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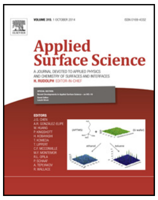

Deep surface rolling for fatigue life enhancement of laser clad aircraft aluminium alloy

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ABSTRACT

Deep surface rolling can introduce deep compressive residual stresses into the surface of aircraft metallic structure to extend its fatigue life. To develop cost-effective aircraft structural repair technologies such as laser cladding, deep surface rolling was considered as an advanced post-repair surface enhancement technology. In this study, aluminium alloy 7075-T651 specimens with a blend-out region were first repaired using laser cladding technology. The surface of the laser cladding region was then treated by deep surface rolling. Fatigue testing was subsequently conducted for the laser clad, deep surface rolled and post-heat treated laser clad specimens. It was found that deep surface rolling can significantly improve the fatigue life in comparison with the laser clad baseline repair. In addition, three dimensional residual stresses were measured using neutron diffraction techniques. The results demonstrate that beneficial compressive residual stresses induced by deep surface rolling can reach considerable depths (more than 1.0 mm) below the laser clad surface.

1. Introduction

The fatigue and corrosion damage of structural components is a major threat to the safety and availability of civil and military aircraft, particularly those being pushed further into and past their initial design fatigue lives. Given fatigue and corrosion damage often initiated at the surface of the components, novel surface enhancement methods and advanced aircraft repair technologies have been extensively investigated in the last decade. For surface enhancement methods, the Shot Peening (SP) process [1,2] is a conventional and inexpensive mechanical surface enhancement method widely used in aerospace and other industries to improve the fatigue performance of components. However airworthiness regulators are unable to quantify the benefits from the SP process and hence generally cannot allow aircraft operators to derive any benefit in the form of scheduled maintenance interval extension. There are several reasons behind this. Firstly, SP could introduce deep folds, laps and embedded/broken (glass) beads, which are not generally detectable on the surface and thus may cause premature fatigue cracking on a SP treated surface. Secondly, any cracking which initiated on the peened surface may be masked by the surface roughness induced by the SP process. Thirdly, the compressive residual stress layer at the component's surface introduced by SP is quite shallow (normally about 0.25 mm deep). Finally, a large degree of cold work (strain hardening due to multiple impacts of peening shots) is introduced to the surface. As a consequence, it can cause damage to the material's microstructure, which may promote accelerated relaxation of the beneficial compressive residual stresses [3,4].

Deep Surface Rolling (DSR), also called deep rolling, has been developed and demonstrated as an alternative mechanical surface enhancement method for improving fatigue performance of aircraft metallic materials and components [5–8]. The DSR process uses high-pressure fluid to float a rolling ball in a socket as it presses and rolls freely along the surface of component, so that near-surface material layers are deformed plastically. Experimental results [9–11] have demonstrated that DSR can improve the fatigue life in metallic materials and components significantly, compared to untreated baselines and shot peened conditions. It was suggested in reference [7] that deep rolling could offer even higher fatigue lives, if the component or coupon was heated to an optimised temperature range during the deep rolling treatment, similar to warm peening. This process is known as "thermomechanical deep rolling". DSR and similar mechanical surface enhancement technologies such as low plasticity burnishing [12,13] have many attractive features, including deep beneficial compressive residual

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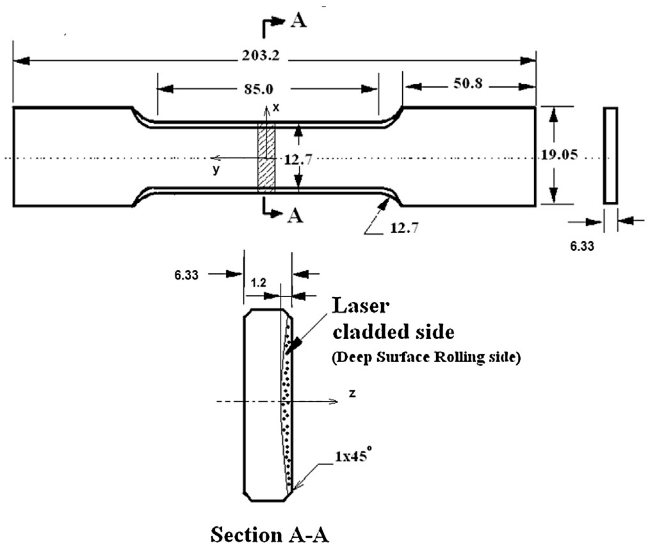

Fig. 1. Laser cladded specimen geometry (All dimensions in millimetre).

stresses at the surface to a depth of 1 mm or further, great tolerance to residual stress relaxation at elevated temperature [5] and under fatigue loading [4,10,11], due to less cold work induced by the controlled DSR process (in comparison with SP), and good surface finish.

Recently at the Defence Science and Technology Organisation of Australia, the research has demonstrated that Laser Cladding (LC) repair technology can be used to deposit different or similar metals or alloys onto the damaged surfaces of aircraft metallic components [14–16]. After the surfaces were repaired using the LC technology, it was found that a relatively narrow Heat-Affected Zone (HAZ) was generated in Aluminium Alloy (AA) 7075-T6 specimens by the localised and rapid fusion of materials during the LC process [17]. To reduce possible detrimental tensile residual stresses in the HAZ, the DSR process as a post-repair enhancement technology was proposed in this study. The neutron diffraction techniques were used to characterise the through-thickness residual stress distributions in three types of specimens: (1) as-clad; (2) post-heat treated and (3) DSR treated. The effect of DSR on fatigue behaviour of the LC AA 7075-T651 was determined by fatigue testing.

2. Laser cladding repair for the specimens with a blend-out

The specimens for the LC repair were made from a 6.33 mm thick plate of AA 7075-T651. The detailed geometry of the specimen and a blend-out (the shaded region in the middle section) are shown in Fig. 1. The chemical composition of the material is listed in Table 1. The yield and ultimate stress for the aluminium base material are 574 MPa and 629 MPa respectively.

A high-power (2500 W) continuous-wave Nd:YAG laser was used to deposit aluminium–silicon (Al–12%Si) powder to build up the blend-out at the middle section of the plate, representative of corrosion damage repair. The average powder particle size was 50 μm and was dried at 90 °C before and during the LC process. The LC process is shown in Fig. 2. The powder was injected to the surface of the blend-out area at an incident angle of 30°. It was delivered to the melt pool by means of an inert carrier gas (Argon) to reduce the oxidation of molten materials. A constant laser power of 1800 W with laser spot size of 5 mm was selected. The laser scan rate was 2200 mm/min which continuously melted the incoming powder and fused it together to form the cladding layer in the blend-out area. After the LC process, the LC deposited plates in Fig. 2(b) were cut into specimens with the dimensions shown in Fig. 1 and the raised cladding was machined flush with the surface of the specimens.

3. Post-enhancement using deep surface rolling

After the specimens with blend-out were repaired using the LC deposition technology, the DSR process as a post-repair enhancement technology was applied to the specimens to reduce detrimental tensile residual stresses in the HAZ. Fig. 3(a) shows the DSR process on a CNC milling machine. Fig. 3(b) illustrates how a hydraulically floated ball was used to press on the surface of the LC deposited specimen under a controlled constant pressure of 150 bars with a feed rate of 1400 mm/min. A series of the DSR passes were applied until the entire surface of the LC repaired region had been treated, including the overlapping area between the HAZ and unaffected substrate.

4. Post-enhancement using heat treatment

Post-heat treatments were performed on five LC specimens using a standard T6 temper to regenerate precipitation and reduce detrimental tensile residual stresses. The heat treatment conducted was a solution heat treatment for 1.5 h at 490 °C, followed by quenching in water and ageing at 121 °C for 24 h.

5. Neutron diffraction residual stresses analysis

The residual stresses found in materials and components after LC are among the most important factors impacting their fatigue performance. Residual stresses in all three types of specimens were measured using the neutron diffraction technique: (1) as-clad; (2) post-heat treated and (3) DSR treated. The neutron diffraction residual stress measurements were performed on the KOWARI strain scanner [18] at the Australian Nuclear Science and Technology Organisation OPAL research reactor. Because the basic principles of this technique were described in [19,20] only details specific to this experiment is provided in this paper. The beam source contains neutrons with monochromatic wavelengths enabling single diffraction peaks to be sampled during strain scanning. Neutrons of 1.7 Å wavelength were extracted from a double focusing Si(400) monochromator at a take-off angle of 78.6° to capture the Al (3 1 1) reflection for the axial and normal components (in the *y* and *z* direction shown in Fig. 1) of the specimen. Considering statistical uncertainty in neutron diffraction, the gauge volume of 0.5 mm × 0.5 mm × 10 mm was selected. This volume allowed reasonably fine spatial through-thickness resolution within a practical measurement time. Consequently, the volume was small enough to provide the necessary through-thickness resolution and eliminated edge effects at the same time. However, the volume was large enough to produce a count rate sufficiently high such that strains were measured with a statistical uncertainty better than 8×10^{-5}, which is within the ±5 MPa accepable range. The three-dimentional residual stresses were then calculated using d-spacing

Table 1
Chemical composition (%) of AA 7075-T651.

Material	Al	Cu	Mn (max)	Si (max)	Mg	Zn	Cr	Fe (max)	Ti
7075-T651	Bal	1.2–2.0	0.3	0.4	2.1–2.9	5.1–6.1	0.18–0.28	0.5	0.2