THE INFLUENCE OF CORROSION TREATMENTS ON FATIGUE OF AIRCRAFT STRUCTURAL JOINTS

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Keywords: *fatigue, structural integrity, corrosion inhibition, mechanically fastened joint*

Abstract

This paper discusses the effect of the application of Corrosion Inhibiting Compounds (CICs) on the fatigue life of riveted single lap joints. The joints were subjected to constant amplitude fatigue testing, at different load levels. Two CICs normally used to prevent aircraft corrosion were applied. The results showed that the application of CICs reduced the fatigue life of single lap joints. The greatest reduction occurred when the joints were tested at intermediate load levels and at the upper bound of the low load levels; a reduction factor of two or more was found. At high and low load levels, a lesser reduction in fatigue life was observed.

Two failure modes were observed; shear failure of the rivets, and tensile failure of the sheet. Shear failure of the rivets occurred when the specimens were tested at high load levels. At low load levels, most of the specimens failed by tensile failure of the sheet. A transition in failure modes, from rivet shearing to sheet failure was observed in the intermediate load range. The transition in failure modes of untreated specimens occurred at a higher load range than was the case for the treated specimens, suggesting that the lubricating properties of CICs promoted slipping in the joints at lower loads compared to the untreated specimens. Further tests are needed to determine the effect of CICs, particularly at lower load levels.

1 Introduction

Corrosion is one of the key issues capable of determining the overall life of an aircraft. The necessity to prevent and control corrosion impacts the whole-of-life cost of the aircraft by driving up the overall maintenance cost, a cost which tends to increase as an aircraft fleet gets older. Various methods to prevent and control corrosion are employed to prevent corrosion degrading the integrity of the aircraft; one way to combat corrosion with relatively low cost is through the use of Corrosion Inhibiting Compounds (CICs).

CICs are now applied widely in the aircraft industry, as stand-alone corrosion management methods, or as part of structured Corrosion Prevention and Control Programs (CPCPs). Aircraft operators use them to inhibit corrosion on undamaged structure and also to prevent further damage in areas already corroded. They can be applied by brushing or spraying, and provide protection over a period which varies according to the CIC and its application method. CICs are available in many different forms, many of which have the ability to penetrate joints and cracks and displace water already present. Some contain chemicals capable of inhibiting corrosion.

Although CICs are able to retard, or inhibit corrosion, their application may have an impact on the fatigue life of mechanically fastened joints, something which could potentially affect the overall economic or safe life of the aircraft. Earlier work conducted in the United Kingdom (UK) [1] showed that the application of CICs caused more than 50% reduction in the fatigue life of single lap joints when tested at high load level, but less of a reduction at low load level. Mousley [2] investigated the effect of different interfaces, including un-bonded (metal-to-paint contact), sealed (with cold bonding applied), hot-bonded (with hot-cured interfay), and flexible interfaces, the latter representing a halfdamaged joint due to long term service to replicate the most likely condition in service. He found that the application of CIC caused a reduction in the joint fatigue life for un-bonded and sealed joints, but not for hot-bonded and flexible joints. Investigations conducted in the Netherlands suggested that different joint geometries exhibited different fatigue lives, with and without CICs [3,4]. Investigations conducted by the Defence Science and Technology Organization (DSTO) [5] in Australia suggested that the application of CICs had neither beneficial nor detrimental effect on the fatigue life of bolted joints. Dhamari [6] later found that increase in clamping force helped increase the fatigue life of symmetrical bolted joints. Russo, Clark, et al. [7] used 1½ dog-bone specimens and found that a significant fatigue life reduction occurred when the specimens were tested at low load level, in contrast to little change in fatigue life at high load level. The opposite result was observed when "conventional" joints (ie. single lap joints, single strap joint) were used in fatigue tests.

This paper discusses the results of laboratory experiments on single lap joints, treated and untreated with CICs. The main focus was to understand the effect of CICs on fatigue life of single lap joints representative of those used in the General Aviation sector (i.e. small aircraft and small airliners), a sector which could benefit substantially from a more structured approach to corrosion management. The paper discusses the level of degradation of fatigue life with the application of CICs, and examines possible causes of fatigue life reduction.

2 Experimental Procedures

2.1 Specimens

The specimens used in this investigation were single lap joints with two rows of rivets. This design configuration (shown in Fig. 1) was selected to replicate structural joints typically used in small aircraft. The sheets were made from 2024-T3 Aluminium alloy with uniform thickness of 1 mm. The sheets were riveted together using six dome-head MS20470AD4-4 rivets, made from 2117-T4 Aluminium alloy, and with a shank diameter of 3.175 mm. The rivet holes were drilled with slightly larger diameter (3.251 mm) to allow radial expansion of the rivets during riveting.

Two different CICs were used in this investigation, LPS-2, and LPS-3. LPS-2 is an oil-based CIC which has the ability to penetrate into crevices or any cracks, and displace water already present. LPS-3 is soft-waxy CIC which has greater viscosity than LPS-2 making LPS-3 less penetrating in terms of its ability to enter crevices.

The application of LPS-2 was conducted after the assembly of the joints, to simulate the application method typically used in the aircraft industry. Unlike LPS-2, the LPS-3 had to be applied prior to assembly due to its greater viscosity to allow it to spread across the entire faying surface of the joint. After the application, the CICs were left to dry for 24 hours to let the carrier solvent evaporate.

It was noticed that 24 hours might not provide enough time for LPS-2 to dry out. Observation on the specimens treated with LPS-2 suggested that even 2 days after application, the CIC was still in liquid form, as indicated by a black trail that appeared during the fatigue test of the specimens as shown in Fig. 2(a). Similar observations have been reported for real aircraft applications. Unlike LPS-2, a 24 hour period was enough for the LPS-3 to dry out as shown in Fig. 2(b).

2.2 Fatigue Tests

Fatigue tests were conducted using an MTS testing machine with a maximum load capacity of 250kN. The tests involved 21 specimens made up of 7 untreated specimens, 7 specimens treated with LPS-2, and 7 specimens treated with LPS-3. Each test used constant amplitude fatigue loading, with a stress ratio of 0.1 and a frequency of 4 Hz. Each end of the single lap joint was bonded to a spacing shim to minimize eccentricity during loading of the joint.

Seven different load levels were tested, 11.3kN, 10kN, 9kN, 8kN, 7kN, 6kN, and 4kN.

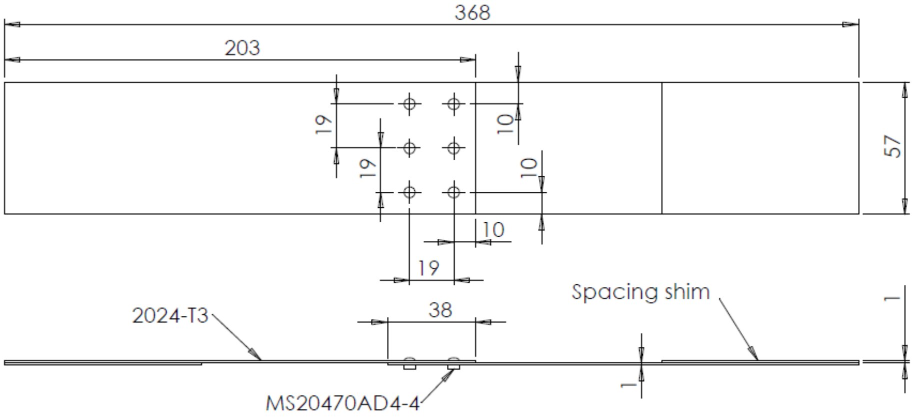

Fig. 1. Single lap joint (units are in millimetres).

Fig. 2. (a) LPS-2 treated specimen; (b) LPS-3 treated specimen.

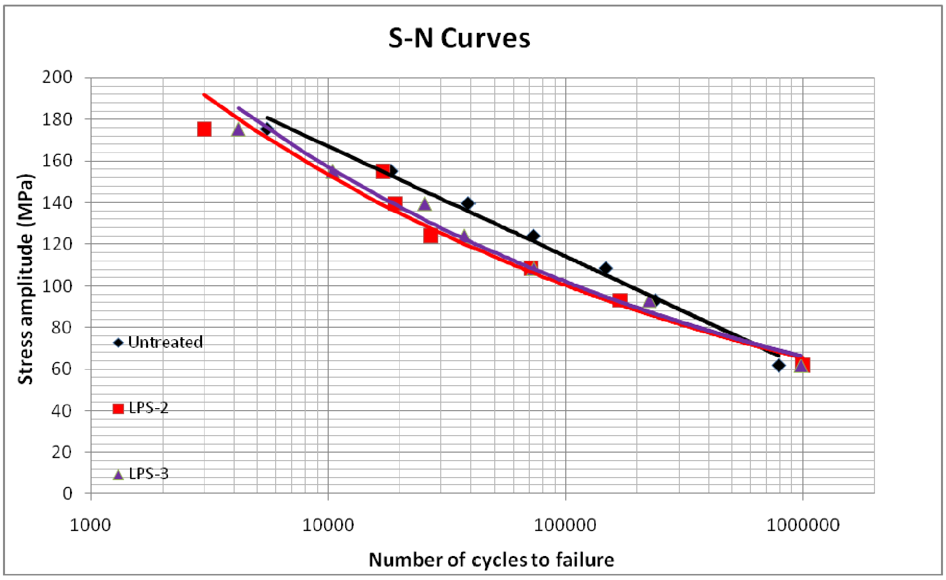

Fig. 3. S-N curves of treated and untreated specimens.

Table 1. Fatigue test results.

Load level	Peak Load (kN)	Non-treated	LPS-2	LPS-3
HIGH	11.3	Rivet failure	Rivet failure	Rivet failure
INTERMEDIATE	10	Sheet failure	Rivet failure	Rivet failure
	9	Sheet failure	Sheet failure	Rivet failure
	8	Sheet failure	Rivet failure	Sheet failure
LOW	7	Sheet failure	Sheet failure	Sheet failure
	6	Sheet failure	Sheet failure	Sheet failure
	4	Sheet failure	Run-out	Sheet failure

As shown in Table 1, and based on failure mode observations, the 11.3kN load level was labeled as "high load level", 10kN, 9kN and 8kN were labeled as "intermediate load levels", and 7kN, 6kN and 4kN were labeled as "low load level". All these loads were within the maximum load capacity (i.e. approximately 12.5kN), determined during initial static tests of the joints, treated and untreated with CICs.

3 Results

3.1 Fatigue lives

The fatigue lives of tested specimens were plotted in S-N curves shown in Fig. 3. Using the fitted curves, it was observed that at the high load level, the fatigue lives of treated specimens were slightly lower than the untreated specimens. Descending into the intermediate load level band, however, a progressively greater life reduction factor - of two or more - was observed for treated specimens. At low load levels, there was also a reduction in fatigue lives of treated specimens, although the reduction was small at the lowest load levels tested. The exact extent of the change at the lowest load level is still somewhat uncertain, since the results include a run-out result on a specimen treated with LPS-2; that will be explored further in additional tests.

3.2 Failure Modes

Two failure modes were observed in the fatigue tests; shear failure of the rivets, and tensile failure of the sheet. At 11.3kN, all specimens, treated and untreated with CICs failed by shear failure of the rivets.

In the intermediate load range, the treated specimens failed by rivet failure or sheet failure, while the untreated specimens all failed by sheet failure.

At the low load levels, tensile failure of the sheet was evident for all specimens, treated or untreated (with the exception of the one run-out which was terminated at one million cycles).

4 Discussion

The effect of applying the CICs was to reduce the fatigue life of single lap joints. A major factor in this reduction in fatigue life could be the lubricating properties of the CICs. Any reduction in friction at the faying surface, sufficient to allow faying surface slippage, would cause more load to be transferred through the rivets. Such a change in load transfer mechanism would explain the changes observed in the failure modes of the joints, and such changes could be associated with earlier occurrence of failure.

At high load levels, reduced friction would encourage slippage of the joint, leading to loading of the rivets, then tilting/rotation of the rivets, which alters the rivet loading. When an asymmetric joint is loaded with tensile load, the joint will exhibit out-of-plane displacement due to the presence of eccentricity in the joint. This out-of-plane displacement is resisted by the rivet heads and the driven rivet heads, causing the rivets to carry not only the shear stress due to bearing pressure exerted by the rivet holes, but tensile and bending stress due to the additional secondary bending.

When the highest load (i.e. 11.3kN) was applied, the shear stress acting on the rivets caused the rivets to fail in shear, identified by the flat, clean fracture surfaces of the rivets shown in Fig. 4.

In all the untreated specimens tested below the 11.3kN level, all failures occurred in the sheet indicating substantial load transfer through the faying surface, and no evidence of overloading of the rivets. Fatigue cracks initiated and propagated at the edges of the rivet holes of the sheet, and caused the sheet to fail in tension

In contrast, the treated specimens in the intermediate load band exhibited a transition in failure mode as the load was reduced, from shear failure of the rivets, to tensile failure of the sheet.

In this band, at 10kN, rivet shearing still occurred on the specimens treated with CICs. However, evidence of the transition was observed since cracks were observed (post failure) to have initiated and propagated at the critical rivet row.

At the 9kN and 8kN load levels in the intermediate load band, again, the untreated specimens failed by sheet failure, while the treated specimens showed mixed failure modes.

Clearly, in this load range the treated specimens were susceptible to joint slippage and rivet failure, at lives similar to that required for sheet failure by fatigue.

It was observed that some of the failed rivets were significantly distorted, as shown in Fig. 5 and Fig. 6, suggesting that secondary bending may have contributed to the failure.

During the fatigue test of an LPS-3 treated specimen tested at 9kN, it was noted that cracks initiated and propagated at the most critical rivet row during the test, but before final failure of the joint, one of the rivet heads in that critical rivet row failed. The failure of one rivet head would cause the other rivet heads to carry larger loads, promoting joint failure by rivet shearing. When the fracture surface of the failed rivet head was analyzed, it was confirmed that the failure occurred at the rivet head/shank transition. Fig. 7(a) and (b) illustrate the progress of failure of the failed rivet.

The progress of fatigue cracks in the sheet could of course lead in itself to changes in load transfer, with additional loading of the rivets, and failure by rivet shear.

The faying surfaces of all treated specimens that failed by rivet shearing in the intermediate load band were also examined. It appeared that at the critical rivet row, cracks already initiated and propagated at some of the rivet holes. This confirmed that 9kN and 8kN, two failure modes competed, and transition in failure modes occurred, from rivet failure normally occurred at high loads, to sheet failure generally seen at low loads.

There were no failures on the driven rivet heads when tested at this load range (i.e. 9kN and 8kN). This might be related to the rivet/shank interference; during riveting, the rivet shank expands radially and can produce residual stress around the rivet hole, depending on interference. However, the expansion, and therefore the residual stresses are not uniform in the through thickness direction, according to Muller [8], who indicated that the residual stresses were larger near the driven rivet head.

Fig. 4. LPS-3 treated specimen tested at 11.3kN.

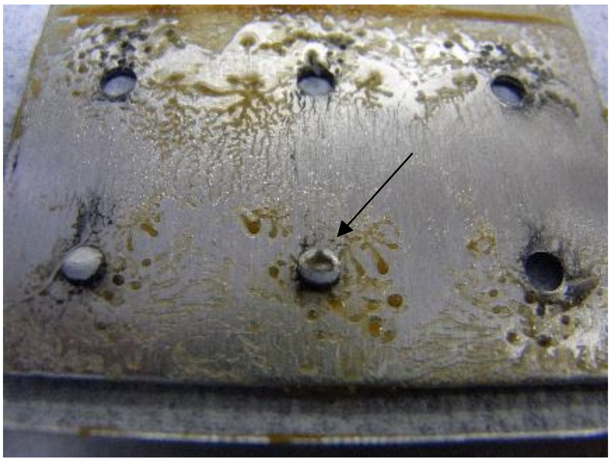

Fig. 5. LPS-3 treated specimen tested at 9kN with rivet head failure. Refer to Fig. 7(b) for the overall view of the joint.

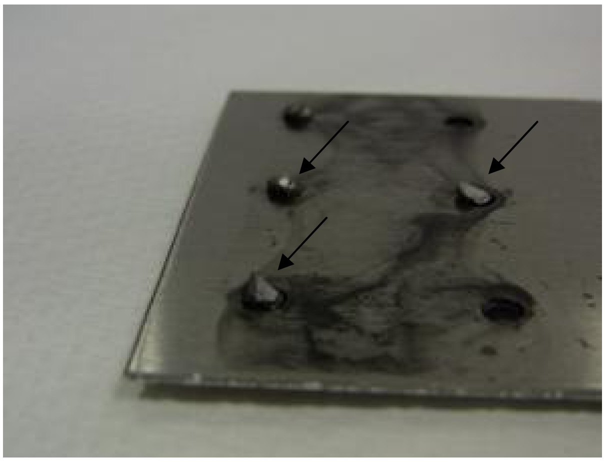

Fig. 6. LPS-2 treated specimen tested at 8kN.

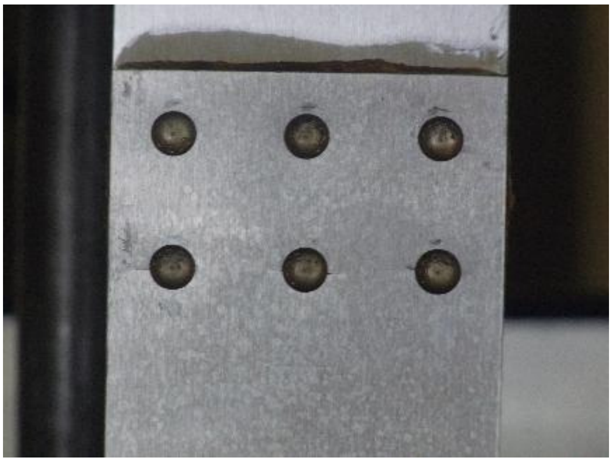

Fig. 7(a). LPS-3 treated specimen tested at 9kN.

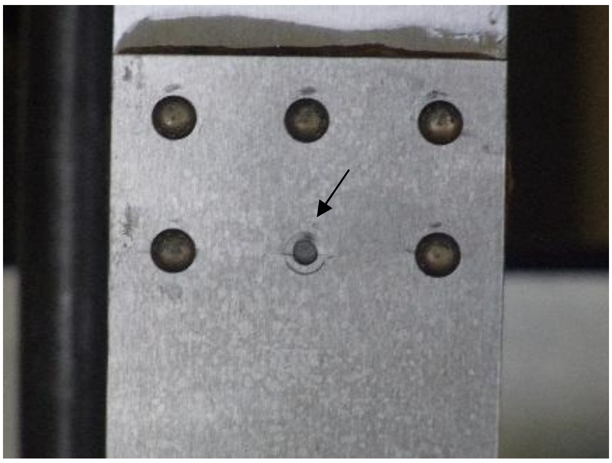

Fig. 7(b). LPS-3 treated specimen tested at 9kN with rivet head failure.

Thus, the sheet in contact with the rivet heads would move more freely due to less rivet/shank interference as the axial load was applied, which caused the rivet heads to carry larger stresses than the driven rivet heads.

Sheet failure occurred on all specimens tested at low load levels (i.e. 7kN, 6kN and 4kN). Multi Site Damage (MSD) was a common feature of fatigue cracking prior to failure. The first crack initiated at one hole, with other cracks nucleating and propagating from the other holes within a further period of only a thousand or so cycles. The cracks eventually linked up, and caused the final failure of the specimen.

All the low-load specimens except for the LPS-2 treated specimen loaded at 4kN, which was a run-out, failed by tensile failure of the sheet. In the 4kN specimen treated with LPS-3, as shown in Fig. 8, failure was progressive, with the first failure occurring from well-developed and reasonably long fatigue cracks, but the specimen continued to carry load until the second failure, with a more plastically deformed fracture surface. At this low load, the structure was able to withstand the load when the first failure occurred, but with substantial plasticity, prior to final failure.

Joint slippage, which leads to increased loading on fasteners (and earlier fastener failure) appears to be capable of explaining the fatigue life reduction, but there are specimens where a life reduction is observed without a change in the final failure mode. In these, the exact mechanism is not yet clear.

Most of the cracks nucleated from fretting damage areas on both untreated and treated specimens. Fretting occurs when there is small oscillatory motion between two clamped metal surfaces, and was readily identifiable by the black aluminium/oxide product [7] around the rivet holes. This black product was more prominent on specimens with greater test life.

According to Hurricks [9], there are three stages involved in fretting fatigue; removal of the thin oxide layer covering the surface of the metal via mechanical wear; adhesion process of the worn metallic surfaces, which initiates the accumulation of wear debris; and the nucleation of micro-cracks caused by additional fretting cycles.

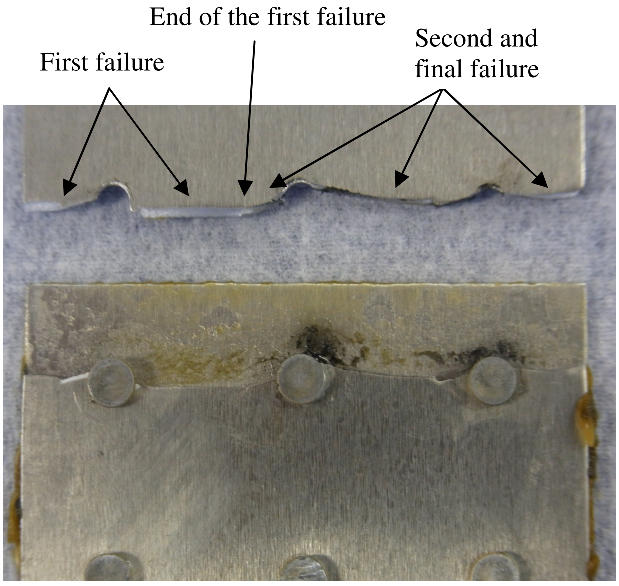

Fig. 8. LPS-3 treated specimen tested at 4kN.

The application of CICs is likely to influence some of these fretting damage mechanisms described above, which could change the fatigue life. The change mechanisms are not clear - as suggested earlier, the application of CIC will reduce the friction on the faying surface, and the reduction in friction could delay the removal of the thin oxide layer of the metal surface. Since the damage process of fretting contact involves wear, corrosive, and fatigue mechanism [10], the presence of CICs might also restrict oxygen access to the fretting interface, inhibiting new oxidation of the already worn metallic surfaces, thus further slowed down the mechanical wear process. This hypothesis was also suggested by Shima et al. [11] when they investigated the effect of oil lubrication on the fretting contact behavior of ball-against-flat steel specimens.

For LPS-2 treated specimens, the fretting debris was spread across the faying surface and concentrated between the rivet rows, presumably because of the lower clamping force at that region. To some extent, fretting product was also carried by the CIC away from the faying surface as shown in Fig. 2(a); this removal could also affect the process.

Unlike LPS-2 treated specimens, the fretting debris on the untreated and the LPS-3 treated specimens was concentrated around the rivet holes. However, for the LPS-3 treated specimens, despite having been applied prior to joint assembly, the CIC was barely present on the contacting surface as shown in Fig. 5, and mainly present at the free edges of the specimens.

5 Conclusion

The presence of CICs caused a reduction in the fatigue lives of single lap joints. The reduction was found to be a factor of two or more. Fatigue life reduction was a maximum at intermediate load levels. Reduced life was also observed, but to a lesser extent, in specimens tested at high and low loads levels. At the lowest load levels tested, the application of CICs did not significantly affect the fatigue life. Run-out occurred on the LPS-2 treated specimen, and more tests will be conducted at low load levels with a longer fatigue test life in order to assess the effect of CICs on the fatigue life of single lap joints.

The application of CICs had a significant influence on the failure modes of treated specimens. Rivet failure occurred when the treated and untreated specimens were tested with the highest load level (i.e. 11.3kN). Transition in failure modes, from shear failure of the rivets to tensile failure of the sheet occurred at the intermediate loads. The maximum reduction in fatigue life occurred at these load levels. At low load levels all specimens failed by tensile failure of the sheet.

While joint slippage, leading to increased loading on fasteners (and earlier fastener failure) appears to be a likely factor in the fatigue life reduction, the exact mechanism is not yet resolved for specimens where a reduced life is observed, but the failure mechanism has not changed; this will be the subject of further research. Fretting fatigue is also potentially a significant contributor to the development of fatigue cracks, and the presence of CICs might have changed the fretting fatigue mechanism.

6 Future works

All the results presented here are part of an initial test series set up to scope the issues for these joints. More tests will, of course, be conducted in the future to simulate the use of CICs in service. This includes applying CICs to the lap joint specimens after being initially tested in fatigue, and conducting more tests focusing on the load band where the structure is normally operated in service.

References

[1] O'Neill PH, Smith RJ. A short study of the effect of a penetrant oil on the fatigue life of a riveted joint. Farnborough, UK: Royal Aircraft Establishment, pp 1305, 1973.

[2] Mousley RF. An effect of corrosion preventative fluids on the fatigue life of riveted joints. The Influence on fatigue. *Proceedings of the Conference*, London, England: Institute of Mechanical Engineers, pp 131-137, 1977.

[3] Schijve J, Jacobs FA, Tromp PJ. Effect on anti-corrosion penetrant on the fatigue life in flight simulation tests of various riveted joints. NLR TR 77103. Amsterdam: National Aerospace Laboratory, 1977.

[4] Kolkman HJ. Effect of penetrant on fatigue of aluminium alloy lap joints. NLR TR 82104. Amsterdam: National Aerospace Laboratory, 1982.

[5] Machin AS, Mann JY. Water-displacing organic corrosion inhibitors—their effect on the fatigue characteristics of aluminium alloy bolted joints. *International Journal of Fatigue,* Vol. 4, No. 4, pp 199-208, 1982.

[6] Dhamari RDA. The effects of water displacing corrosion preventatives on the fatigue behaviour of mechanically fastened aluminium joints. PhD thesis: Aerospace, Civil & Mechanical Engineering, Australian Defence Force Academy, UNSW, 2005.

[7] Russo S, Sharp PK, Dhamari R, Mills TB, Hinton BRW, Clark G, Shankar K. The influence of the environment and corrosion on the structural integrity of aircraft materials. *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 32, No. 6, pp 464-472, 2009.

[8] Müller RPG. An experimental and analytical investigation on the fatigue behaviour of fuselage riveted lap joints. PhD thesis: Delft University of Technology, 1995.

[9] Hurricks PL. The mechanism of fretting - A review. *Wear*, Vol. 15, No. 6, pp 389-409, 1970.

[10] Szolwinski MP, Farris TN. Mechanics of fretting fatigue crack formation. *Wear,* Vol. 198, No. 1-2, pp 93-107, 1996.

[11] Shima M, Suetake H, McColl IR, Waterhouse RB, Takeuchi M. On the behaviour of an oil lubricated fretting contact. *Wear,* No. 210, No. 1-2, pp 304-310, 1997.

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