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Understanding the behaviour of silver as a low friction coating in aerospace fasteners

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ABSTRACT

Nuts and bolts used in aero-engines are manufactured from heat-resistant super-alloys. When used in a like on like couple, these materials have a high coefficient of friction, and frequently seizure occurs. In order to prevent this, a silver coating is applied to the nut threads, providing a low friction boundary at the interface. Additionally, a radial crimp is applied to the nut, in order to provide a self-locking feature preventing vibration self-loosening.

In this study, the coefficient of friction of the thread contact will be investigated both during initial joint assembly, and after thermal ageing. Additionally, a finite element model will be employed to investigate the contact mechanics as a consequence of the crimp.

The low coefficient of friction observed during initial assembly was found to be a consequence of shear flow of the silver coating, with an approximate doubling of this value once the coating aged. Areas of silver removal were found to be coincident with areas of high contact pressure in the joint, attributable to the crimp feature.

1. Introduction

Mechanical components in aero-engines operate over a temperature ranges from −50 to 760 °C. As a consequence the fasteners used to join components together are manufactured from heat resistant super-alloys. When used in a like couple super-alloys have high coefficients of friction, and seizure frequently occurs. To prevent this, a silver coating is normally placed on the nut threads. Additionally, in order to avoid vibration loosening, a radial crimp is added to the end of the nut providing a self-locking feature. Unfortunately, this also has the effect of localizing the contact stresses in two small areas, increasing the risk of removing the silver coating from the nut threads and triggering seizure. Whilst seizure of the joints is undesirable, transfer of removed silver from the nuts to other parts of the engine is a significant issue. In particular, silver can combine with corrosive species in the presence of moisture and attack Ni and Ti alloys leading to an increased inspection requirement.

When a bolted joint is assembled and a load supported, the bolt is elongated. Additionally, due to the helical nature of the thread contact, a moment exists which seeks to unscrew the bolt, and is resisted by thread friction [1]. The problem of self-loosening due to vibration was first identified by Junker [2], where it was highlighted that when a shear load was applied to the joint in a given direction exceeding the friction force, the joint would now be free of friction in all directions. This topic area has subsequently been investigated in multiple studies, with Pai & Hess [3] notably identifying that vibration loosening occurs as a consequence of localised slip at the thread face. In order to counteract this phenomenon, a variety of self-locking devices have been developed and investigated. These have included, spring washers, double nuts, adhesives and thread inserts, all having varying strengths and weaknesses. As highlighted by Martinez et al. [4] and Petrova et al. [5], adhesives are very sensitive to temperature changes and are not reliable if subjected to multiple assemblies. Similarly, Kumar [6], investigated Nylock nuts, which use a nylon collar to increase the coefficient of friction. However, this type of locking feature is only applicable to applications with an operating temperature lower than the melting point of nylon (150 °C) [7]. Furthermore, jam nuts and double nuts increase the joint weight, being problematic when large volumes of bolts are utilised [1]. As a consequence, in applications with harsh environments, such as those found in the aerospace industry, fasteners with a mechanical locking feature are frequently used, where the nut is physically deformed providing a clamping effect when the bolt is tightened.

As highlighted, when joints are used in harsh environments, both the nut and bolt are manufactured from Nickel based super-alloys such as Inconel and Waspaloy. These materials have high resistance to creep, high yield stresses and a tensile strength above

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1000 MPa, and are capable of sustaining high loads at elevated temperatures. Furthermore, they are corrosion and oxidation resistant, with the potential to further improve their properties through different heat treatments [8]. On the other hand, they have high coefficients of friction when used in a like on like couple, as high as 0.6–0.8 if unlubricated, leading to seizure at high contact pressures [8].

In order to prevent seizure when using these materials in like on like couples, lubricants and thin coatings are applied. For example, Houghton et al. [9] investigated the use of DLC coatings in a sliding wear test, and demonstrated a significant reduction in seizure, although this improvement was found to be sensitive to the alloy composition of the substrate used. In this application, as in many bolted joint applications, silver coatings have been used as both a corrosion inhibitor and a dry lubricant [10]. Silver belongs to a family of soft coatings, and can easily shear to reduce friction to as little as 0.1–0.15. Yang et al. [11], further investigated three wear regimes: mild, moderate and severe wear, where the coefficient of friction was found to gradually increase for the coating as it sustained increased levels of damage. Furthermore, Sherbini et al. [12] analysed different coating methods, and found ion-plating to be the most satisfactory for Tribology applications. However, electroplating is preferred in various applications due to its cost effectiveness [13]. At present these studies have not investigated the behaviour of silver coatings in bolted joints, despite this type of coating being widely used in the aerospace industry, and also frequently in conjunction with a crimp feature.

In this study the mechanical behaviour of the silver coating has been investigated both experimentally and through Finite Element Modelling. An experimental test platform is developed to investigate the coefficient of friction of crimped fasteners during tightening to an end load of 11.6 kN. The performance of the silver coating is investigated over a period of 6 re-uses, and its durability assessed. Removal of silver in the joint, and the associated contact pressures required for this to occur, are then further analysed through a Finite Element Modelling approach. Following on from this, samples were aged at 760 °C for 50 h, and the coefficient of friction post-test analysed.

2. Methodology

2.1. Test specimens

Fasteners used in the aerospace industry manufactured from heat resistant super alloys were investigated in this study. As shown in Fig. 1, the joint comprised of a simple nut and bolt, with a radially crimped locking feature applied to the chimney of the nut through a clamping vice. The nut, currently in use in engine applications, was 6.35 mm in diameter (1/4″) and manufactured from Inconel 718. Additionally, it had a UNF 28 TPI thread form, which had been electroplated with a silver coating to a nominal 5–10 μm thickness. The crimp on the chimney section was also measured and found to reduce the diameter of this section by 0.35 mm. The bolt used to assemble the joint had a matching diameter and thread form, and was manufactured from Waspaloy.

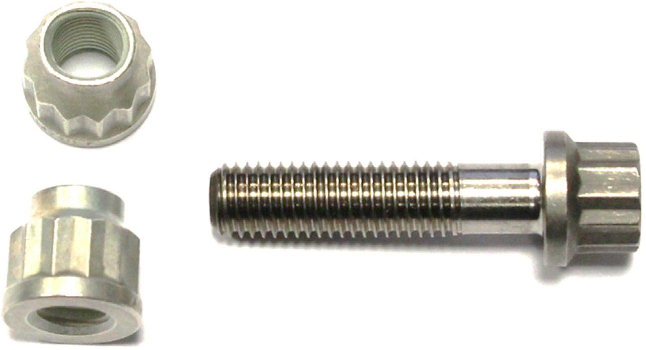

Fig. 1. Specimens.

2.2. Test platform

Fig. 2 shows the test platform used to test the silver coated joints. A motor, fixed on the table, turns the nut onto the bolt, compressing the load cell which measures the clamp force. The bolt is situated in a torque sensor, which in turn measures the reaction torque. The load cell is donut shaped, and has the form of a thick washer with a ¼″ diameter hole in the middle, a maximum capacity of 22 kN and an accuracy of 0.15 kN. The torque sensor is a reaction sensor, with a maximum capacity of 100 Nm and an accuracy of 0.2 Nm, which is free to move in all directions as it is mounted on a frictionless aluminium guide, to prevent undesired misalignment. The load cell, torque sensor and motor are connected to a computer station, so that load, torque and position are continously recorded in a text file at a sampling rate of 1000 Hz and analysed during postprocessing. A steel washer is also included in the set-up, ensuring that the load is applied on the correct face of the load cell. Finally, a thrust needle bearing is placed under the bolt head, to minimise under head friction during the test, with the frictional resistance of the bearing also previously characterised.

The under head friction torque is one of the four values responsible for the total torque. As shown in Eq. 1, the torque required to tighten a joint can be broken down, and is the sum of the clamp or pitch torque, the thread friction torque, the under head friction torque, and the self-locking torque, also known as break-away torque, defined as the torque necessary to screw a locking device [14].

$$T_{tot} = T_{pitch} + T_{threads} + T_{underhead} + T_{selflock} \tag{1}$$

Assuming that the thread pitch and other geometrical parameters are known, along with the coefficients of friction both on the threads (μ_1) and under the head (μ_2), the total torque required to tighten a joint becomes:

$$T_{tot} = F\left(\frac{P}{2\pi} + \frac{r_1\mu_1}{\cos\beta} + r_2\mu_2\right) + T_{self-lock} \tag{2}$$

where F is the clamp load, P is the thread pitch and r_1, r_2 and β are geometrical factors [14].

In this study, the under-head friction is zero through subtraction of the bearing torque, and the locking torque is similarly known, as it is the resisting torque during the screwing on process before the clamping load is applied. Eq. (2) can then be simplified to give a relationship between thread friction, thread torque, load, and geometry, and becomes:

$$\mu = \frac{\cos\beta}{r_1}\frac{T_{thread}}{Load} \tag{3}$$

2.3. Test procedure

2.3.1. Cold use

As highlighted, during engine assembly joints are typically assembled and reassembled multiple times, with 6 re-uses being a common target. Thus, 6 re-uses have been performed on an as new joint, with an end load of 11.6 kN targeted. This end load was selected as it reflects a common design standard for joints of this size in the aerospace industry. Mobil Jet Oil II was applied to the bolt prior to assembling the joint, and a thrust bearing used to

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