TWENTY-FIFTH EUROPEAN ROTORCRAFT FORUM

Paper Number N12

IMPROVED DURABILITY AND DAMAGE TOLERANCE OF BUSHED LUGS IN HELICOPTERS

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SEPTEMBER 14-16, 1999
ROME
ITALY

ASSOCIAZIONE INDUSTRIE PER L'AEROSPAZIO, I SISTEMI E LA DIFESA
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

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ABSTRACT

Aircraft and rotorcraft attaching lugs and clevises typically incorporate bushings or liners to facilitate alignment and provide a replaceable wear surface. In operation these joints are subjected to severe oscillatory or dynamic loads, especially those induced in helicopter rotor assemblies. The high cyclic stresses on the joint can result in severe fatigue damage in the form of fretting, cracks or ultimately fracture of the joint. For helicopter rotating components in particular, premature fatigue failure under high cycle fatigue (HCF) loading conditions can be catastrophic. Increased structural fatigue life and reduced in-service maintenance problems can be realized with the Fatigue Technology Inc. (FTI) ForceMate® (FmCx™) system of installing high-interference bushings into rotorcraft structures. The process provides a significant improvement in the fatigue life of bushed holes in metallic structures and offers reduced bushing installation costs. 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 interference fitted bushing. Installation is accomplished without the loss of corrosion protection because of the initial clearance fit of the bushing in the hole. Installation costs are reduced by the elimination of liquid nitrogen needed for shrinkage of bushings as well as the significant reduction in installation time and manpower.

This paper will describe the ForceMate system in detail as well as an alternative bushing installation method, BushLoc® (BlCx™), and the manufacturing benefits realized with their use. Fatigue lives of simulated lug geometries in aluminum, steel, and titanium with bushings installed using the ForceMate process are compared with lives of lugs with bushings installed using conventional shrink fit methods. Life improvement factors of greater than 3:1 were shown under constant amplitude and flight-by-flight spectrum loads in cyclic testing. Under helicopter HCF load test conditions, the ForceMate process has shown life increases of 15 to 20 times, as well as a 15 percent increase in fatigue strength. This is an important consideration in helicopters that are required to meet new damage tolerance requirements. Civil and military helicopter applications in rotor heads and pylon attachments are discussed along with high cycle fatigue test results.

1 INTRODUCTION

During manufacture of aircraft and rotorcraft, bushings are used in a number of locations, including attachments of wings, engines, pylons, and landing gear fixtures, to name a few. Usually these locations are highly loaded primary structure that should provide an economical service life without corrosion or fatigue failure during normal use. In helicopter rotor assemblies, many of the components such as blades, swash plates, linkages and actuators etc, are attached through bushed lugs. During operation these joints are subjected to severe oscillatory and dynamic loads which induce very high stresses in the joint. Under these high cycle load conditions these joints are subject to high probability of fatigue failure at the bushing-to-lug interface often initiated by fretting or corrosion, or both. Subsequent fatigue crack growth is rapid owing to the high stress intensity factors associated with this geometry.

A common method for reducing fretting and providing fatigue life improvement of bushed holes is the installation of an interference fitted bushing. Conventional bushing installation is by thermal shrinking (shrink fit) or press fit. Installations are labor intensive, cumbersome, dangerous, and frequently leave bushings with inadequate or inconsistent levels of interference. This paper describes a method whereby an initially clearance fit bushing is radially expanded into the lug/fitting by pulling an expansion mandrel through the internally pre-lubricated bushing, resulting in a high interference fit and simultaneous cold expansion of the material around the hole (see Figure 1). The process, ForceMate®, provides a significant improvement in the fatigue life of bushed holes in metallic structures and offers reduced bushing installation costs. Fatigue life improvement is attributed to both the creation of residual compressive stresses in the metal surrounding the hole and to the reduction in applied cyclic stress range caused by the high interference fitted bushing. The initial clearance fit of the bushing ensures that protective coatings on the bushing remain intact and that the hole is undamaged during bushing installation. The resulting high interference fit virtually eliminates fretting induced fatigue under high cyclic and high vibration helicopter load conditions.

2 BACKGROUND

2.1 Traditional Bushing Installation Methods

Conventional interference fitted bushings are installed using shrink fit or press fit methods. The interference is defined as the degree to which the bushing outside diameter is greater than the hole inside diameter. Traditional techniques using a liquid nitrogen bath to "shrink" the bushing prior to installation are limited to diametrical interference of 0.05 to 0.07 mm (0.002 to 0.003 inch). Attempts to install bushings at higher interference often result in scoring and galling of the inside surface of the hole. Also, they require very tight hole and bushing tolerances to insure process integrity. The bushings have to manufactured specifically for the hole they are to be installed into.

In addition to scoring and scraping the bore of the hole, any kind of sealant, primer or plating may be scraped from the bushing and hole during this installation process. Compounding this problem is the condensation that coats the bushing as it is removed from the liquid nitrogen. The combination of condensation, removal of protective coatings, and the damage inflicted on the bore of the hole sets up a strong potential for corrosion inside the bushed hole.

These shrink and press fit methods are also labor intensive and often precipitate rework because of damage incurred during installation, incorrect seating or inadequate interference. Inadequate interference can manifest itself as serious in-service problems involving bushing rotation or migration, leading to warranty problems, such as jammed components or fretting-induced fatigue. These conditions can lead to catastrophic results in helicopter rotating components, especially under HCF conditions.

2.2 Advanced Expanded Bushing Installations

To overcome many of the previously described problems associated with "traditional" shrink or press fit bushing installations, FTI has pioneered methods to mechanically expand bushings into holes. Using the principles developed to cold expand holes in metals to impart beneficial residual compressive stresses around the hole to prevent growth of fatigue cracks, two different bushing installation processes have evolved. In each case an initially clearance fit bushing is placed into the hole and then radially expanded into the hole using an expansion mandrel that is pulled through the bushing. The resultant high interference fit and simultaneous cold expansion of the surrounding material effectively eliminate problems associated with shrink and press fit bushings.

The two processes to be described are: ForceMate, designed as a high interference fit bushing installation method; and BushLoc, an alternate interference bushing installation method that is also being used for field repairs of damaged/discrepant holes. This paper will focus on the ForceMate process since it is designed as the primary bushing installation method and is most commonly used by the helicopter industry.

3 OVERVIEW OF PROCESSES

3.1 The ForceMate® (FmCx™) Process

ForceMate radially expands an initially clearance fit, internally lubricated bushing into the hole using a tapered expansion mandrel which is attached to a hydraulically operated puller unit as shown schematically in Figure 1.

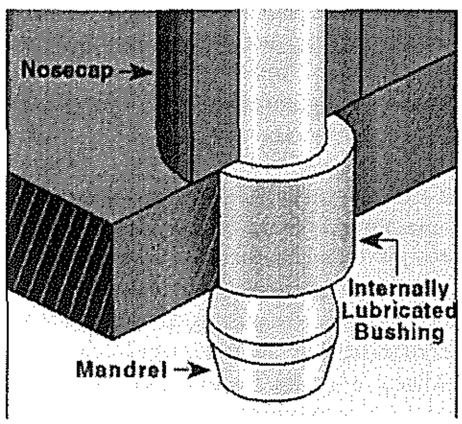

Figure 1: Typical ForceMate Process

The process steps for installing a bushing using the ForceMate process are shown in Figure 2. The specially sized bushing, with a proprietary dry film lubricant on the inside surface, is placed over a tapered expansion mandrel. The attachment end of the mandrel is placed into a hydraulic puller unit: the mandrel bushing assembly is placed into the prepared hole; and the puller unit is activated to pull the expansion mandrel through the bushing which is located by the nosecap assembly. When the mandrel is drawn through the bushing, the bushing and surrounding metal is subjected to radial expansion forces. The radial expansion and subsequent unloading impart 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 diameter (1.00 inch) ForceMate bushing.

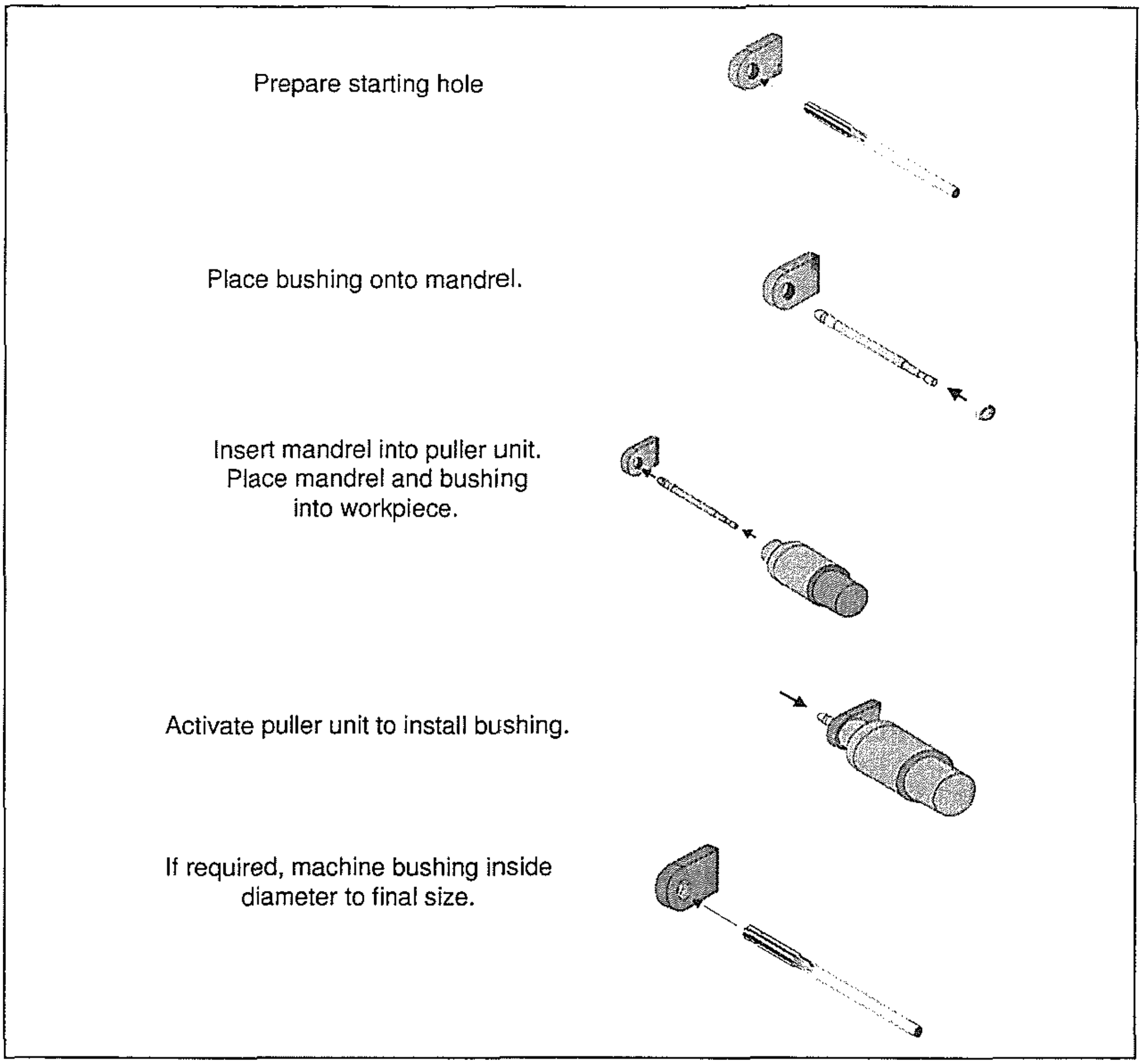

Figure 2: ForceMate Process Overview

The inside surface of the bushing after ForceMate processing has a tapered profile, with a slightly larger diameter at either end than in the middle. A subsequent reaming operation is performed to size the bushing inside diameter to the final size and to remove lubricant residue. In multi-flanged assemblies, the final reaming operation also ensures alignment of the bushing inside diameters.

Cold expansion creates a zone of residual compressive stresses around the hole [1, 2] These compressive stresses effectively reduce the magnitude of the applied cyclic tensile stresses and hence increase fatigue and crack growth life. There is exhaustive data available concerning the beneficial effects of cold expansion on fatigue performance.

Similar to interference fitted pins, interference fitted bushings have also been shown to provide fatigue life enhancement of a bushed hole through a reduction in applied cyclic stress range at a hole [3, 4]. The amount of improvement depends on the ratio of the bushing modulus to the material modulus and the bushing wall thickness. Bushing inside diameters are expanded between 2 and 6%, depending on the bushing and lug materials and dimensions. The reduced applied expansion seen by the surrounding material will still provide significant fatigue life improvement in lug geometries [5 to 8].

The high bushing interference associated with the FmCx process result in a significant reduction in fretting in the bushing-to-hole interface and preclude the intrusion of corrosive agents. The reduction in applied cyclic stress range of the interference fitted bushing and cold expansion of the hole, provide significant retardation of fatigue crack growth and, as a consequence, allow longer inspection intervals. Since inspection of most bushed holes invariably involves disassembly of a complicated structure or assembly, maintenance costs are reduced.

Straight and flanged ForceMate bushings have been manufactured from most typical aerospace bushing materials, including aluminum-nickel-bronze, beryllium copper, titanium, high strength steels and other bushing alloys such as 410 stainless (modified) and precipitation hardened steels. Initial starting hole requirements for the ForceMate process are +/- 0.025 mm (0.001inch). This requirement is typically to the same, or is less restrictive than shrink fit hole tolerance requirements and, in conjunction with the mandrel diametrical tolerance of +/-0.010 mm (0.004 inch), ensures that the minimum applied expansions are achieved.

3.2 The Bushloc® (BICx™) Installation Process

FTI's alternate cold expanded bushing installation method is the BushLoc process. The installation of a bushing using BushLoc is slightly different from ForceMate, which uses a pre-lubricated bushing. BushLoc is accomplished using specially designed tooling similar to that used to spilt sleeve cold expand a hole. A pre-lubricated, stainless steel split sleeve is placed over a tapered expansion mandrel. A bushing, sized to specific BushLoc dimensions, is then placed onto the mandrel and over the sleeve, and then placed in the hole, as shown schematically in Figure 3. The key differences between BushLoc and ForceMate are that the former uses a split sleeve during the installation process, has relaxed bushing tolerances, and the bushing can be locally manufactured. The BushLoc process imparts beneficial residual stresses to the material surrounding the bushing similar the ForceMate process.

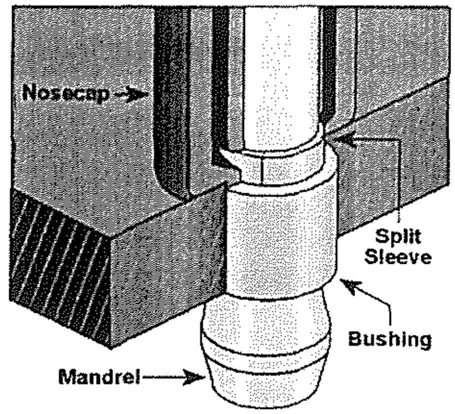

Figure 3: Typical BushLoc Installation

4 ADVANTAGES OF COLD EXPANDED BUSHINGS

Cold expanded bushings are superior to shrink and press fit bushings in many ways. The primary advantage outside of the manufacturing and operating savings is the fatigue life improvement resulting from the beneficial residual stress induced around the hole. Increasing the fatigue life reduces the need for frequent inspections and increases overall structural integrity. The typical life improvement using ForceMate, ranging from 3:1 to greater than 20:1, allows the cold expanded bushing to be used as an integral part of design life goals or terminating repairs in aged structures [9].

Fatigue Life Improvement The action of cold expanding the bushing generally imparts compressive residual stresses around the hole (depending on the bushing/parent material combination) that reduce the mean stress at the hole, thereby improving fatigue life. A comparison of shrink fit and ForceMate residual stresses for a 25.4 mm (1.0 inch) 4340 steel bushing installed into 7075-T73 aluminum lug with a w/D of 2.5 is shown in Figure 4. Note the residual tensile stresses of the shrink fit method in this example. Furthermore, the high interference fit of the bushing acts to reduce the stress amplitude at the hole, as illustrated in Figure 5. These two effects work synergistically to significantly improve fatigue and crack growth lives. These beneficial residual stresses have a profound effect on the resulting fatigue and crack growth life of both new and repair bushing installations for a 25 mm (1.0 inch) diameter beryllium copper bushing installed into 7075-T651 aluminum alloy, as shown in Figure 6 [10].

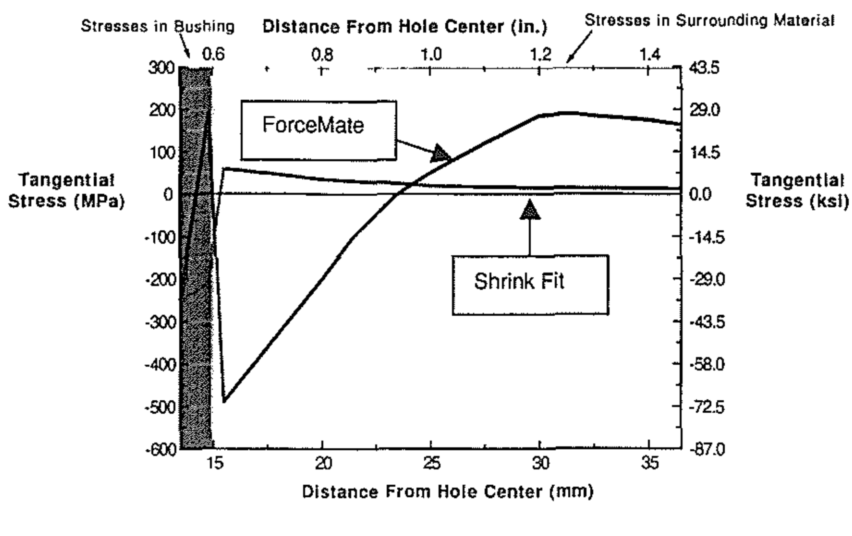

Figure 4: Comparison of Residual Stresses – Shrink Fit Versus ForceMate

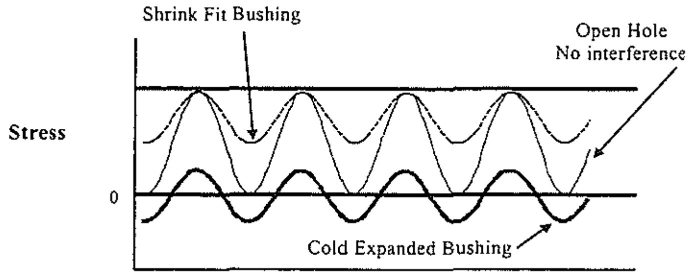

Figure 5: Comparison of Shrink Fit and Cold Expanded Bushings - Cyclic Stress of a Bushed Hole

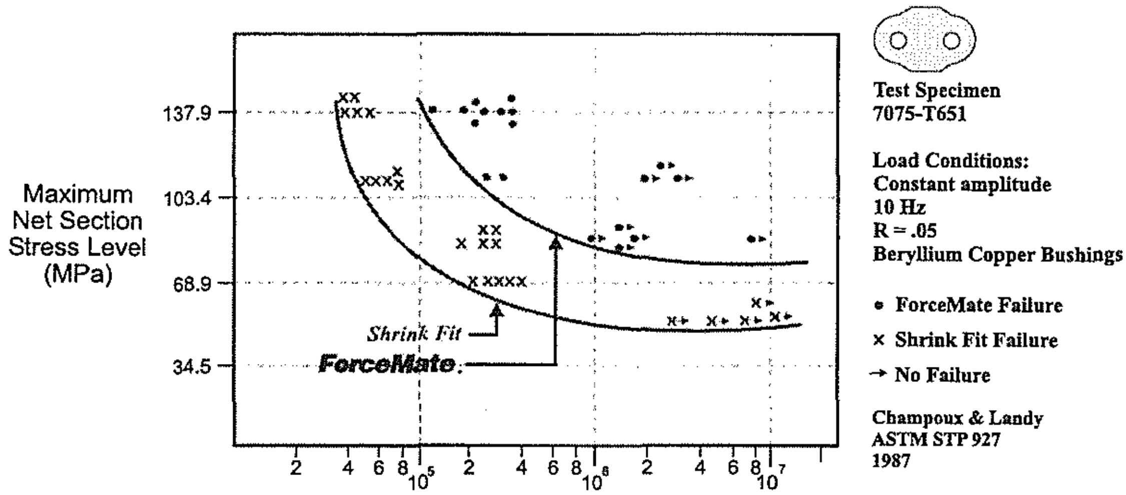

Figure 6: Fatigue Life Comparison of Shrink Fit and ForceMate Bushing Installations

Of significant advantage to helicopter rotating component design is the increase in fatigue strength resulting from the ForceMate installation. The S-N curve comparison of a shrink fit installed bushing to a ForceMate bushing in the example in Figure 6 clearly shows the stress level necessary to initiate fatigue failure has been greatly increased in the case of the ForceMate installation.

Further improvement has been realized by pre-coating the ForceMate bushings with an "anti-fretting" epoxy coating, BlueCoat™, made by the 3M company, developed by Bell Helicopter Textron Inc., and licensed to FTI as a bushing anti-fretting coating. This coating also enhances bushing removal. Under helicopter load test conditions, the ForceMate process has shown a life increase of 15 to 20 times, as well as a 15 percent increase in fatigue strength. An example of actual test results comparing titanium lug specimen fitted with stainless steel BlueCoat bushings to non-coated bushings, are presented in Figure 7. Incorporation of the process in design and repairs can significantly improve durability and damage tolerance of attaching lugs, thereby enhancing helicopter safety. This is particularly important now for helicopters that are designed to meet new damage tolerance requirements.

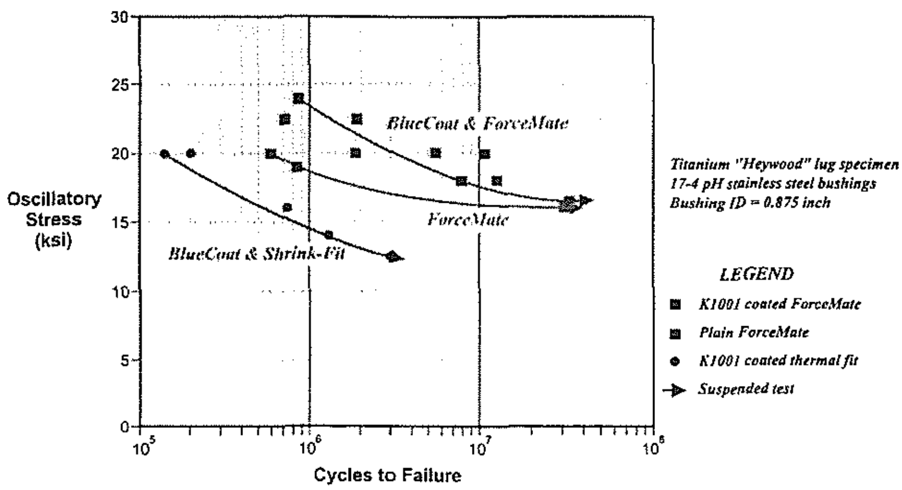

Figure 7: ForceMate BlueCoat Rest Results

Interference Fit The resulting high interference of each of the bushing installation methods, ForceMate and BushLoc, improves resistance to push out and torque significantly. High retention of cold expanded bushings allow them to be used in areas prone to bushing migration due to vibration or high stresses. Push-out forces are typically doubled when compared to those of a shrink fit bushing installation, as shown in Figure 8. The figure shows not only the near doubling of push-out resistance, but shows the consistency of the range of push-out. For the shrink fit bushing push-out ranged from 3.6 KN to 8.9 KN (800 to 2,000 lb.) because of the variability of the interference. By comparison the ForceMate installation push-out ranged from 11.5KN to 12.9 KN (2,600 to 2,900 lb.) for a 25.4 mm (1.0 inch) diameter bushing installed in 7075-T73 aluminum.

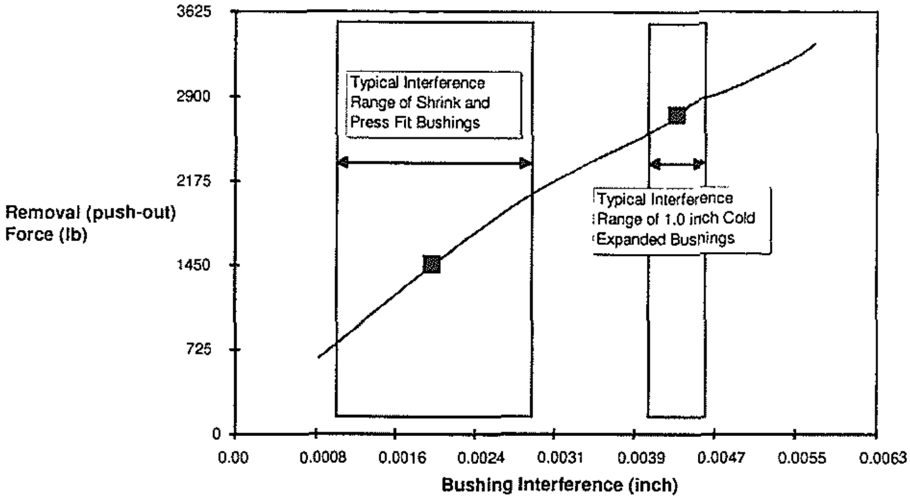

Figure 8: Comparison of Push Out Forces - Shrink Fit Versus ForceMate

Corrosion Resistance Cold expanded bushings provide better corrosion resistance due to the nature of the installation. Each bushing is initially installed into the hole with a slight clearance fit. The small gap allows the use of liquid or solid sealants, platings and coatings that can be applied to the bushing without damaging or scraping them off during installation. Shrink or press fit bushings are installed either net or slight interference fit with little or no gap for corrosion preventative compounds or sealants. As discussed earlier, the protective plating is typically scraped off as bushings are installed into the hole. Additionally, condensation from the shrink fit process remains, which can lead to corrosion.

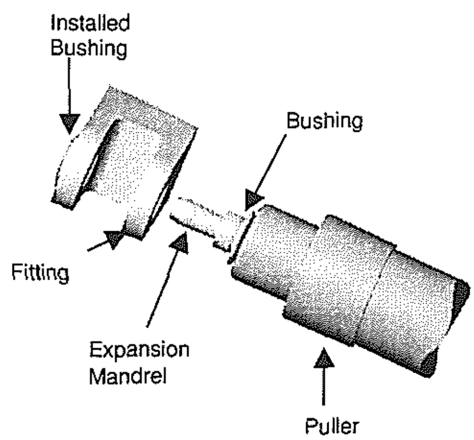

Figure 9: Single Bushing Installation

Multiple Lug Installations Installation of ForceMate bushings into multiple lug configurations is easily accomplished. If access to both sides of the lug is unrestricted, the bushings may be independently installed in each lug, as shown in Figure 9.

Bushings may be independently installed in multiple lugs simultaneously, as shown in Figure 10. In this case, the separate bushings are installed into the clearance fit holes, then a lug support is inserted between the lugs to hold the bushings in place and to support the lugs during pull through of the mandrel from one side only. Each bushing is individually installed. After installation a line ream or hone will ensure alignment. Both flanged and non-flanged bushings, or a mixture of both, can be installed using this method. There are examples of each method used on helicopter applications.

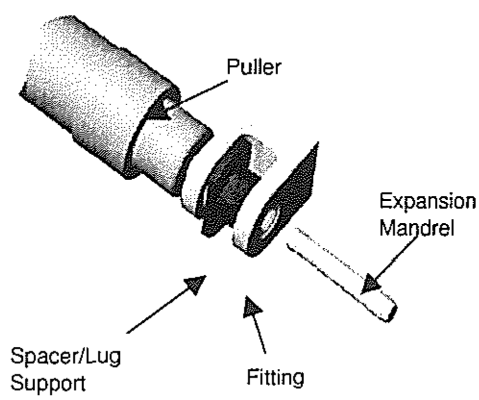

Figure 10: Multiple Bushing Installation

Repair Configurations In addition to using the ForceMate process in new production, it can be used in rework/repair situations along with the BushLoc bushing process. Each of the cold expansion bushing process can be tailored to a wide variety of diameters and lengths to meet just about any application. ForceMate bushings can be made to meet the most exacting specifications including dimension, tolerance, and material. The BushLoc process offers flexibility for cold expanded repair bushing installation by permitting a range of bushing length, inside diameter and outside diameter to be installed.

Several different expanded bushing repair configurations have been evaluated. The following examples demonstrate the versatility of the process to either install multiple bushings or repair multi-layered stack-up joints containing fatigue cracks or damage.

Figure 11 shows a multi-layered stack-up with individual segmented bushings. All three bushings are installed simultaneously. In this type of installation, the combinations of bushings and parent materials may be different. Final line reaming of the installed bushings would be required if different combinations were used because the final inside diameters would vary due to the different amounts of "springback" after bushing expansion.

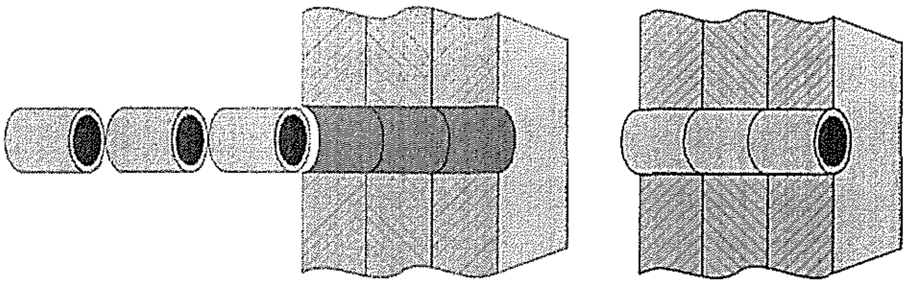

Figure 11: Schematic of Multiple Bushing Installation

Figure 12 shows different outside diameter bushings can be simultaneously installed allowing minimum material removal to correct hole discrepancies or to remove corrosion damage or fatigue cracks. This "Christmas tree" arrangement, and the previous multiple bushing installation, can be done without necessarily breaking down the structure to install the bushings.

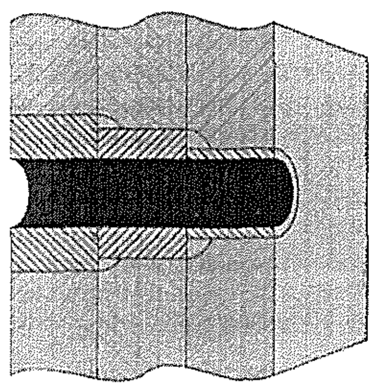

Figure 12: Multiple Variable Wall Thickness Installed Bushings

Other advantages of the cold expanded bushing process include:

- Generally wider manufacturing/rework tolerances of holes and repair bushing
- Quick and consistent installation
- Commonality of installation tooling

4.1 Examples of ForceMate Applications

ForceMate is used in a number of aircraft and helicopter structural applications. Areas that utilize ForceMate for fatigue life improvement, elimination of bushing migration/rotation, weight reduction, manufacturing easement, cost reduction, or a combination of reasons include:

- Engine and pylon attachments
- Primary structural attachments
  - Wings
  - Horizontal/vertical stabilizers
  - Leading edge attachments
- Landing gear attachments
- Helicopter blade and grip attachments
- Rotor spindle attachments
- Gear box attachments
- Door and cargo ramp hinges

5 HELICOPTER ROTOR APPLICATIONS

There are a considerable number of main and tail rotor applications that include ForceMate to increase fatigue life of attaching lugs for blade grips, swash plate actuator arms both fixed and rotating, scissor attachments, pitch change arms, dampers, servo actuators and control rods. Most major helicopter manufacturers are either using ForceMate or have it under test/evaluation. In every case where it has been evaluated, it has been adopted as the bushing installation method of choice due to its high resistance to micro-movement or fretting and migration.

By eliminating micro-movement, fretting induced fatigue under high cycle load conditions is virtually eliminated. And, as discussed earlier, the high interference fit in combination with the induced compressive residual stresses greatly increases the fatigue strength of the fitting. In many cases testing is terminated when ForceMate fitted lugs are evaluated in either standard "Heywood" lug specimens or actual spin pit testing. A further example of HCF test data of aluminum lugs fitted with BlueCoated stainless steel bushings is shown in Figure 13. This example also shows the life of reworked oversized bushings. The increase in fatigue strength is evident in this test.

Special configuration bushings with large flanges to mate against the connecting fitting are easily accommodated with ForceMate. In most cases the flange is counterbored to avoid distorting the flange during bushing expansion. In some cases minor "dishing" of the flange is inevitable, as is some gapping under the flange. These are normally within acceptable manufacturing tolerance; however, a secondary seating operation using a slightly modified mandrel is used to seat the bushing.

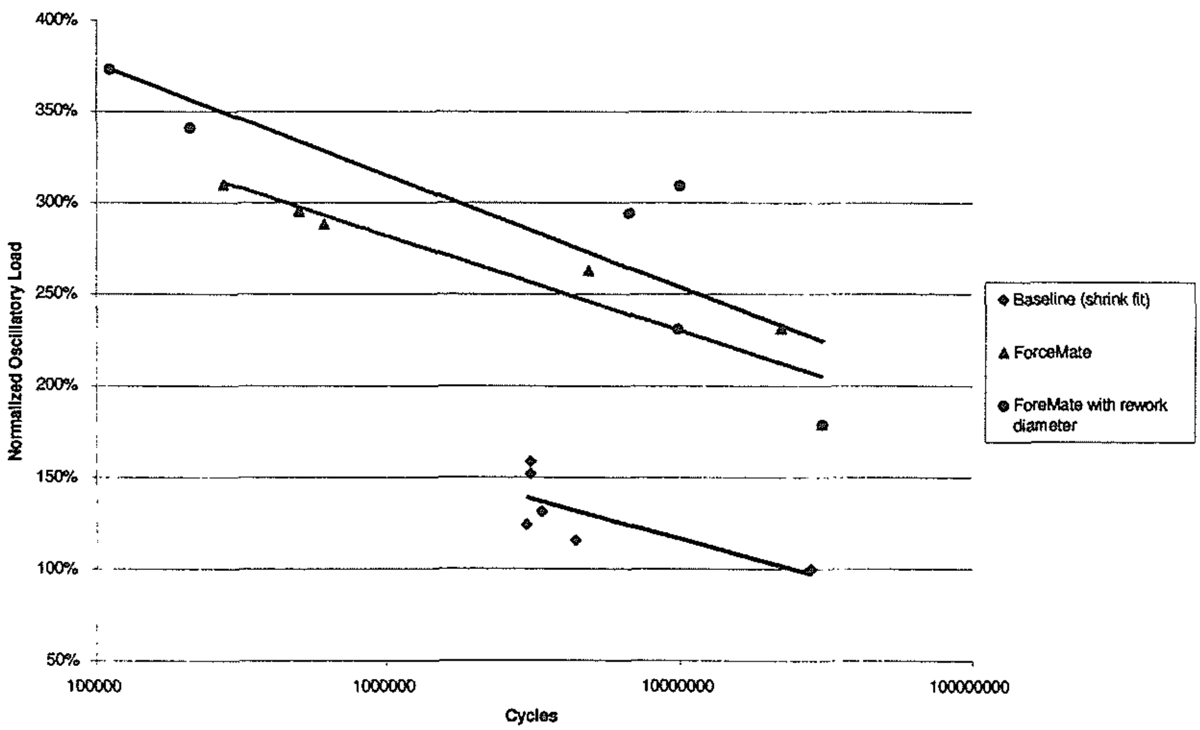

Figure 13: High-Cycle Fatigue Testing in Aluminum Lugs with BlueCoat Bushings

ForceMate bushings from about 10 mm to over 65 mm inside diameters manufactured from BeCu, stainless steel to titanium, are used in helicopter rotor assemblies. Oversize bushings are usually provided to accommodate manufacturing discrepancies. These oversize bushings utilize the same installation tooling as the nominal.

5.1 Blade Grips

The corresponding blade grip attachment also incorporates ForceMate in the design since it is subjected to high rotational and vibration loads. The use of ForceMate also facilitates bushing removal and replacement because the bushing is normally subjected to wear from the blade attachment pin.

In one Eurocopter application the composite blade hub incorporates a steel boss or insert into which is installed a replaceable ForceMate bushing. Trials have validated installation and removal of the ForceMate bushing up to six times with the same nominal bushing. Rework of the blade can be accomplished in the field without having to return the blade to the manufacturer for installation of special repair bushings.

5.2 H-1W Center Wing Improvement

The U.S. Navy's AH-1W Cobra Helicopter lug attachment of the center wing assemblies (see Figure 14), incorporates FTI's ForceMate flanged bushings with the BlueCoat anti-fretting epoxy coating to increase the fatigue life of the wing. In this case, ForceMate provides residual compressive stresses in the lug to increase the fatigue life and eliminate micro-movement (fretting). Life improvement over the original thermal fit bushings and shot peening of the wing lugs was significant: from 1,500 hours to over 4,000 hours.

In a paper presented at the American Helicopter Society 53rd Annual Forum [11], Bell Helicopter described the operating and support cost savings of installing ForceMate bushings of $24.1 to $44.3 million in addition to a significant fatigue life improvement in the AH-1W Cobra Helicopter. The O&S cost savings reflect reduced requirements for spares and savings in man-hours associated with wing replacement.

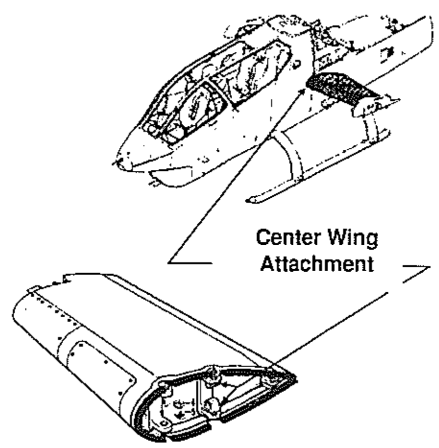

Figure 14: AH-1W Center Wing Attachment

6 CONCLUSION

The ForceMate and BushLoc systems for installing high interference fit bushings are particularly suitable for helicopter structural applications. In highly loaded rotor assemblies, ForceMate is being used by all major helicopter manufacturers to meet high cycle fatigue design lives and to eliminate a potential source of catastrophic fatigue failure. The high interference fit of the ForceMate bushing virtually eliminates micro-movement of the bushing and therefore fretting, which is one of the primary causes of fatigue failure in bushed lug applications. The installation also imparts beneficial compressive residual stresses into the surrounding material or lug which reduces the stress intensity factor and thereby increasing damage tolerance of the installation. The combined residual stresses plus the high interference fit increases the fatigue strength of the bushed assembly.

ForceMate has demonstrated manufacturing savings and increased production rates in helicopter bushing installations. Life cycle costs are also considerably reduced providing a major cost saving to operators. The simplified installation utilizing an initial clearance fit bushing removes a major potential source for installation damage. Elimination of hazardous cryogenic fluids used with traditional bushing installations reduces cost and time and eliminates the potential for corrosion from induced moisture. The method has been extensively tested in coupons, components and actual in-service evaluation on a large number of helicopter applications.

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