



Integrity of High Strength Fasteners for Aircraft Structures

A Review of the Literature

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INTRODUCTION

High strength and ultrahigh strength mechanical fasteners are broadly characterized by tensile strengths ranging from 1,000 to 2,000 MPa, and are often used in critical applications. In the aerospace industry, such applications typically consist of load bearing structures in the airframe and engine. Threaded mechanical fasteners and bolted joints are deceptively simple components. Damage resulting in loss of integrity or failure can occur by a complex interaction of material characteristics, environmental conditions, manufacturing flaws, installation conditions, and joint design criteria. The two most critical failure modes are stress corrosion cracking (SCC), which is an environmentally generated class of hydrogen embrittlement, and fatigue. From a cynical perspective, a bolt is simply a smooth round bar with a series of built-in notches, tantamount to a series of built in “defects” that inevitably lead to failure. The consequences of failures can range from minimal to catastrophic, even resulting in loss of life. The prevention of failure is therefore a fundamental preoccupation for aircraft designers, fastener manufacturers and application engineers alike.

The primary purpose of this literature review is to ascertain the current level of understanding of the metallurgical phenomena and application conditions and leading to fatigue or stress corrosion cracking of high strength fasteners used in aircraft load bearing structures. We will begin with a broad overview of fastener terminology followed by a brief discussion of the materials and properties of high strength fasteners in aircraft construction. Finally, a detailed review of the two failure modes and key parameters will be presented based on selected research papers and articles in literature.

HIGH STRENGTH FASTENERS: PROPERTIES AND MATERIALS

Fastener terminology

The following is a list of terms that broadly categorize the types of fasteners used in the assembly of aircraft structures.

Bolt – “an externally threaded fastener designed for insertion through holes in assembled parts, and is normally intended to be tightened or released by torquing a nut.”¹

Screw – “an externally threaded fastener capable of being inserted into holes in assembled parts, of mating with a preformed internal thread or forming its own thread, and of being tightened or released by torquing the head.”¹

Stud – “a ‘headless’ external threaded fastener that can be designed either as bolt or a screw.”²

Blind fastener – “a fastener that is accessed from only one side of the workpiece during installation. Typically it is comprised of a threaded screw or pin assembled with a sliding collar.”³

Rivet – “a headed fastener whose shank is passed through joint plies and the unheaded end is then upset to form a second head while pulling the joint plies together. Rivets may be solid, tubular, or split.”²

Nut – “internally threaded product intended for use on external or male screw threads such as a bolt or a stud for the purpose of tightening or assembling two or more components.”²

Washer – “a metallic ring or a perforated circular plate used to form a seat for the head of a bolt or a nut. Washers can be spring loaded.”²

Note the terms “bolt” and “screw” are commonly interchanged in lay parlance, yet there are detailed specified differences between the two. In brief, a bolt is designed for assembly with a nut. For the purpose of this paper we will use the term bolt to generically include all externally threaded fasteners, including studs and threaded blind fasteners. High strength and ultrahigh strength

fasteners will typically fall under this classification. Rivets are predominantly used in aircraft assembly; however they are not used in critical load bearing structures.⁴ Washers are an integral part of fastening systems and joint assemblies and as such fall under the jurisdiction of fastener specifications. However due to their non load bearing nature, washers will not be discussed here.

Fastener materials and applications

The choice of fastener raw material is governed by industry standards that specify allowable material grades for each fastener type and strength class. The selection of a specific raw material with which to manufacture a given part is initially based on the material characteristics such as maximum strength, ductility, and notch strength. However, the fabrication and engineering performance requirements of the fastener govern the ultimate raw material choice made by the fastener manufacturer and his customer. Other selection considerations are based on the temperature and corrosiveness of service conditions, properties of joining materials and the choice of coating.⁵

Steel fasteners offer the most sought after combination of high strength capability at low cost. Protective coatings such as electrodeposited zinc and cadmium, or organic aluminium based coatings have also provided steel fasteners with effective and low cost corrosion protection. For this reason, fasteners made of carbon and alloy steel constitute the majority of fasteners in use today. However, aerospace applications are more demanding than most others. New engine designs require increasing high-temperature resistance in hot zones to improve thrust. Airframe and structural designs are prioritizing weight reduction to improve fuel efficiency. Durability models seek to reduce corrosion of components to lower maintenance costs and extend air worthiness. These advances have dictated the development and increasing use of other high performance materials such as stainless steels, iron-based alloys, aluminium alloys, titanium alloys, nickel-based, and

cobalt-based alloys. The following is a brief description of the key materials, characteristics and some applications.⁵

Carbon and alloy steels

Medium carbon low alloy (MCLA) steels – Bolt strengths range between 1,000 to 1,400 MPa. These materials are typically used for fasteners in critical applications where strength is most the important attribute, such as in landing gear components. These steels are particularly susceptible to brittle fracture modes such as hydrogen embrittlement (HE), and stress corrosion cracking (SCC). Typical grades used for fasteners are 4340, 4140, and 300M.^{4,5}

High fracture toughness steels – These materials have better ductility and fracture toughness than MCLA steels, while achieving bolt strengths up to 2,000 MPa. AerMet 100 is the most likely material to replace MCLA steels in critical fastener applications.^{4,5}

Stainless steels

Semiaustenitic and martensitic precipitation hardening stainless steels – These materials represent the evolution of stainless steels from traditional 300 series austenitic and 400 series martensitic stainless steels. They provide the same corrosion protection as the 300 series, plus bolt strengths up to 1,500 MPa, achieved through precipitation hardening by the addition of aluminium in particular. PH13-8Mo is the most likely candidate to be used for fastener manufacturing, and can be used in critical applications such as landing gear without the need for a protective coating.^{4,5}

Superalloys

Fasteners made from superalloys are exclusively used in high temperature applications in the engine, predominantly in the high pressure compressor, combustion chamber, and high pressure turbine area.

Iron-nickel based superalloys and nickel-based superalloys – Bolt strengths typically range between 1,000-1,200 MPa. The most likely materials to be used for fastener applications are A286, Inconel 718, and Nimonic 80 A. ^{4,5}

Cobalt-based superalloys – Bolt strengths range between 1,000-1,400 MPa. The most likely material to be used for fastener applications is MP35-N. ^{4,5}

Titanium alloys

Alpha-Beta – This class of titanium alloys is the most likely to be used for fastener manufacturing. The most common alloy is Ti-6-4 which can achieve bolt strength of 900 MPa. Titanium fasteners are used in primary structural applications that do not require ultrahigh strength, such as in the relatively cooler zones of the engine compressor and anywhere in the airframe such as in doors, flaps, wing attachments, stabilizer attachments, etc. ^{4,5}

Aluminium alloys

The most likely alloy to be used is 7075-T6 alloy which can achieve bolt strength of 550 MPa. Aluminium fasteners are primarily used in secondary structural applications with minimal tensile or shear loading. ^{4,5}

DAMAGE AND FAILURE MODES

As was mentioned in the introduction, the failure modes that are of greatest concern with high strength fasteners are fatigue, and stress corrosion cracking.

Fatigue

Fatigue in metals is the process of (i) initiation and (ii) propagation of cracks under the action of cyclic loading. If the crack is allowed to progress, the uncracked portion of the part becomes sufficiently reduced such that the part is no longer capable of carrying the applied load, resulting in fracture. This process can take place at stress levels (calculated on the initial cross-section) that are well below the strength of the part under static loading conditions.⁶

Aside from intrinsic material characteristics, the presence of cracks, crack like discontinuities and stress concentration points such as sharp radii and angles are the primary contributors to fatigue failure. Many design parameters have been developed through testing that either simulate the application conditions or compare specific fastener characteristics under standard fatigue loading conditions. This empirical approach has resulted in significant improvements in the fatigue strength of threaded fasteners and in the ability of design engineers to make informed fastener selections. For example, Skochko⁷ demonstrated the benefits of roll threading versus thread machining for low alloy steel fasteners. The complex influences of thread pitch and thread root radius were illustrated by Dragoni⁸ and Majzoobi et al.⁹ who both observed that the core diameter of the bolt and not its nominal diameter is the normalizing factor for comparing fatigue results. Berger et al.¹⁰ investigated the fatigue strength of steel fasteners based on property class, surface coating and lubrication. One of their observations was an increase of high cycle fatigue life with bolts that were roll threaded after heat treatment (hardening), owing to the introduction of compressive

stresses in the thread root. In terms application simulation, temperature, environment and loading conditions have been found to be contributing factors. Loading conditions in particular is an extensive topic that is significantly complicated by nonuniformities or imperfections in the geometry of the joint or the fasteners Mangold.¹¹ Hobbs et al.¹² demonstrated the deleterious effect of slightly eccentric cyclic loading on fatigue life of the fastener. Interestingly, Alexander et al.¹³ observed that the opposite is true when eccentricity of loading is large enough to produce a bending stress that exceeds axial stress by a 2:1 ratio. High service temperatures, particularly in engine applications, can lead to creep-fatigue interaction known as dwell fatigue that causes an unanticipated reduction of fatigue life. Dwell fatigue occurs when non-continuous loading cycles result in strain-hold periods conducive to creep deformation. Rho et al.¹⁴ demonstrated that this phenomenon can be influenced by modifying the hold periods and the loading waveform such that strain-hold periods are in compression.

Since the 1970's, fracture mechanics principles have been applied to predict the fatigue and fracture limit states of bolts in application. This analytical approach essentially models the behaviour of a material containing a crack or crack like feature. The principal parameters required for fracture mechanics analysis are: (i) stress in the region of interest, (ii) initial flaw shape and size, and (iii) fracture toughness of the material. These data are used to calculate a nondimensional parameter known as stress intensity factor K .¹⁵ Fracture mechanics methodology has led to a better understanding of the conditions influencing fracture and the development of predictive models that are backed by experimental crack growth rate data, Liu.¹⁶ Among many applications of this approach is the ability to approximate stress intensity factors for cracks located in critical areas of a bolt such as the fillet or thread root, Cipolla.¹⁷

The combination of computer based finite element analysis (FEA) and fracture mechanics models has resulted in the development of increasingly sophisticated and powerful predictive fatigue models that have opened the field to previously uncharted territory. Oster and Mills¹⁸ used FEA to expand on the work of Cipolla¹⁷ and others by calculating stress intensity factor solutions for continuous circumferential cracks in a range of sizes of threaded steel fasteners. Mettu et al.¹⁹ used the same approach to calculate intensity factor solutions for stainless steel, aluminium and titanium alloys. Thanks to this type of work, calculated stress intensity solutions are being incorporated into computer models for use by design engineers as a broad based design tool. Hukari²⁰ used fracture mechanics and FEA to re-examine the acceptance criteria for thread laps by studying the effect of various lap geometries, and setting the framework for distinguishing benign laps from critical ones. This work initiated rethinking and revision of lap acceptability standards that have been in effect for decades in fastener industry. Another notable innovation using fracture mechanics and FEA is Allaei's work incorporating vibration models with the dynamic coupling action between joint components (bolt, interfaces, host structure) that forces vibration energy to be localized.²¹ As this unique model evolves, it will be used to predict, for the first time, the effects of localized vibration on fatigue life of fasteners.

Many other aspects of the fastened joint have been successfully investigated by this approach. Zhao²², Stefanescu²³, Zhang²⁴, and Chakherlou²⁵ each independently studied ways in which to render fastener holes more resistant to fatigue cracking. Their conclusions all pointed to significant benefits of applying compressive stresses around the hole perimeter, notably by using cold expansion forming rather than drilling. With the increasing use of composite materials, a great number of studies have been conducted on the fatigue life of composite materials under compression within a fastened joint. For example, Trodus²⁶ observed that with countersunk

fasteners, the flexibility of composite materials leads to bending deformation during cyclic loading, resulting in the fastener head digging into the composite and causing ply cracking. Starikov modelled the fatigue resistance of composite joints using both countersunk and protruding head bolts and concluded that the former results in asymmetrical load transfer, which is consistent with findings by Trodus.²⁶ Xiong developed a model for composite bolted joints with multiple fasteners, and observed a linear dependence between the composite joint resistance to fatigue and the number of bolts.²⁷

Hydrogen embrittlement and stress corrosion cracking

The loss of mechanical properties in iron and steel due to the embrittling effect of nascent hydrogen was first documented in 1874 by Johnson who observed the significant loss of ductility of steel wire caused by immersion in strong acids.²⁸ Hydrogen in steel can cause a time-delayed or slow strain rate fracture at applied stresses below the yield strength of the material. In other words the strength of the material is degraded over a period of time. In order for this to occur, three elements must be present at sufficient levels; (i) hydrogen, (ii) stress, and (iii) material susceptibility. There are three sources for hydrogen – steelmaking, processing, and service environment. There are three sources of stress – applied stress, residual stress from plastic deformation (e.g. cold heading or welding), and residual stress from heat treatment. Raymond²⁹ and most of the literature classify hydrogen embrittlement into two broad categories based on the source of hydrogen: internal hydrogen embrittlement (IHE) and environmental hydrogen embrittlement (EHE).

IHE is caused by residual hydrogen from steelmaking or from processing steps such as pickling and electroplating. Since the source of hydrogen is not by corrosion, IHE will not be discussed any further. EHE is caused by hydrogen introduced into the metal from external sources

while it is under stress, such as is the case with an in-service fastener. A number of different mechanisms fall under the EHE classification, but we will focus on the ones that are relevant to the scope of this review. The term Stress Corrosion Cracking (SCC) is applied when hydrogen is produced as a by-product of surface corrosion and is absorbed into the lattice. Cathodic hydrogen absorption (CHA) is a subset of SCC and can be explained as follows. Metallic coatings such as zinc are designed to sacrificially corrode to protect say a steel bolt from rusting. If the steel becomes exposed, a reduction process on the exposed steel surface simultaneously results in the evolution of hydrogen. Hydrogen reaction embrittlement (HRE), prevalent among titanium alloy fasteners is quite distinct from SCC, even though the sources of hydrogen can be the same. Once hydrogen is absorbed, it can react near the surface or it may diffuse substantial distances before it reacts, forming a hydride. Most forms of EHE are not reversible because they occur in the presence of stress, resulting in the initiation of microcracks.³⁰

Craig identifies two distinct processes for hydrogen damage based on predominantly accepted models. These are (i) hydrogen stress cracking, and (ii) loss in tensile ductility. He defines (i) hydrogen stress cracking as being “characterized by the brittle fracture of a normally ductile alloy under sustained load in the presence of hydrogen”... “at loads below the yield strength.”³⁰ The time delayed nature of the process reveals that it is transport dependant, meaning that hydrogen must diffuse into areas of high triaxial stress. (ii) Loss in tensile ductility is defined as a process by which steels and nickel based alloys lose their ductility in the presence of hydrogen. The process is pronounced at higher hydrogen contents and increasing strain rates.

Despite innumerable studies on the subject of stress corrosion cracking, fastener specifications have adopted a variety of broad brushed approaches that have evidently missed the mark of effectively preventing the occurrence of SCC failures. This is largely due to the

complexities of the acting phenomena, but more specifically due to lack of information on relative hydrogen susceptibilities of fastener materials. Consequently predictive models, such as those used for fatigue do not readily apply here. Instead, much more information has been drawn from failure case studies^{31,32,33,34} and experimental analyses that are specific to given materials or applications.^{35,36,37,38} This type of information is used to define design criteria by being incorporated in Failure Modes and Effects Analyses (FMEA) performed by design and manufacturing engineers³⁹.

Recently, the use of rising slow strain or incremental step load (ISL) testing has demonstrated very promising capabilities as an accelerated test metric to measure the hydrogen susceptibility of materials, and is beginning to be used for research purposes. ISL is unique in that it measures the threshold stress intensity for hydrogen stress cracking in an accelerated manner (≤ 24 h). It measures the onset of sub-critical crack growth in a notched specimen subjected to a modified, incrementally increasing, slow strain rate load.⁴⁰ This test method is well suited for fasteners, as they are naturally notched specimens. The ISL stress-strain or load-time curves are characterized by a gradually increasing step-like pattern. The threshold is defined as the maximum load at the onset of cracking.

The ISL test method can measure the threshold stress of materials that have had prior exposure to hydrogen (internal hydrogen), or it can measure the threshold stress of materials that have not had prior exposure to hydrogen by simulating hydrogen charging conditions during the test (environmental hydrogen). In this case the test is performed in conductive salt water under cathodic potential ranging from -1.2V versus SCE to testing in air. The hydrogen susceptibility ratio H_{sr} , as defined by Raymond, is a parameter that can be used measure of the susceptibility of a material to hydrogen assisted cracking, given its threshold stress. H_{sr} is calculated as the ratio of the K_{Isc}

threshold stress of a material under specific environmental conditions over its fracture stress K_{IC} tested under benign conditions.⁴⁰ This expression can be used to measure the susceptibility or sensitivity of a material to hydrogen under the entire range environmental or internal hydrogen charging conditions. The result is a threshold curve. By repeating the tests with the same material at different hardness or microstructural conditions, we can effectively create the signature curve of that material's sensitivity to hydrogen assisted cracking.⁴¹

The significance of this approach is that it can generate relative susceptibility data fairly quickly, that can be used for selecting appropriate materials and properties for given applications. When used appropriately, this will be the most powerful tool available to aircraft design engineers for minimizing the risk of SCC fastener failures. The ISL test method is described in detail in ASTM F1624.⁴² Many studies began documenting the benefits of ISL testing in the 1970's and 1980's prior to the creation of ASTM F1624.^{43,44,45}

CONCLUDING REMARKS

The most prevalent and critical failure modes with high strength and ultrahigh strength fasteners are fatigue and stress corrosion cracking. “Improvements” being made to alloys and manufacturing processes are not exclusively aimed at eliminating fatigue and SCC failures. Indeed much of the research is being conducted as part of the greater drive to improve the economics of air travel by increasing aircraft thrust to weight ratio, reducing manufacturing costs, increasing operating efficiency and increasing the service free life of the aircraft. Predictive analytical models, experimental verification, and Failure Modes and Effects Analysis (FMEA) are a few of the preventive tools available to aircraft manufacturers. Forensic engineering and failure analysis are key reactive tools to ensure that we will draw the important lessons from past failures and implement corrective and preventive measures. Publication of notable failure case studies and compiling of failure analysis libraries is a primary source of “lessons learned”. Ultimately it is the responsibility of design engineers to best utilize available resources to ensure that the joint design and execution will not increase the risk of fatigue or SCC within evolving design parameters. Similarly it is the responsibility of the manufacturing and process engineers to ensure that fasteners and joint components are manufactured within given geometric and processing parameters, especially when destined for critical structural applications in the airframe or engine. As a final thought, there is undoubtedly a fine balance between economics and safety that is specific to each industry. Since the aircraft industry has a very low tolerance for risk, change and progress are very slow and incremental, and design cycles very prolonged. Considering what is at stake, we can be thankful that it is so.

REFERENCES

- 1 "B18.2.1 Square and Hex Bolts and Screws, Inch Series.."
- 2 "ASTM F 1789 Standard Terminology for F16 Mechanical Fasteners.," ASTM Book of Standards.
- 3 <http://www.avdel.textron.com>, "Avdel® Blind Fastening Systems " (Textron Fastening Systems).
- 4 F. C. Campbell, *Manufacturing technology for aerospace structural materials*. (Elsevier, Amsterdam, Kidlington 2006).
- 5 C. A. Hood, "Fastener materials," in *Handbook of Bolts and Bolted Joints*, edited by John H. Bickford and Sayed Nassar (M. Dekker, New York, 1998), pp. 1-33.
- 6 J. W. Fisher, Geoffrey L. Kulak, and Ian F.C. Smith, *A Fatigue Primer for Structural Engineers*. (Lehigh University, 1997).
- 7 G. W. Skochko and T. P. Herrmann, "Review of factors that affect fatigue strength of low alloy steel fasteners," in *Structural Integrity of Fasteners, ASTM STP 1236*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 1995), Vol. 1, pp. 32-47.
- 8 E. Dragoni, "Effect of thread pitch on the fatigue strength of steel bolts," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* **211** (8), 591-600 (1997).
- 9 G. H. Majzoobi, G. H. Farrahi, and N. Habibi, "Experimental evaluation of the effect of thread pitch on fatigue life of bolts," *International Journal of Fatigue* **27** (2), 189-196 (2005).
- 10 C. Berger, B. Kaiser, and U. Kremer, "Crack initiation and crack propagation of fasteners under fatigue loading," *Rissbildung und -fortschritt bei schwingbelastung von schraubenverbindungen* **33** (9), 507-510 (2002).
- 11 A. Mangold, "FEM-Investigation to evaluate the influence of geometric imperfections on fatigue of preloaded bolt connections of Wind Energy Converters," *FEM-Untersuchung zur Beurteilung des Einflusses von geometrischen Imperfektionen auf die Lebensdauer von Schraubenverbindungen bei Windkraftanlagen* **74** (6), 462-470 (2005).
- 12 J. W. Hobbs, R. L. Burguete, P. F. Heyes, and E. A. Patterson, "Effect of eccentric loading on the fatigue performance of high-tensile bolts," *International Journal of Fatigue* **22** (6), 531-538 (2000).
- 13 D. F. Alexander, G. W. Skochko, W. R. Andrews, and S. R. Briody, "Fatigue testing of low-alloy steel fasteners subjected to simultaneous bending and axial loads," in *Structural Integrity of Fasteners, ASTM STP 1391*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 2000), Vol. 2, pp. 72-84.
- 14 B. S. Rho, K. J. Kim, and S. W. Nam, "The effect of hold time and waveform on the high-temperature, low-cycle fatigue properties of a Nb-A286 alloy," *Metallurgical and Materials Transactions A* **32**, 2539-2546 (2001).

- 15 P. M. Toor, "An overview of structural integrity of fasteners," in *Structural Integrity of Fasteners, ASTM STP 1236*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 1995), Vol. 1, pp. ix-xxiii.
- 16 A. F. Liu, "Behavior of fatigue cracks in a tension bolt," in *Structural Integrity of Fasteners, ASTM STP 1236*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 1995), Vol. 1, pp. 126-140.
- 17 R. C. Cipolla, "Stress intensity factor approximations for cracks located at the thread root region of fasteners," in *Structural Integrity of Fasteners, ASTM STP 1236*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 1995), Vol. 1, pp. 108-125.
- 18 D. M. Oster and W. J. Mills, "Stress intensity factor solutions for cracks in threaded fasteners," in *Structural Integrity of Fasteners, ASTM STP 1391*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 2000), Vol. 2, pp. 85-101.
- 19 S. R. Mettu, A. U. de Koning, C. J. Lof, L. Schra, J. J. McMahon, and R. G. Forman, "Stress intensity factor solutions for fasteners in NASGRO 3.0," in *Structural Integrity of Fasteners, ASTM STP 1391*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 2000), Vol. 2, pp. 133-139.
- 20 R. J. Hukari, "Thread lap behavior determination using finite element analysis and fracture mechanics techniques," in *Structural Integrity of Fasteners, ASTM STP 1391*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 2000), Vol. 2, pp. 120-132.
- 21 D. Allaei, "Effects of Nonuniformities in fasteners on localized vibration and fatigue," in *Structural Integrity of Fasteners, ASTM STP 1236*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 1995), Vol. 1, pp. 3-19.
- 22 W. Zhao and S. N. Atluri, "Stress intensity factors for surface and corner cracked fastener holes by the weight function method " in *Structural Integrity of Fasteners, ASTM STP 1236*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 1995), Vol. 1, pp. 95-107.
- 23 D. Stefanescu, J. R. Santisteban, L. Edwards, and M. E. Fitzpatrick, "Residual stress measurement and fatigue crack growth prediction after cold expansion of cracked fastener holes," *Journal of Aerospace Engineering* **17** (3), 91-97 (2004).
- 24 X. Zhang and Z. Wang, "Fatigue life improvement in fatigue-aged fastener holes using the cold expansion technique," *International Journal of Fatigue* **25** (9-11), 1249-1257 (2003).
- 25 T. N. Chakherlou and J. Vogwell, "The effect of cold expansion on improving the fatigue life of fastener holes," *Engineering Failure Analysis* **10** (1), 13-24 (2003).
- 26 A. R. Trodus, presented at the Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, 1996 (unpublished).
- 27 Y. Xiong, "An analytical method for failure prediction of multi-fastener composite joints," *International Journal of Solids and Structures* **33** (29), 4395-4409 (1996).

- 28 W. H. Johnson, "On some remarkable changes produced in iron and steel by the action of hydrogen and acids," in *Hydrogen Damage*, edited by Cedric D. Beachem (ASM International, Metals Park, OH, 1977), pp. 1-2.
- 29 L. Raymond, "Evaluation of hydrogen embrittlement," in *ASM Metals Handbook* (ASM International, Metals Park, OH, 1987), Vol. 13 Corrosion, pp. 283-290.
- 30 B. Craig, "Hydrogen damage," in *ASM Metals Handbook* (ASM International, Metals Park, OH, 1987), Vol. 13 Corrosion, pp. 163-171.
- 31 A. Abbott, T. Mooney, D. Baudrana, and D. J. Wolf, "Premature failure of zinc-plated bolts [3] (multiple letters)," *Metal Finishing* **101** (2), 78-79 (2003).
- 32 H. C. Lee, J. m Choi, B. Lee, and T. G. Kim, "Failure analysis of stress corrosion cracking in aircraft bolts," *Engineering Failure Analysis* **14** (1), 209-217 (2007).
- 33 K. G. Reddy, A. K. Jha, and V. Diwakar, "Failure of cadmium plated maraging steel tension bolt," *Engineering Failure Analysis* **8** (3), 263-269 (2001).
- 34 A. Venugopal Reddy, *Investigation of aeronautical and engineering component failures*. (CRC Press, Boca Raton, Fla., 2004).
- 35 D. Barke, W. K. Chiu, and S. Fernando, "Residual stress assessment of stress corrosion in high strength steel components," in *Structural Integrity of Fasteners, ASTM STP 1391*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 2000), Vol. 2, pp. 105-119.
- 36 O. S. Es-Said, K. Zakharia, Z. Zakharia, C. Ventura, D. Pfof, P. Crawford, T. Ward, D. Raizk, J. Foyos, and R. Marloth, "Failure analysis of K-monel 500 (Ni-Cu-Al alloy) bolts," *Engineering Failure Analysis* **7** (5), 323-332 (2000).
- 37 M. A. E. Natishan and W. C. Jr. Porr, "The effect of grain boundary carbon on the hydrogen-assisted intergranular failure of nickel-copper alloy K-500 fastener material," in *Structural Integrity of Fasteners, ASTM STP 1236*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 1995), Vol. 1, pp. 81-91.
- 38 D. R. Johns and K. Shemwell, "The crevice corrosion and stress corrosion cracking resistance of austenitic and duplex stainless steel fasteners," *Corrosion Science* **39** (3), 473-481 (1997).
- 39 <http://www.asq.org>, "American Society for Quality."
- 40 L. Raymond, "The susceptibility of fasteners to hydrogen embrittlement and stress corrosion cracking," in *Handbook of Bolts and Bolted Joints*, edited by John H. Bickford and Sayed Nassar (M. Dekker, New York, 1998), pp. 723-756.
- 41 S. Brahimi, presented at the AESF SUR/FIN, Cincinnati, OH, 1999 (unpublished).
- 42 "ASTM F 1624 Standard Test Method for Measurement of Hydrogen Embrittlement in Steel by the incremental Loading Technique," ASTM Book of Standards.
- 43 W. J. Pollock and C. Grey, "Assessment of the degree of hydrogen embrittlement produced in plated high-strength 4340 steel by paint strippers using slow strain rate testing," in *Hydrogen Embrittlement: Prevention and Control, ASTM STP 962*, edited by L. Raymond (American Society for Testing and Materials, Philadelphia, PA, 1988), pp. 372-386.

- 44 W. R. Crumly, "Screening tests for hydrogen stress cracking susceptibility," in *Hydrogen Embrittlement: Prevention and Control, ASTM STP 962*, edited by L. Raymond (American Society for Testing and Materials, Philadelphia, PA, 1988), pp. 173-177.
- 45 L. Raymond, "Accelerated small specimen test method for measuring the fatigue strength in the failure analysis of fasteners," in *Structural Integrity of Fasteners, ASTM STP 1391*, edited by Pir M. Toor (American Society for Testing and Materials, Philadelphia, PA, 2000), Vol. 2, pp. 192-203.