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Supersonic particle deposition as a means for enhancing the structural integrity of aircraft structures

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ABSTRACT

The paper presents the results of experimental studies into the application of supersonic particle deposition (SPD) for repairing and enhancing the airworthiness and integrity of aging aircraft structures. Presented are the results of coupon tests on the application of SPD doublers to mechanically fastened joints and to simulated corrosion damage tested under constant amplitude fatigue loads. These successful tests are then supported by an application to an F/A-18 Hornet wing attachment centre barrel laboratory test article.

1. Introduction

The high acquisition costs associated with the purchase of modern civilian and military aircraft, coupled with the existing economic and market forces have sometimes resulted in utilization of aircraft beyond their original design life goals. This trend coupled with a number of high visibility aviation accidents has served as a trigger for government and industry action on aging aircraft issues. In this context the April 1988 Aloha accident revealed a number of fundamental weaknesses both in structural design and maintenance. In this incident failure was due to the presence of multiple cracks in neighbouring locations, a phenomenon which is referred to as Multi Site Damage (MSD), coupled with corrosion damage, multiple fastened strap repairs and a less than complete maintenance system lead to the compromise of the structural integrity of the aircraft. In the military sphere the June 2007 Report to Congress by the Under Secretary of the Department of Defense (Acquisition, Technology and Logistics) [1] estimated the cost of corrosion associated with US DoD systems to be between $10 billion and $20 billion annually. That report outlined the need for research into four primary areas one of which was: Repair processes that restore materials to an acceptable level of structural integrity and functionality. Therefore given the importance of structural repairs, and noting that it has recently been shown [2–7] that supersonic particle deposition (SPD), also known as cold spray, technology has the potential to meet this challenge, the present paper discusses SPD applications to a range of load bearing aircraft structural representative coupons and components.

SPD is an additive process in which metal particles entrained in a supersonic jet of an expanded gas impact a solid surface with sufficient energy to cause plastic deformation and bonding with the surface so that the powder is reconstituted into a metal without the creation of a heat affected zone. (Heat affected zones are undesirable in many structural applications). SPD is now an approved Military Standard process for Powder Deposition [8] and has been accepted by Original Equipment Manufacturers, Military Regulatory Authorities and the FAA for limited applications (e.g. geometry restoration in non-load bearing applications e.g. [9,10]).

Previous studies of a (Rosebank Engineering) patented process using aluminium alloy 7075 metal powder, with particles sizes in the range of 30–50 μm (and used in all the cases described in this paper), have shown that SPD can be used to enhance the fatigue life of thin skins with pre-existing defects [2]. In one test, SPD was applied over a centrally notched 1.27 mm thick 2024-T3 clad aluminium alloy dogbone type specimen subjected to constant amplitude loading with a maximum stress of σ_{max} = 180 MPa and an $R = \sigma_{min}/\sigma_{max}$ = 0.1. The baseline specimen, i.e. without a SPD doubler, failed from fatigue at approximately 35,000 cycles. In

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contrast, the 1 mm thick SPD patched specimen test was stopped after approximately 60,000 cycles with little evident damage in the 7075 SPD or crack growth in the 2024-T3 skin. In another test, the 2024-T3 specimen was first loaded to grow a crack. This first phase of the test was stopped at 18,886 cycles when the crack length was approximately 3.2 mm. A 10 mm wide and 1 mm thick SPD strip was then deposited and the test was continued. It was shown that the SPD strip significantly reduced the crack growth rate (by a factor of approximately 3). Similar results were obtained on 7050-T7451 aluminium alloy specimens indicating the load bearing ability of SPD 7075 coatings, see [2] for more details.

The present paper first illustrates how SPD 7075 coatings can be used to mechanically seal fastened joints and thereby potentially alleviating problems that can result from environmentally induced damage at fastener holes. We next illustrate how SPD can be used to restore the structural integrity of corroded simulated aircraft structures without the need to repair corrosion blend-outs using mechanically fastened repairs that involve additional drilling of holes, which may parasitically over-stiffen the area and act as stress concentrators in the base structure. The additional holes can also act as sites at which corrosion can develop and subsequently initiate cracking. The coupon tests established the potential for SPD coatings to address this problem associated with aging aircraft. We next illustrate how this procedure can be used on a built-up structure taken from an operational aircraft by the application of twelve SPD doublers to an F/A-18 Hornet wing attachment centre barrel under service representative fatigue test loading at the Defence Science and Technology Organisation.

2. Maintaining the limit of validity of fuselage lapjoints

The 1988 Aloha aircraft accident, where some cracking in a joint ran from one mechanical repair to another (note that the total crack was metres long but only a small section shown in Fig. 1), see Fig. 1 from [11], revealed that the problem of cracking in fuselage lap joints can be exacerbated by the existence of multiple corrosion repairs in a joint. The repairs acted as weak spots from which some cracking initiated. Furthermore, despite the common practice of sealing the edges of the mating surfaces, it has been shown in other cases that fluid/moisture can still enter the joint through the fasteners/skin interface [12] and thereby initiate corrosion down the bore of the fasteners and in the interface between the layers around these fasteners.

The extent of the problems associated with fuselage lap joints is aptly illustrated by the April 2011 incident whereby cracking in a fuselage lap joint in a Southwest Airlines Boeing 737–300 aircraft resulted in a large 1.52 m (5 foot) hole in the roof [13]. This incident led to the grounding of 79 of Southwest's older Boeing 737 aircraft [13] and to the cancelation of almost 700 flights.

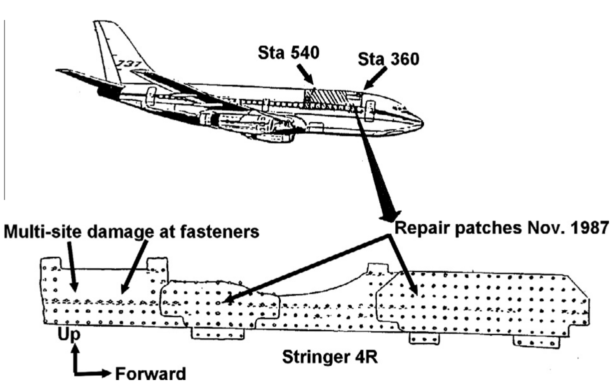

Fig. 1. The linking from multiple repairs in the Aloha, from [11].

Subsequent inspections, which found cracks in a total of four Southwest aircraft [14], led to the US FAA mandating the inspection of 175 Boeing 737 aircraft that had seen more than 35,000 pressurisation cycles. The problem of cracking in fuselage lap joints was not confined to Boeing 737 aircraft. On 26th October 2010 an American Airlines 757–200 aircraft was forced to land at Miami International Airport due to a sudden decompression arising from cracking in a fuselage joint [15]. This aircraft had experienced less than 23,000 cycles. This led to the discovery of cracking in other 757 aircraft and a subsequent January 2011 FAA Airworthiness Directive [15] mandating the inspection of all 757–200 and 757–300 aircraft.

As a result of these incidents and other considerations, the FAA introduced the concept of a limit of viability (LOV), defined as the onset of multi-site and/or multi-element damage, which the FAA now uses to define (or limit) the operational life of civil transport aircraft [15,16].

One challenge addressed in this paper was to develop a SPD application that, when used in conjunction with the standard practice of using a sealant to stop the environment entering the joint via the gap between the mating fuselage skins, can seal the fasteners and thereby alleviate corrosion damage and consequently extend the time to crack initiation at the joint so that the LOV is not degraded by corrosion.

Matthews et al. [5] revealed that a 1 mm thick 7075 SPD doubler could be used to both lower the stresses in the joint and potentially seal the joint against environmental ingress. The lap joint specimen geometry used in [5] and the present study is shown in Fig. 2. The testing was conducted in an ambient environment. This specimen geometry was developed as part of the FAA Aging Aircraft Program, where it was shown via testing, to reproduce the crack length history seen in Boeing 727 and 737 fleet data [10,11]. The basic specimen used consisted of two 2024-T3 clad aluminium alloy sheets 1.016 mm (0.04 in.) thick, fastened with three rows of BACR15CE-5, 1000 shear head counter-sunk rivets, 3.968 mm (5/32 in.) diameter, see Fig. 2. The width of the specimen was chosen to coincide with the typical distance between tear straps of a B-737 aircraft. Since the amount of out-of-plane bending in a typical fuselage joint is an important factor in the fatigue performance of the joint, the amount of local bending in the specimen was made similar to that seen in a typical fuselage joint by testing the specimens bonded back-to-back and separated by a 25 mm thick honeycomb core, see [11,12] for more details. This test configuration was crucial in ensuring that the specimens reproduced fleet behaviour, see [10]. As in [11] the upper row of rivet holes contained crack initiation sites, induced prior to assembly of the joint by means of an electrical spark erosion technique, on either side of the rivet holes. These initial cracks were (each) nominally 1.27 mm long. This crack length was chosen so that the (initial) defect was obscured by the fastener head and as such was representative of largest possible undetectable flaw size. Of the eight fastener holes in the specimen only the inner six contained crack initiation sites, see [6] for more details. The SPD was deposited immediately after the specimen was assembled and a total of six panels were tested. The specimens were tested under constant amplitude loading, with the maximum and minimum loads P_{max} = 40 kN and P_{min} = 2 kN respectively at a frequency of 5 Hz in laboratory conditions. These loads were determined from operational data obtained for the US DoT MSD Committee Review Board for the B-737 aircraft, see [11,12] for more details, and a stress picture[1] showing the stresses in the baseline specimens is

[1] Obtained using thermography techniques [17,18]. A detailed discussion of Lock-in thermography and Lock-in dissipative thermography can be found in Harwood and Cummings [18]. Jones et al. [18] were the first to use Lock-in infra-red thermography to study the ability of SPD to extend the fatigue life of cracked structures.