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Fatigue life variability due to variations in interference fit of steel bushings in 7075-T651 aluminum lugs

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ABSTRACT

Fatigue of metallic components is a concern in rotary wing aircraft. There exists a potential for loss of an aircraft if a component fatigue life does not take into account all factors than can cause life variation. Much literature was located dealing with the impact of large interference fits and cold working. Literature covering small changes was lacking. This study focused on small changes in interference such as those that could come from a tolerance on a drawing. Testing was completed on 7075-T651 Aluminum alloy lugs with steel bushings of varying interference fit. Testing three different levels of interference fit revealed three different S–N curves even though the variation from fit to fit was small. Significant improvements can be achieved in the S–N curve simply by small changes in interference. From a safety point of view these changes should be looked at as potential reductions.

1. Introduction

Aluminum alloy lugs with steel bushings can be found in many areas of rotary wing aircraft. These types of joints allow for parts to be removed and installed easily, allow for movement during operation, and resist wear. These joints need to withstand a wide range of vibratory loads which puts them at risk for fatigue failure. If the joint is a single load path in a critical area, failure could lead to loss of an aircraft. Interference fit between the lug and bushing has historically been used to improve fatigue lives. A substantial amount of literature has been reviewed that focuses primarily on the impact of large interference fits and cold working. The large interference fits and cold working have been shown to improve fatigue life greatly. The goal of this paper is to present data obtained from testing that shows the impact to a component fatigue life caused by small variations in interference fit. Having test data for small variations of interference fit will permit a better understanding of fatigue life scatter in full scale components manufactured with these small variations.

Two approaches exist for defining fatigue life: (1) safe-life and (2) damage tolerance [1,2]. In the safe-life approach the component is removed prior to initiation of a crack. Removal is generally at a time well before fatigue failure would occur due to the use of very conservative safety factors. In the damage tolerance approach it is assumed that a crack already exists in the component and it will be managed though crack growth analysis and mandatory periodic inspections. Because testing here will develop S–N (stress life) curves, the results/discussion will apply to the safe-life approach.

Two ways that a component fatigue life can be improved are through the use of cold working and interference fit. Cold working generates significant residual compressive stresses. Caution is needed to avoid the short transverse grain of the material or sheets that are too thin to avoid fracture and warping [3]. In contrast to cold working, controlled interference fit results in tensile residual stresses. The contact pressure and residual tensile stress have been shown to increase fatigue life up to a point; however, excessive interference which causes localized yielding can reduce the enhancement [3]. It is suggested in [3] that due to the limitations of theory, theory should not replace testing when utilizing fatigue enhancers, “There are limits towards the application of fatigue quality enhancements and test validation is required to ensure proper application of fatigue quality enhancers in aircraft design.”

Many theories are presented as to why fatigue life can be improved with interference fit [3–10]. The primary reasons for life improvement are: (1) residual hoop stresses introduced into the inner diameter of the hole by the interference fit, (2) increased contact forces between internal and external part, and (3) better transfer of load.

The first reason that interference fits improve fatigue lives is that they introduce residual stresses on the inner diameter of the hole. Tensile hoop stresses result from lower levels of interference whereas compressive hoop stresses result from higher levels of interference (cold working the bushing into the lug). When

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interference fit results in a tensile hoop stress, the magnitude of the local alternating stress decreases while the magnitude of the local mean stress increases in the region of the interference fit. The primary cause of fatigue crack initiation is the alternating stress; however, eventually the mean stress increase can become high enough to offset the benefit of the reduced alternating stress [4]. When the interference fit results in a residual compressive hoop stress, the local mean and local alternating stress in the region of the interference fit are both decreased. If the critical area of the part is in the region of the interference fit, these changes result in improved fatigue life.

The second reason that increased interference fits improve fatigue lives is that they result in higher contact forces between the surfaces. When a part such as a lug with a bushing is loaded, local deflections can cause a loss of contact between regions of the lug and bushing. This movement makes parts such as these susceptible to fretting. By increasing the contact forces between the lug and bushing, relative movement is reduced. In the case of aluminum parts, the oxide powders generated by fretting are harder than the parent aluminum. These oxide powders and rubbing action create stress risers that get worse over time [4]. Fretting has more of a strength reduction in the higher cycle region of the S–N curve because more time is spent in the crack initiation phase. Strength reductions of 10–76% due to fretting are reported in [11] which agrees well with the 67% reduction reported in [12] and the 17–69% reduction reported in [5]. In contrast, a life reduction of 75–85% due to fretting is reported in [6].

The third reason that increased interference fits improve fatigue lives is that they result in lower stress concentrations (K_t) on the component inner diameter. As opposed to the load having to go around the bushing, more load gets transferred through the bushing. This improved load transfer yields a lower K_t. The elastic analysis in [7] shows that the friction between the sheet and bolt has an effect to reduce the stress concentration of the hole. The analysis shows that both an open hole in the center of the sheet and a frictionless bolt in the center of the sheet yield a stress concentration of 3. In the no-slip case, friction allows load to transfer from the sheet to the bolt and this results in lower stress concentrations from externally applied loads (K_t of 1.75–2.0 depending on modulus of bolt). These two cases, frictionless and no-slip, are expected to bracket the real loading because the author feels that in real life some slip will be present between the bolt and sheet. Based on this, the exact reduction in K_t is not known but it is expected some reduction will occur.

Testing in [8] which compared press-fit (0.2% interference) to cold working (0.6% interference) showed a 1.56 load factor difference at the high load region of the curve and a 2.41 load factor difference in the low load region for 7075-T651 aluminum lugs. As a follow on, [9] performed similar tests on steel and titanium lugs but the benefits were not as great as the benefits to aluminum as in [8]. The test in [8] will be used as the basis for the testing here, except this testing will range from about 0.027% to 0.25% interference. Testing in [4] and [10] also showed improvements; however, very limited data is available in [4] and in [10] there was no change until a very large interference (0.27%) was achieved. The lack of change for small interferences in [10] may be due to the bushings being press-fit vs. shrink-fit; however, from the data presented this cannot be determined.

2. Experimental procedure

2.1. Test specimen manufacture

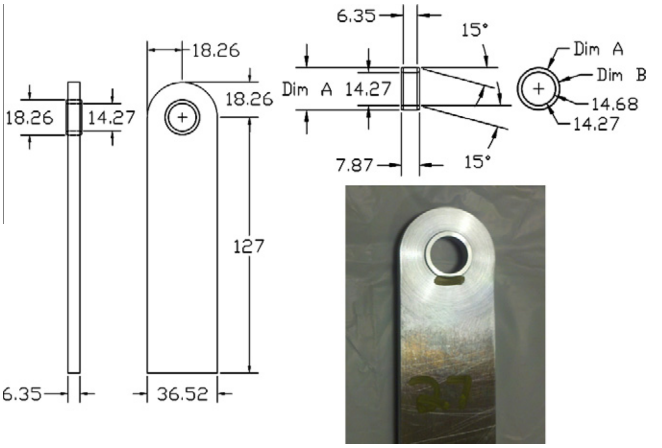

Fig. 1. Fatigue test specimen, drawing and final assembly (dimensions in mm unless noted).

Test coupons as shown in Fig. 1 were manufactured from one sheet of Bare 7075-T651 Aluminum Plate, per specification AMS-QQ-A-250/12. Coupons were cut out of the sheet such that the axial load in the test would be in the sheet rolling direction. The outer edges of the coupons were cut by a computer guided milling machine to give a smooth consistent surface to the final dimensions. On the lug side of the coupon, a hole was first drilled out and then finalized with a reamer. To be able to accurately control the levels of interference fit, the inner diameter of the lugs were measured to ±0.00254 mm (±0.0001 in.) using a bore gauge, in three directions, following reaming.

To ease assembly, the length of the bushing was extended (greater than lug thickness) and a chamfer added to the inner and outside diameter as shown in Fig. 1. The outside diameters of the bushings were based on the measurements taken from the 44 coupons such that the desired diametrical interference fit of 0.0051, 0.0279 and 0.0457 mm (0.0002, 0.0011 and 0.0018 in.) would be achieved as close as possible. To simplify manufacturing, only three different sized bushings were ordered, this resulted in small tolerance differences within the three levels of fit. The bushings were centerless ground out of 17-4PH, Condition 1025 Stainless Steel, to match prior testing [8], to an outside diameter of 18.2702, 18.2931 and 18.3210 mm (0.7193, 0.7202 and 0.7213 in.). The final bushings all came in near the low end of the drawing tolerance. Fig. 2 shows the final actual interference obtained for each part along with the desired interference from the drawing.

Prior to assembly, the top and the bottom surfaces of the lugs were hand polished in a circumferential direction with 600 grit sand paper in the lug region only. A final cleaning with isopropyl alcohol was performed and the parts were inspected visually with no discernible defects. The shrink-fit was performed by submerging the bushings in liquid nitrogen so that no external force was required to fit the parts. Heat was not required on the lugs. Shrink-fit results in both higher contact pressures and interlocking of surface asperities unlike press-fit [13]. Shrink-fit was chosen because it performs better than press-fit. Testing performed in [13] showed that press-fitting a harder material with a softer material resulted in both changes to part dimensions and profiles, shrink-fitting retained more of the original dimensions and profiles.

Following assembly, all parts were measured for width at the center of the lug and thickness at 0°, 90°, and 180° around the lug. All measurements were within acceptable tolerance. A light polish with 600 grit paper in the circumferential direction removed any marks caused during the interference fit and measurement process. As a final step, all parts were cleaned with isopropyl alcohol and marked with a paint pen to record the orientation of the lug in the bushing. The final assembled part can be seen in Fig. 1.