

Metallurgical Failure Analysis of Titanium Wing Attachment Bolts

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Two titanium alloy wing attachment bolts from a commercial jetliner failed during the course of a routine service operation. Failure of the bolts occurred during the re-torque process as the wing was being reattached. Metallurgical failure analysis indicated that the fracture mechanism was ductile overload and that the mechanical properties of the bolts were consistent with exemplar bolts that had been supplied. After eliminating other sources of excessive load application, the most probable cause of failure was ascribed to variances between the frictional characteristics of the bolt at the time of re-torque and at the time of initial torque application several years earlier.

Keywords: aerospace fasteners, failure analysis, fractography, titanium

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Introduction

As in many industries, aerospace systems and components are subject to time-dependent degradation. The ongoing structural integrity of aircraft has been the subject of intense review recently.[1,2] While corrosion of structural members is of particular importance, failure of fasteners can have catastrophic repercussions as well. Changes in load path and stress distributions caused by fastener failures can produce unexpected failure of structural members. While aircraft manufacturers have gone to great lengths to characterize the parameters affecting the performance of bolted joints, their practices do not necessarily extend to ongoing service operations. Particularly in the case of older aircraft, the original materials and specifications pertaining to bolted joints may not be available many years after initial assembly. This paper presents a metallurgical failure analysis of two wing attachment bolts. The failure occurred during the course of a routine service operation. This case illustrates what can be the worst-case scenario with the reuse of aerospace fasteners and addresses the reasoning behind some of the aerospace industry's "best practices" regarding fastener use.

Background Information

Two fractured wing attachment bolts were submitted for examination, one of which is shown in Fig. 1. The fractured bolts were original equipment on an approximately 20-year-old business jet airliner. The aircraft had been brought in for service, and the standard wing de-mating process was initiated to evaluate the extent of corrosion to the airframe. For reasons that were not clear at the time of the investigation, the complete service protocol was cancelled, and the decision was made to reattach the wings.

Two of the approximately 100 wing attachment bolts failed after torque application. The aircraft manufacturer conveyed the required torque to the service firm. This was the only information pertaining to the assembly of the joint that was supplied. Immediately on recognition that a failure had occurred, each of the wrenches used were verified

Fig. 1 *Photograph of an as-received failed titanium wing attachment bolt*

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for proper calibration. Because direct overtorque was seemingly ruled out as a failure mechanism, an independent metallurgical failure analysis was chartered to determine the cause. Additional information pertaining to the bolts was not available at the time of this investigation.

Fig. 2 *Higher magnification photograph of the fracture surface shown in Fig. 1*

Fig. 3 *Composite stereomicroscope photograph of the left-hand bolt fracture surface inside the nut taken under oblique lighting. The fracture origin is denoted by the arrow.*

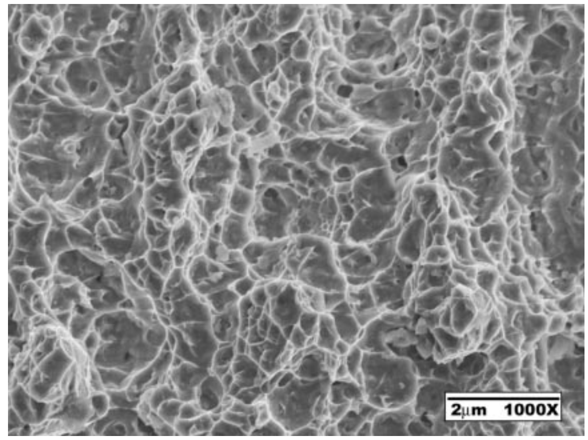

Fig. 4 *Scanning electron micrograph (SEM) of microvoid coalescence that characterized the entire bolt fracture surface*

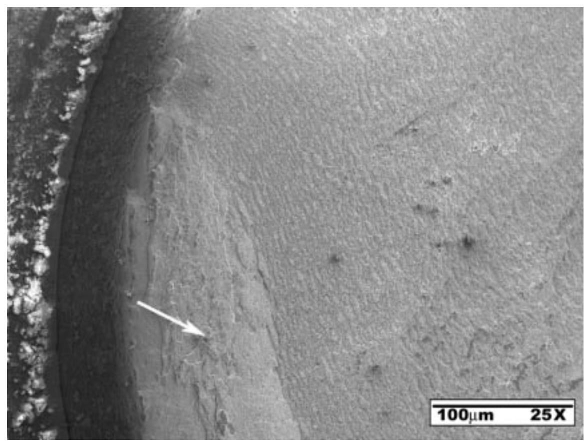

Fig. 5 *Lower magnification SEM of the bolt fracture surface. The shear lip (final overload) is denoted by the arrow. Although the fracture surface was characterized completely by microvoid coalescence, a "ratcheting" effect (suggestive of cyclic crack growth or a somewhat discontinuous plastic deformation mechanism) was visible.*

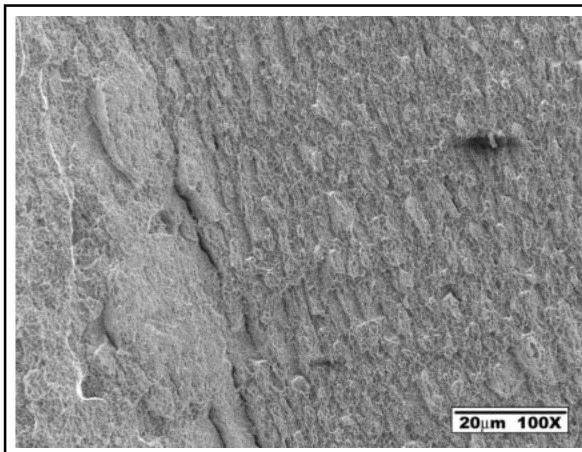

Fig. 6 *Higher magnification SEM of the ratcheting effect observed on the fracture surface*

Visual and Light Microscopic Examination

One of the submitted bolts was photographed to document the as-received condition (Fig. 2). Visual examination revealed that both bolts fractured in the vicinity of the last engaged thread root. This fracture location is to be expected because the highest stress concentration and most severe loading would be anticipated to occur in this region.[3] Little visible evidence of changes in the thread surface condition (i.e., thread compounds, mechanical damage) was discernable. The macroscale appearance of the fracture is quasi-helical, suggesting some degree of torsional loading (common for a threaded fastener).

Stereoscopic examination of the fracture surfaces under oblique lighting revealed the fracture origins (Fig. 3). The general appearance of the fracture surface at this length scale is consistent with ductile overload. However, no visual signs of gross macroscopic plastic deformation or fabrication and/or material defects were observed at this length scale.

Scanning Electron Microscopy and Energy Dispersive X-Ray Microanalysis

Fracture surfaces from both of the fractured bolts were prepared for examination with the scanning electron microscope (SEM) in order to characterize the fracture micromechanism(s). Microvoid coalescence, indicative of a ductile overload, was observed as the only evident fracture micromechanism on both bolts (Fig. 4-6). An apparent "ratcheting" effect was observed on both fracture surfaces. While the wave-like appearance of this portion of the fracture surface would seem to be consistent with cyclic crack progression, it should not be confused with typical fracture surface markings related to fatigue. Possibilities for this fracture surface topography include the microstructural arrangement, events related to the dynamics of the final fracture event, and non-uniform load application during the final failure sequence. It is interesting to note that at the macro length scale, these fracture surface markings were resolvable and could be misinterpreted as fatigue arrest lines. Without the aid of electron microscopy, the operative fracture micromechanism would not be completely clear. No evidence of other progressive fracture mechanisms such as stress-corrosion cracking was observed.

Energy dispersive X-ray microanalysis (EDXA) was used to qualitatively determine the bolt chemistry and to verify the presence of any coatings on the bolt or other associated components. The EDXA results suggest that the bolt material was Ti-6Al-4V (Fig. 7). Evaluation of the thread surface indicated high levels of molybdenum and sulfur, indicative that a thread lubricant consistent with molybdenum disulfide (MoS_2) was present. Examination of the nuts revealed the presence of cadmium plating, common for aerospace fasteners[4] (Fig. 8).

Metallographic Evaluation

To ascertain the role of microstructure in this failure, a metallographic evaluation was conducted. This evaluation was facilitated by preparing a standard metallographic mount through a longitudinal cross section of a portion of one of the failed bolts and the exemplar bolt. The microstructures of both bolts were duplex in nature and typical of Ti-6Al-4V alloy (Fig. 9). The observed microstructures were

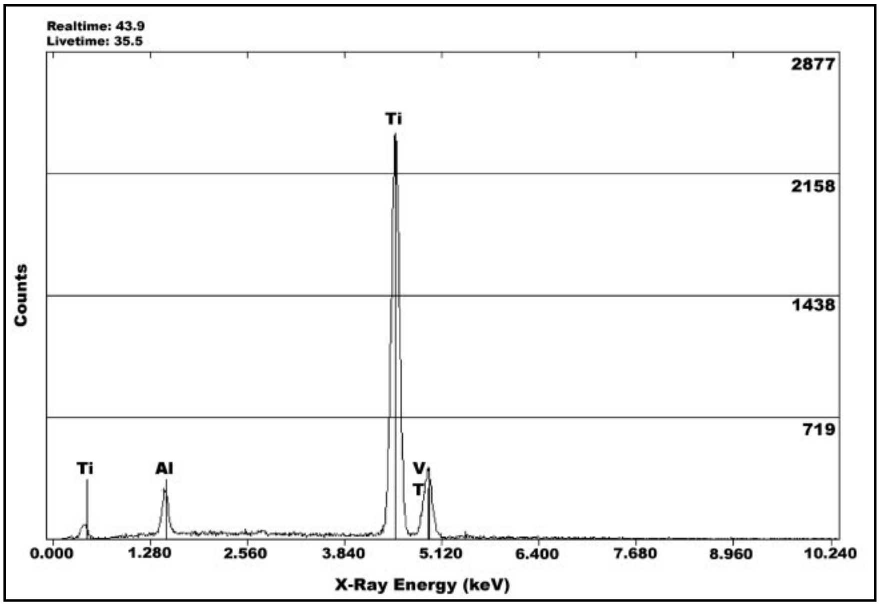

Fig. 7 *Energy dispersive X-ray microanalysis (EDXA) spectrum indicating the nominal bolt chemistry*

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similar and were typical for thread-rolled fasteners. No substantial inclusions or other defects were observed at this length scale. A significant texture sufficient to result in the observed fracture topography was not present.

Microhardness Evaluation

Microhardness measurements were taken on the longitudinal cross sections of the failed right-hand bolt and the exemplar bolt. The hardness readings were acquired via 500 gram load Knoop (HK_{500}) and converted to the Rockwell "C" scale (HRC). The average measured hardnesses for both bolts were virtually identical. The average measured hardness of the failed right-hand bolt was 37 HRC. The average measured hardness of the exemplar bolt was 38 HRC. The similarity in hardness suggests that the strength of the bolts was adequate and did not contribute to the failure.

Discussion

On consideration of the available metallurgical evidence, it was very clear that the failure mechanism responsible for bolt fracture was, in fact, overload. As is often the case in assessing ductile overload failures, two different viewpoints can be adopted. The first would ascribe the failure to the direct application of a load that exceeds the specified strength of the component; the second would ascribe failure to inadequate materials properties that allow for plastic deformation and failure at the specified load. In this case, neither viewpoint directly addresses the root cause of failure. Review of the evidence and examination results indicates that the material was within specifications. Based on the background information collected, direct application of a torque exceeding the manufacturer's specifications did not occur. (From the viewpoint of the metallurgical failure analysis, it was assumed that the calibration procedure was accurate.)

Evaluation of the extenuating factors surrounding this failure indicates that the one significant event is the reuse of bolts that had previously been in service for some time. Traditional progressive failure mechanisms such as fatigue and stress-corrosion cracking were eliminated through the fractographic investigations, thus critical factors in the assembly of the bolted joint such as frictional characteristics were addressed by analytical procedures. Much of the valuable information regarding the frictional characteristics of the nut and bolt were lost subsequent to failure; however, it is useful to qualitatively evaluate their effects on bolt tension.

A general form of the bolt torque-tension relationship is[5]:

$$F_{bolt} := \frac{(T - T_p)}{(C_1 \cdot p + C_2 \cdot d_{2.} \cdot \mu_{thread} + C_3 \cdot d_m \cdot \mu_{base})}$$

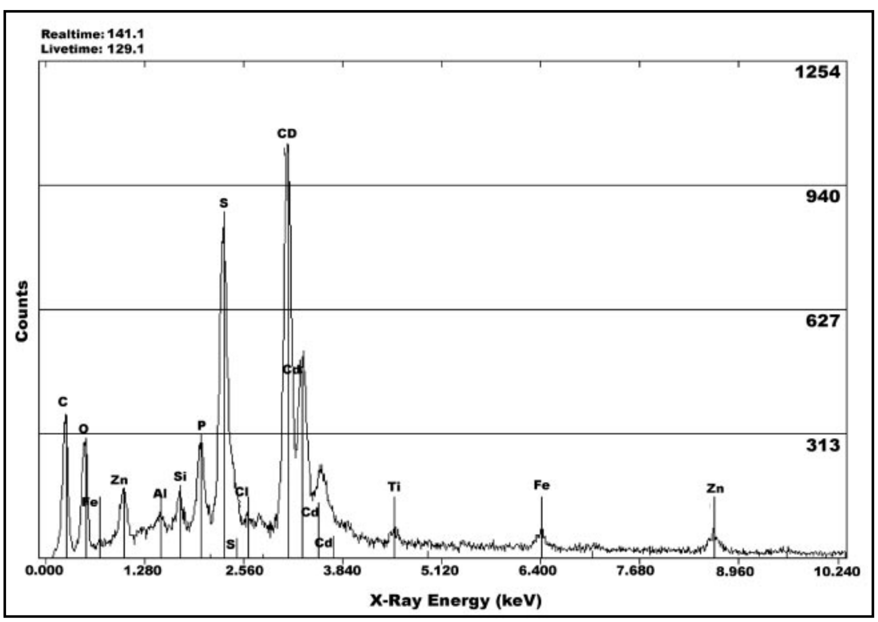

Fig. 8 *Energy dispersive X-ray microanalysis (EDXA) spectrum indicating the cadmium plating and the presence of sulfur-based thread compound*

Where F_{bolt} is the bolt tension, T is the applied toque at the nut, T_p is the locking torque of the nut, p is the thread pitch, d_2 is the thread pitch diameter, d_m is the nut-base friction diameter, and μ_{thread} and μ_{base} are the thread and nut-base coefficients of friction, respectively. The C_i are constants related to the individual geometric variables.

From this relationship, it is clear that, while the applied torque is critical in control of the bolt tension, changes in the frictional characteristics of either the bolt threads or the nut base can significantly change the resulting tensile loads in the bolt. This variance is one of the chief concerns in bolt reuse, because aging and service conditions can alter the frictional characteristics of the bolted joint components with time. Changes in materials and processes over time (e.g., lubricants such as MoS_2 and wet sealant composition) serve to further complicate the relationship between friction, installation torque, and bolt tension, because current technologies and procedures may not be compatible with aging fasteners. Ideally, torque-tension relationships should be developed for each and every combination of fastener, washer, and structural material to ensure the design-specified clamp force is present.

In the absence of any other evidence regarding deviation in the two failed bolts from those that were successfully reused, the most likely cause of failure is changes in the frictional characteristics of the joint assembly.

Aircraft manufacturing and maintenance industry "best practices" are designed to produce optimal fastener preload. If there is any doubt in the frictional properties of the original fastener components, new components with known and predictable torque-tension relationships must be used. This practice is in place for many reasons, not the least of which is the potential alteration of tribological properties of the original fastener components, which could result in unpredictable preloads.[6] One potentially catastrophic outcome of such a preload is the premature fatigue failure of a fastener or the adjoining structural components. The presence of a mean tensile stress superposed with the service loading conditions and random vibrations would have a detrimental effect on the fatigue life of the bolted joint.[7]

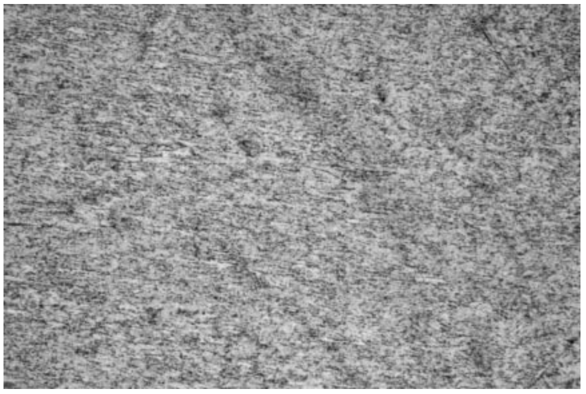

Fig. 9 *Micrograph of the failed right-hand bolt microstructure (Kroll's Reagent; 350× magnification at 6.6 in. width). The duplex microstructure consists of elongated alpha (light) in a beta (dark) matrix.*

Similarly, inadequate preload can also negatively affect the fatigue life of fasteners and structural components.[8] Excessive friction would result in lowered preload for a given installation torque. Insufficient preload in fastened joints can change the load path and lead to excessive loading and premature failure of adjacent fasteners and structural components.

Another potential hazard in reuse is mismatching the fasteners and washers with the holes of origin. Fastener grip lengths and washer thickness are selected in the design process to provide optimal properties. A shift up or down in grip length can result in improper installations such as excessive stress concentrations (grip length too long, deformation concentrated in too few threads) or threads in the load bearing area (grip length too short).

Conclusions

Failure of the two titanium alloy wing attachment bolts occurred by a ductile overload fracture mechanism. Metallurgical and mechanical property evaluation and comparison with exemplar bolts did not reveal any material deficiency that would have precipitated failure. Direct overload via application of a torque that exceeded manufacturer specifications was ruled out as a possible cause due to the accurate calibration of the torque wrenches after reinstallation. Because the bolts had previously been in service, the most probable cause of failure was determined to be changes in the frictional characteristics of the fastener system. Slight variations in the frictional characteristics of the fasteners could result in substantial tensile overloading of the bolts at the prescribed torque level.

Based on the results of this investigation, it is readily apparent that the industry "best practice" of not reusing fasteners could have prevented this series of failures from occurring. It was recommended that the ~100 unfailed fasteners that had been reused be removed from service and replaced with new fasteners. While the recommendation may seem reactionary in some respects, the potential for future fatigue failures in these fasteners due to excessive mean tensile stresses outweighed the economic cost of replacement.

References

1. S.C. Cedarquist: "Improving Aging Airplane Safety," *Mater. Performance,* 2000, *39,* pp. 20-5.
2. M.E. Hoffman and P.C. Hoffman: "Corrosion and Fatigue Research-Structural Issues and Relevance to Naval Aviation," *Int. J. Fatigue,* 2001, *23,* pp. S1-10.
3. R.G. Baggerly: "Evaluating the Effects of Overtorque in Bolts," *Practical Failure Analysis,* 2001, *1* (1), pp. 41-6.
4. S.M. Sadri: "Aerospace Bolts," *Handbook of Bolts and Bolted Joints,* J.H. Bickford and S. Nassar, ed., Marcel Dekker, Inc., 1998.
5. J. Barron: "Computing the Strength of a Fastener," *Handbook of Bolts and Bolted Joints,* J.H. Bickford and S. Nassar, ed., Marcel Dekker, 1998, pp. 163-78.
6. J.A. Williams: *Engineering Tribology,* Oxford University Press, 1994.
7. N.E. Dowling: *Mechanical Behavior of Materials,* 2nd ed., Prentice Hall, London, 1999.
8. H. Terada: "Structural Fatigue and Joint Degradation," *Int. J. Fatigue,* 2001, *23,* pp. S21-30.