4). Passivation enhances the chemistry of the passive layer (the upper three to five atomic layers of a metal's surface) by increasing the ratio of the very stable chromium atoms to the more reactive iron atoms (4). The dry film lubrication mechanism is based on the sacrificial transferring lubricant between the two mating surfaces, which helps to dramatically reduce the wear and the coefficient of friction (5). In dry film, molybdenum disulfide (MoS_2) based lubrication is commonly used in applications where load-carrying capacity, operating temperature, and coefficient of friction are primary concerns (4).

To guarantee performance, all aerospace fastener specifications require a minimum ultimate tensile strength and a minimum shear strength that is qualified by tests that load the fasteners in pure tension or pure shear, respectively (3). Fastener tensile strength is the maximum amount of axial stress that a fastener material can take before breaking (6). While shear testing is different from tensile testing in that the forces applied are perpendicular to the longitude axis of fasteners, shear testing applies a lateral shear force to the fastener shank until failure results (7). The commonly used double shears strength is defined as the maximum load typically applied to a fastener's longitude axis that can be supported before fracture (7). Double shear is the load applied in two planes that would result in the fastener being cut or sheared into three pieces (7).

Although extensive tensile and shear testing have been conducted on fasteners across the whole industry, many key questions remain unanswered (8, 9). First, it has been observed that there is considerable variation in results between in-process bare and fully finished conditions for both tensile and double shear strength (10). It is also well known in the aerospace fastener industry that many surface processing methods, such as passivation which result in no surface dimension change and are processed at temperatures less than 93°C, still lead to noticeable strength changes (10). Notably, some surface processing such as dry film lubrication or ion vapor deposition increases the fastener diameter by as little as 0.0102–0.0254 mm (5). However, tested tensile and double shear strength has been observed to decrease by up to 4%, which seems to be beyond the normal explanation of purely dimensional changes (10). Secondly, fastener testing inherently involves a few components and variables, such as test nuts and fixtures, which could introduce some small degree of variability in results. More importantly, to compensate for the strength decrease due to surface finishes, all fasteners are heat treated to a higher strength level, leading to, in some cases, excessively high strengths that could cause manufacturing issues and customer rejections (10). Thus, a thorough understanding of the impact of fastener processing and coating is crucial for fastener manufacturing.

Despite the known in-process bare and finished fastener strength dependencies, no detailed public literature on the impact of surface processing on fastener strength has been available. Little to no systematic comparisons of the effect of surface processing, including types, thickness, etc., on strength values, have been reported. Although fastener tensile and double shear tests seem relatively simple, fast, and inexpensive to implement, there is no literature about the in-depth quantitative knowledge of fastener failure via different surface treatments. Therefore, this study aimed to achieve a better analytical understanding of the relationship between fastener testing values and fastener surface processing.

In this study, we conducted a detailed characterization of fastener surface processing impact on tensile and double shear strength. The bolt, a typical fastener type, was chosen for this evaluation.. We hypothesized that dry film lube processing would affect the tensile and double shear strength while passivation would not. This study provides valuable information about differences in the surface processing of fasteners in the aircraft manufacturing industry.

RESULTS

The objective of this project was to systematically evaluate the effect of surface processing on fastener properties via tensile and double shear testing. We tested three fastener groups, including bare (untreated), passivated, and dry film processed. Each of these groups was carefully tested for tensile and double shear strength, which were then statistically analyzed. All testing was conducted per standard aerospace specifications using the same fixture and instrumentations (6, 7). As expected, compared to the bare group, the tensile strength of fasteners after the application of dry film lube surface finishes was observed to decrease significantly (**Figure 1A**, 1.5% reduction, and p=0.015), whereas passivation treated fasteners remained unchanged (**Figure 1A**, 0.1% reduction, and p=0.97). Tukey's HSD tests for multiple comparisons revealed the mean value of tensile strength was significantly different between bare and dry film (p=0.024) and passivated and dry film (p=0.043) surface processing. Compared to the bare group, no significant changes were observed for fasteners after passivation treatment (p=0.97).

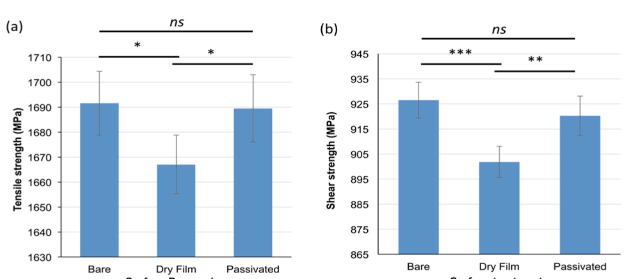

Figure 1: Tensile Strength and double shear strength for fasteners with Bare, or Dry Film, or Passivation Processing. The average values of tensile strength of fasteners after Bare, Dry Film, or passivation processing were shown in (A), while average values of double shear strength of fasteners after Bare, Dry Film, or passivation processing were shown in (B). In (A-B) the error bars representing the standard 95% confidence interval for each processing group. n = 25 is applied for each surface treatment group. Groups were statistically compared using Tukey's HSD tests for multiple comparisons and the corresponding significant p-values are indicated by asterisks as follows: ns = p>0.05, * = p<0.05, ** = p<0.01, *** = p<0.001, **** = p<0.0001.

Similarly, compared to the bare group, the double shear strength of fasteners after the application of dry film lube surface finishes was observed to decrease significantly (**Figure 1B**, 2.7% reduction, and p<0.01). Tukey's HSD tests for multiple comparisons revealed the mean value of double shear strength was significantly different between bare and dry film (p<0.001) and passivated and dry film surface processing (p=0.0017). Further comparison analysis indicated no significant changes for fasteners after passivation treatment compared to the bare group (p=0.43). Thus, compared to the bare group, dry film processing leads to a mean lower tensile and double shear strength of approximately 1.5% and 2.7%, respectively, while surface passivation barely changes measured tensile and double shear strength compared to the bare group.

DISCUSSION

The goal of this study was to evaluate the effect of surface processing on fastener strength. Confirming our expectations and consistent with our hypothesis, our results demonstrated that dry film surface processing dramatically affects both tensile and double shear strength. However, we did not expect such a dramatic decrease in strength from dry film processing.

The tested strength decrease after dry film processing is quite surprising because we did not expect material degradation during the surface processing. First, the fasteners were made from 13-8 PH material from AMS5629 raw material specification (3). The fasteners have a stabilized microstructure and were aged between 510–538°C for four hours, which is much higher than typical dry film lube baking temperatures performed at 204°C (3). Only heat treatment at a temperature within 10°C close to the final aging temperature of 510–538°C could modify the microstructure, leading to mechanical property changes (3, 5). Thus, it is unexpected to have any microstructural or mechanical property changes to the fastener material during dry film surface processing.

Another possible explanation, however, is that dry film lube tends to increase the overall fastener diameter. Even under the same maximum shear testing fracture load, the calculated shear strength would be lower due to an increased diameter, as demonstrated by the equation below:

$$\text{Double shear Strength} = \text{Failure Load} \div (0.25 \text{ X } \pi \text{ X Fastener Diameter}^2) \quad (7)$$

This change, estimated to be 0.0102–0.0254 mm, cannot explain the magnitude of the double shear strength decrease. For example, for a bare fastener with a diameter maximum incremental of 0.0254 mm, the re-calculated double shear strength decrease should be maximum at 0.6%, which is well below the experimental test results of 2.7% fasteners (Figure 1b). Thus, it is expected that the tested strength decrease may have a different root cause. Since the tested strength decrease is unlikely due to material degradation or dimensional changes, we then hypothesized that with additional surface processing applied, the interaction between the test fixture and fasteners would have changed.

During testing, we expected that the additional coating due to surface processing is compressed to a minimum thickness but not removed or stripped off. Thus, the interaction between the fastener and test fixture would be different due to the presence of lubrication which has a lower friction coefficient. The main advantage of dry film lube is the extremely low friction coefficient, 0.05, which is significantly lower than the typical bare metal surface friction coefficient of between 0.3 and 0.5 (5). With a lower friction coefficient, a fastener tends to slide and bend easier, leading to lower tested tensile and shear values (2). This is consistent with previous studies that show surface friction coefficients can affect tested strength values (10). Therefore, the surface characteristics effects, such as friction coefficient modification via surface treatment could dramatically change the tested strength values. In the process of passivation, it is not expected to dramatically change the friction coefficient or dimensions of the material, resulting in minimal or no tensile and double shear value changes. This is consistent with our experimental results.

Although there is a wide variety of fastener types, it is expected that there is a similar impact of surface processing on tested strength for any fastener types that consist of shank and threads. The exact impact, however, might be different. The double shear testing is only conducted on the shank, regardless of the fasteners' heads and threads. Additionally, all double shear testing is governed by the same testing specification with the same dimensions, tolerances, and fixture materials (6, 7). Similarly, all aerospace threads were governed by the same characteristics and specification, AS8879 (12), resulting in a similar interaction between fastener threads and nuts during tensile testing that was controlled by the same specification, NASM 1312-8 (6). Thus, the expected double shear and tensile testing impact due to surface processing should be similar for fasteners such as screws that contain shank and threads.

However, some fastener types such as lockbolts, consist of locking grooves instead of threads, resulting in different tensile testing interaction mechanisms between the lockbolt and collar. For blindbolts that consist of multiple components and even different surface treatments for each component, a more complicated impact is expected. A separate evaluation is needed for future study.

Our experimental results and analysis indicate that surface characteristics effects, such as friction coefficient modification, might be the root cause of tested strength decreasing instead of intrinsic material degradation. This study has yielded important insights into the field of fastener testing values. Tested fastener strength depends not only on the intrinsic material strength, but it is also the effects of surface characteristics that ultimately affect the interactions between the fastener and test fixtures. Thus, to reach the desired customer properties of finished products, a compensation factor should be adopted based on the surface processing types. For example, many aerospace Ti-6Al-4V bolts require 655 MPa minimum double shear strength with applied dry film lubrication (13). To compensate for the decrease due to the application of dry film lubrication, the double shear strength in bare or prior to lubrication should be 675 MPa minimum using a 3% compensation factor. Depending on the different types of surface processing, different compensation factors should be developed to compensate for the impact of surface processing. This evaluation may provide a solid foundation to develop the right compensation factor to improve aerospace fastener processing.

Future studies could focus on the direct correlation of surface friction on tested strength quantitatively with the design of experiments using different types of fasteners and surface processing. Multiple different surface processing with different well-defined coefficients and even roughness could be selected. This could provide a comprehensive understanding of surface processing on tested strength, leading to optimized fastener processing for airplane structural integrity.

MATERIALS AND METHODS

Components

The aerospace fasteners used in this investigation were provided by Avantus Aerospace (Compton, CA). The most common fastener bolt type, part number ST3M744-5D10 with a diameter of 0.794 cm, was chosen. These fasteners were processed from a single batch per standard procedures, starting from forging, heat treatment, grinding, and thread rolling, followed by splitting into three different surface processing groups (3, 13).

In the aerospace industry, heat treatment is widely used to adjust properties to the desired values. In this evaluation, a standard fastener heat treatment was conducted at 926°C for 1 hour, followed by air-cool to -73°C for 2 hours within 24 hours. Final precipitating age hardening was completed between 510–538°C for 4 hours following air cooling (3). This standard heat treatment should have a stable structure with a combination of optimal strength, ductility, and corrosion resistance performances. The passivation and dry film processing processes have been well established and dictated by industry standards (4, 5). The details are 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 randomly splitting into three different surface processing groups. All fasteners of each group with a minimum quantity of 25 were carefully labeled and measured before treatments were applied.

Various surface processing

In this investigation, three different surface processing groups were selected and compared, bare or untreated, passivation, or molybdenum disulfide (MoS2) dry film lube processing. Fasteners were placed randomly into each group, with 25 fastener parts minimum in each group. Both surface processing methods selected are widely used in the aerospace industry and our processing followed industry standards (4, 5). Briefly, the passivation process step includes initial thorough soap cleaning to remove any oil or debris, then nitric acid dipping at 60°C for approximately 20–30 minutes, and clean washing using multiple stage deionized (DI) water, followed by final drying at 82–93°C for 20 minutes (4). In our evaluation, the passivation process was performed at a temperature lower than 93°C, and no dimension change is expected. Dry film lubrication was batch processing and applied per aerospace lubricant specification AS5272 (5). For fasteners receiving dry film processing, initial soap cleaning, and multi-stage of dipping fasteners into a lubricant solution, following tumbling, elevated temperature baking, performed at 204°C.

Testing

Two strength tests were performed following industry standards in this study: fastener tensile strength and double shear strength properties (6, 7). Each fastener was tested using the same test fixture/equipment. To eliminate the impact of testing fixtures within each group, fasteners were further split into a subgroup of five pieces, resulting in five subgroups per each surface processing group. All 15 subgroups were labeled, randomized, and tested.

The tensile testing was conducted by fixturing the fastener into the test fixture and nuts, followed by applying a force to the fastener by separating the testing machine crossheads. The maximum load for each fastener was recorded as the ultimate tensile failure load that the fastener can be sustained without fracture. A hardened tool, a steel blade, was used for double shear testing by accurately cutting out the diameter of the fastener, which was then inserted in a fastener support fork. These two components were mounted in a steel holder for stability. The fastener that will be tested will rest on the fork, then a compressive force will be applied directly to the top of the blade to shear the fastener. Once the load drop reached 2%, the test shall stop, and shear strength will be calculated.

Statistical Analysis

After testing, all 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. In addition, Tukey's HSD (honestly significant difference) procedure was used to compare ANOVA data to test differences among the means of all three processing groups for significance. Tukey's HSD test is a statistical tool used to determine if the relationship between two sets of data is statistically significant (14). Furthermore, a 95% confidence interval was calculated and evaluated. During this evaluation, statistical software JMP was used to assist the analysis.

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