ADVANCED STRUCTURAL FASTENING AND JOINTING METHODS UTILIZING SYNERGISTIC COLD EXPANSION AND HIGH INTERFERENCE FIT METHODOLOGY

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Fastened joints in both metallic and composite structure rely on good interference fit of fasteners to transfer load. In fatigue critical joints or attaching lugs in metals, hole cold expansion, or "cold working," is used to induce residual compressive stresses around the hole. These beneficial stresses interact with the interference fit fastener to greatly improve the fatigue and damage tolerance life of the joint and hence the life of the structure or component. The benefits of this technology are well documented [1] and cold expansion is used effectively to either increase fatigue life and damage tolerance of holes or to reduce the weight of the structure in most commercial and military aircraft. In helicopter structure it has also been shown to significantly increase the fatigue strength of riveted joints [2].

Cold expansion technology

The basic hole cold expansion process is accomplished by pulling an oversize tapered mandrel, pre-fitted with an internally lubricated stainless steel split sleeve, through the hole as shown in Fig. 1. A nosecap assembly restrains the sleeve in the hole while the mandrel is pulled. The disposable sleeve allows one-sided processing of the hole, protects the hole from damage and allows the tapered mandrel to radially expand the hole beyond the elastic limit of the material in a repeatable, controlled manner. The sleeve is removed from the hole after cold expansion and the hole then sized for the fastener, if required.

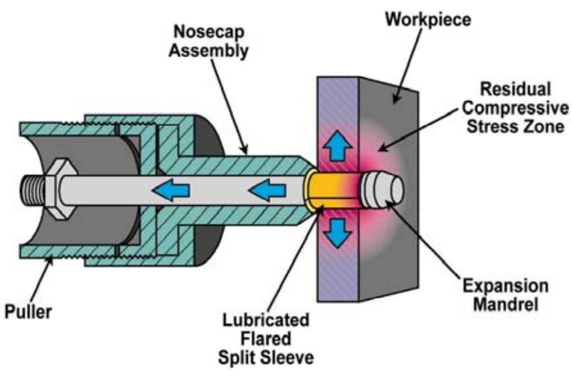

Fig. 1

The mechanical expansion of the hole yields the surrounding material and the subsequent elastic “spring back” of material beyond the plastically enlarged hole generates a large zone of permanent residual compressive stress around the hole. The extent of this compressive stress zone typically extends one radius to one diameter around the hole as seen in the view through a photoelastic coating in Fig. 2.

The hole is nominally expanded 4 percent of the hole diameter for aluminum alloys and 5 percent for high strength steels or titanium. Cold expanded hole fatigue lives generally range from 3 to 10 times the fatigue life of similar non-cold expanded holes as shown in Fig. 3 for 2024 T851 aluminum alloy [1].

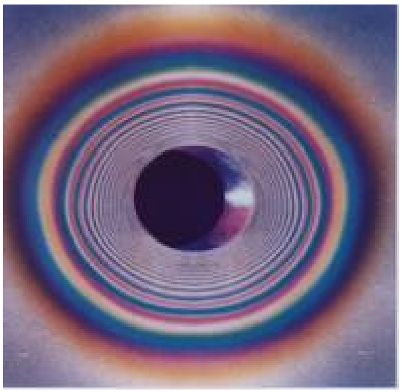

Fig. 2

Damage tolerance

The primary effect of the cold expansion residual stresses is to reduce the crack growth rates [3] by reducing the stress intensity factor range (ΔK) and the stress ratio (R, min. stress/max. stress) [4]. These beneficial residual stresses are useful in meeting ongoing damage tolerance (DADTA) requirements by reducing the stress-intensity factor for residual cracks thereby permitting use of smaller initial flaw sizes in crack growth analysis. These DADTA requirements, whereby all fatigue critical holes are assumed to have an existing 1.2 mm (0.050 inch) flaw or damage, are also applied to attaching lugs and clevises.

Preventing cracks from growing is particularly beneficial when reworking aged structure where the probability of missing a crack during inspection is high. Fig. 4 shows that cracks about 1 mm in length growing from a 6 mm (1/4 inch) diameter hole in 7075-T6 aluminum alloy, under 248 MPa (35 ksi) net stress, are totally arrested when subjected to the same applied cyclic loads [5]. The residual compressive stress zone acts like a strong clamp on the material around the crack minimizing crack opening displacement, thereby preventing growth. The process is just as effective in high-strength steel and titanium [6]. Fatigue life improvement of 3:1 is typical.

Results from crack growth tests incorporating cold expansion of holes prompted a revision of the DADTA initial flaw size philoso-

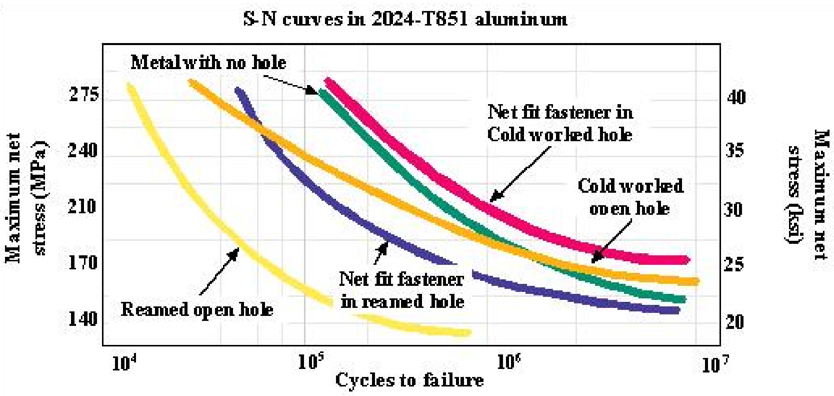

Fig. 3

phy. For many commercial and military aircraft, advantage is taken of the crack retardation benefits of cold expansion by reducing the initial flaw size to as small as 0.125 mm (0.005 inch) if cold expansion is incorporated. The same philosophy could be applied to repairs on other aging military and commercial aircraft for fatigue-related service bulletin repairs to determine ongoing inspection intervals if required.

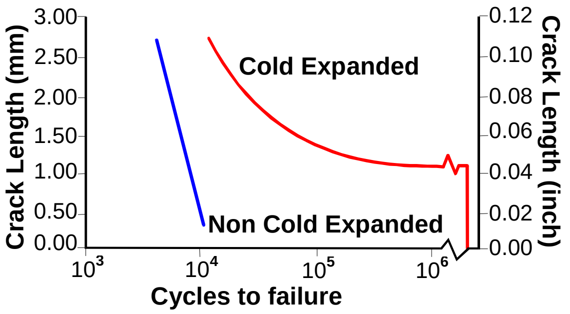

Fig. 4

Changes to helicopter airworthiness requirements include damage tolerant criteria for new helicopter designs to supplement the safe-life design approach [7]. These criteria for rotating dynamic components assume a 0.375 mm (0.015 inch) semicircular surface flaw or a 0.375 mm corner notch in a hole. In load transfer joints such as lugs or clevises, the inspection interval established from the time the original flaw grows to a critical crack length may be relatively short, especially under high cycle fatigue (HCF) load conditions. The incorporation of hole cold expansion or other derivative expanded products can meet these requirements.

Derivative process

Most aircraft and rotorcraft attaching lugs and clevises incorporate bushings or liners to facilitate alignment and provide a replaceable wear surface. The same principle used to radially cold expand holes in structure has been applied to installation of bushings in lugs. The ForceMate® (FmCx™) process was developed by Fatigue Technology Inc. (FTI) to overcome many of the problems associated with “traditional” shrink (freeze) or press fit bushing installations and is a very cost effective method for installing high interference fit bushings in lugs such as engine and landing gear attachments as well as helicopter rotor assemblies. The shrink fit method has many inherent problems ranging from hole damage to low interference fit, leading the bushing movement and migration and possible corrosion issues. It is not a satisfactory method to use in fatigue critical lugs.

ForceMate bushings eliminate fatigue and fretting problems associated with bushed lugs and also improves damage tolerance through a combination of the resultant high interference fit and the induced beneficial residual stresses from the cold expansion installation. Two helicopters recently had rotor assemblies certified “flaw tolerant” after incorporating ForceMate bushings in all primary dynamic rotor components and attachments. Significant long-term life cycle cost benefits are realized in commercial and military aircraft [8] by eliminating fatigue related problems in primary lug attachments that required repeat inspection.

ForceMate process

The ForceMate expanded bushing method is shown schematically in Fig. 5. The bushing, with a proprietary dry film lubricant on the inside surface, is placed over a tapered expansion mandrel which is then attached to a hydraulic puller unit. The mandrel/bushing assembly is placed into the prepared hole with a tolerance of +/-0.025 mm (0.001 inch); which is the same, or less restrictive, than shrink fit hole tolerance requirements. The bushing is retained in the hole by the nosecap assembly, and the expansion mandrel is pulled through the bushing. Bushing inside diameters are expanded between two and six percent, depending on the bushing and lug materials and dimensions. The radial expansion and subsequent unloading yields the bushing, imparts beneficial residual stresses around the hole, and simultaneously installs the bushing with a high interference fit. Typically, 0.10 to 0.20 mm (0.004 to 0.008 inch) diametrical interference is achievable for a nominal 25.4 mm (1.00 inch) diameter ForceMate bushing.

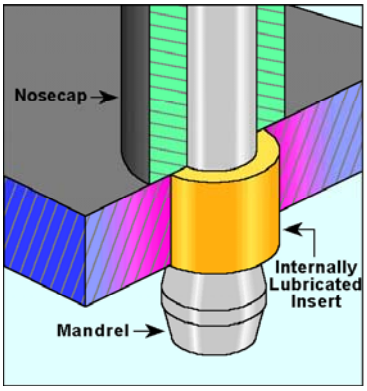

Fig. 5

Fatigue life improvement

Fatigue life improvement is attributed both to the creation of residual compressive stresses in the metal surrounding the hole and to the reduction in applied cyclic stress range caused by the radially expanded interference fitted bushing. These two effects work synergistically to significantly improve fatigue and crack growth lives of lugs as shown in Fig. 6 [9] for a 25 mm (1.0 inch) diameter beryllium copper bushing installed into 7075-T651 aluminum alloy "Heywood" lugs. Any corrosion protective coatings on the bushing is preserved due to the initial clearance fit of the bushing in the hole. The resulting high interference fit virtually eliminates fretting induced fatigue in-service. Of significant advantage to helicopter rotating component design is the increase in fatigue strength and endurance limit resulting from the ForceMate installation.

Fatigue and damage tolerance testing

As discussed previously, airworthiness authorities now require that structures meet damage tolerance requirements. Application of these requirements in helicopter main tail rotors for example, could lead to a significant weight penalty to reduce the stress levels below crack growth thresholds. Installation of high interference fit ForceMate bushings has been shown by coupon and full scale component fatigue testing to significantly increase damage tolerance life of lugs by retarding or arresting the growth of 0.375 mm (0.015 inch) corner cracks in lug specimens. Additionally, ForceMate bushings coated with an "anti-fretting" epoxy coating, BlueCoat™, prevented fretting under high cycle

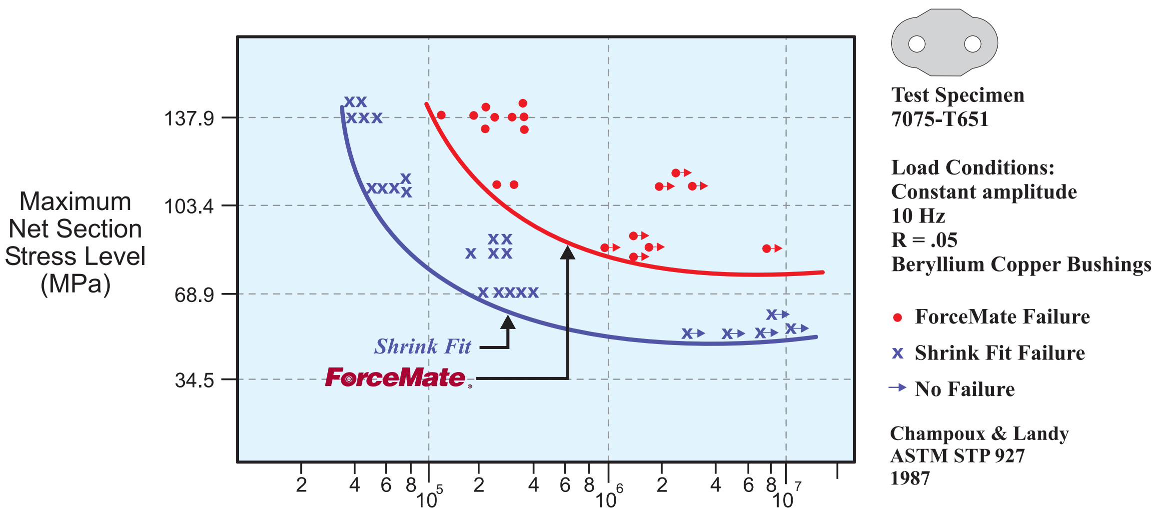

Fig. 6

fatigue (HCF) conditions.

To evaluate the effectiveness of 25 mm (1.0 inch) diameter ForceMate 17.4 PH stainless steel bushings under HCF and simulated damage tolerance, double-ended 7075-T73 aluminum lug specimens (100 percent load transfer) were prepared, Fig. 7. Two different tests were conducted. The first test at 41 MPa (6 ksi) gross stress compared the baseline shrink fit bushings against ForceMate with and without the anti-fretting coating, "BlueCoat™.

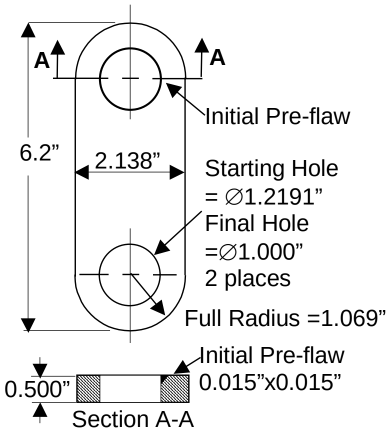

Fig. 7

The second phase of the test compared the same configurations; however, the lug specimen was pre-flawed with a 0.375 mm corner flaw prior to installing both the shrink fit and ForceMate bushings. Test results in Fig. 8 show that all ForceMate specimens ran to run-out (no failure) at 10 million cycles, providing relative fatigue life improvement to the baseline specimen (no flaw) of at least 5:1 and for the damage tolerance specimens of 13:1. Follow-on testing of specimens at higher stress levels show similar trends.

In another damage tolerance test, 28.125 mm (1-1/8 inch) stainless steel ForceMate bushings, were installed into 100 percent load transfer titanium lugs and tested at 90 kN load (20 ksi). A standard damage tolerance initial corner flaw of 1.25 mm (0.050 inch) was induced prior to installation of the bushing. The damage tolerance life improvement of the ForceMate bushings compared to shrink fit bushings was 20:1, as shown in Fig. 9.

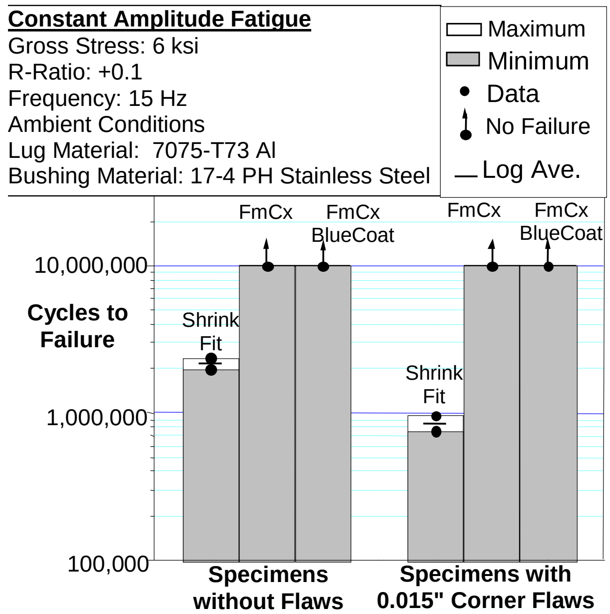

Fig. 8

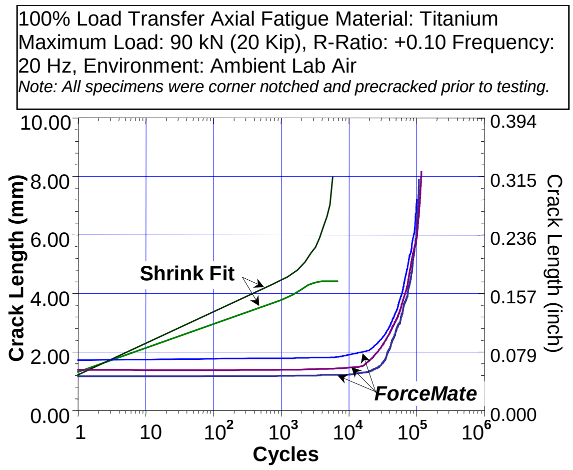

Fig. 9

Derivative cold expanded rivetless nut plate

Aerospace structures incorporate a wide variety of fastening methods to facilitate assembly of manufactured components and structural assemblies. Attaching these often require use of "blind" nuts or captivated nut plates. Nut plates are typically riveted to structure to retain it in place and prevent rotation during panel installation. They are time-consuming to install and require specified orientation to ensure the rivet holes are not adversely placed close to a free edge. The high stress concentration of the combined fastener hole and attaching rivet holes is often a source of fatigue crack initiation. This precludes their use in primary structural attachments.

A derivative “rivetless” nut plate called ForceTec, shown schematically in Fig. 10, eliminates these fatigue problems. The process expands a bushing type retainer that incorporates a nut-retaining feature. The retainer, made from either aluminum, stainless steel or titanium, is cold expanded into the fastener hole at high interference fit which in many cases also induces beneficial residual compressive stress around the fastener hole. This system significantly reduces the high stress concentration associated with the riveted method and also protects the hole during fastener insertion and removal and from fretting a removable sealed or non-sealed nut element is inserted.

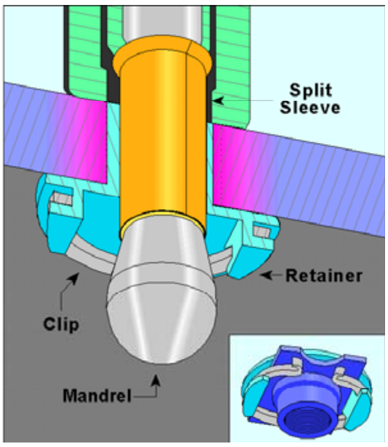

Fig. 10

Torque and pushout resistance in accordance with NASM 25027 is provided by the high interference fit of the retainer in the material. Like the ForceMate bushings, ForceTec greatly improves the damage tolerance of the fastener installation.

Extensive coupon and full scale fatigue testing showed a significant increase in endurance as well as fatigue and damage tolerance life improvement compared to the conventional riveted nut plates. Load transfer fatigue testing in Fig. 11 shows a significant increase in fatigue life over riveted nut plate systems. Like the other expanded processes, ForceTec has the potential for design and stress engineers to reduce structural weight by being able to operate at higher stress levels as a result of the high interference fit and the beneficial induced residual stresses in the material.

ForceTec is used for primary structural attachment as well as access panel retention on a number of aircraft. It has also been used to replace highly fatigue prone riveted nut plates on a military fighter aircraft. In this repair program the riveted nut plates were removed, the satellite rivet holes were cold expanded and plugged with solid rivets and the fastener hole was enlarged to accept the ForceTec retainer. An extensive coupon test program showed the repaired configuration attained a four times life improvement over the original configuration under a severe fighter spectrum load. Furthermore, full-scale component testing of an access panel door cutout showed over a 12 times increase in life when ForceTec was installed over the riveted nut plate configuration.

This expanded nut plate principle has also been adapted to a one-sided installed nut that provides many of the same features as ForceTec; however, it does not provide a floating nut for misalignment. This “blind” nut, referred to as TukLoc, is effective for matched panel assembly.

In this case a threaded nut attached to a barrel is inserted into a closed structure from the outside. The barrel is both radially expanded into the hole for retention and also collapsed on the backside by means of a combination threaded pull rod and expansion mandrel as shown schematically in Fig 12. The resultant installation is a convenient fully blind installation for external attachment of skin panel or sub-structure. It has also proven to be an ef-

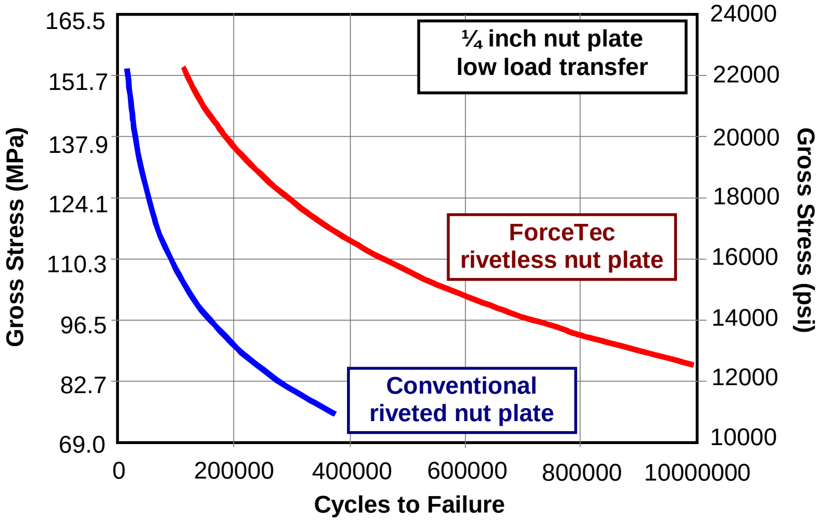

Fig. 11

fective structural repair method for a damaged joint fastener on closed structure. These two nut plates have also been successfully installed in composite structures and joints giving enhanced durability of the assembly.

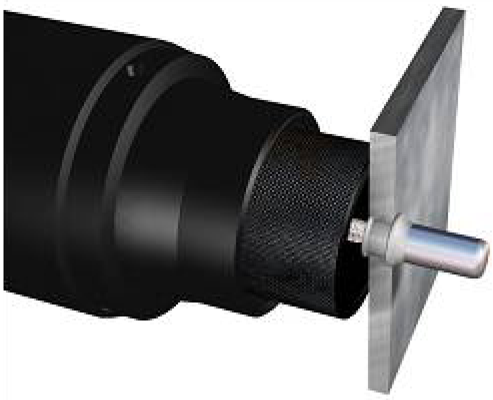

Fig. 12

Composite structural application

With the advent of more composite structures in aerospace design, manufacturing benefits and structural improvements can also be realized with the use of expanded products in these materials. The products can be installed and expanded into composites without causing damage by controlling the level of expansion to avoid delamination of the substructure. Interference fit products provide improvement in the ability to handle open hole compression and show no adverse effects under tensile loads. The use of expanded rivetless nut plates eliminates the need to drill small attachment holes for common riveted style nut plates. Expanded rivetless nut plates eliminate the need for adhesive bonding and all of the associated requirements for surface preparation and curing for bonded-on fasteners and have proven to be more reliable in-service. These expanded products have also shown greater resistance to lightning strikes by providing excellent contact between the composite and the fastener or bushing and no detrimental air gaps. Additional benefit in manufacturing and also repairs is the method of installation, which in many cases requires access to only one side of the structure. These expanded products are being used in many metallic applications and more recently being approved for use in aerospace composite structure.

Conclusion

Cold expansion technology is an effective and proven method to extend the fatigue and damage/flaw tolerance of aircraft structure and helicopter dynamic components. Induced beneficial residual stresses shield the hole from cyclic stresses and reduce the stress intensity factor associated with crack growth. Under typical structural loads and stress levels, the life is extended due to the significant increase in fatigue strength that cold expansion imparts. In bushing installations or installing rivetless nut plates into holes, the additional synergistic high interference fit attained by expanding them in place, further enhances the installation and prevents migration or fretting and protects the hole. In rework and structural life extension programs, cold expansion technology has been shown by coupon, component and full scale testing to be the most cost effective way of extending structural life and enhancing damage tolerance of fatigue critical or life limiting structures and dynamic components.

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