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Effect of laser shock peening on residual stress and fatigue life of clad 2024 aluminium sheet containing scribe defects

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ABSTRACT

Laser peening at a range of power densities has been applied to 2 mm-thick sheets of 2024 T351 aluminium. The induced residual stress field was measured using incremental hole drilling and synchrotron X-ray diffraction techniques. Fatigue samples were subjected to identical laser peening treatments followed by scribing at the peen location to introduce stress concentrations, after which they were fatigue tested. The residual stresses were found to be non-biaxial: orthogonal to the peen line they were tensile at the surface, moving into the desired compression with increased depth. Regions of peen spot overlap were associated with large compression strains; the centre of the peen spot remaining tensile. Fatigue lives showed moderate improvement over the life of unpeened samples for 50 μm deep scribes, and slight improvement for samples with 150 μm scribes. Use of the residual stress intensity K_{resid} approach to calculate fatigue life improvement arising from peening was unsuccessful at predicting the relative effects of the different peening treatments. Possible reasons for this are explored.

1. Introduction

Laser peening is a comparatively recently-developed technique for surface treatment of metal components and structures. In laser peening treatment the sample is subjected to short duration pulses from a laser which generates a confined plasma on the surface. The plasma has an extremely high pressure (up to 10 GPa) [1] which is in turn transmitted into the sample via shock waves which plastically deform the near-surface region. The local plastic deformation causes compressive residual stresses to develop at the surface.

Over the past decade there have been many published investigations to measure the residual stress fields produced after laser peening, and to document the improvements, particularly in fatigue durability and strength, that can be produced. It is concluded that residual stress fields from laser peening are larger and extend to a greater depth in the components than is found with traditional mechanical shot peening, and that the fatigue strength and durability of samples subjected to laser treatment are superior to those produced by mechanical peening. There appear to be two variants of the laser peening treatment. One variant [2–4] uses a spot size of approximately 1 mm diameter or less, and pulse frequencies up to 10 Hz. The other uses spot sizes of 3–10 mm diameter and pulse frequencies of the order of 0.1–0.2 Hz [5–7].

In order to treat samples and components representative of engineering use the peening treatment needs to be applied over areas considerably greater than the spot size. This is accomplished by following a procedure in which sequences of peened spots are laid down in a raster pattern. The overlap between the spots in a row and between rows of spots can be varied from a few % up to a full 100% or greater (see Fig. 1).

A number of workers (e.g. [8–10]) have developed elastic–plastic finite element models based on the effects of different parameters on the pressure pulse peak and the influence that this has on plastic deformation of the surface layers, for prediction of residual stresses in laser peening. Parameters which influence the pressure peak and residual stresses are the power density of the pulses, the spot size, the pulse duration and the degree of overlap in the raster sequence. In work by Ling et al. [5], modelling laser peening of 304 stainless steel, increasing power density from 3.4 GW/cm^2 to 6.5 GW/cm^2 increased peak residual stresses from −150 MPa to −750 MPa. Spot size changes from 1 mm to 3 mm diameter produced significant changes in the depth at which the peak occurred. Increasing the degree of spot overlap from zero to 100% increased residual stresses compressive peak from −250 to −350 MPa.

Residual stresses and fatigue performance produced by laser peening have been measured in steels [2,5,8] titanium alloys

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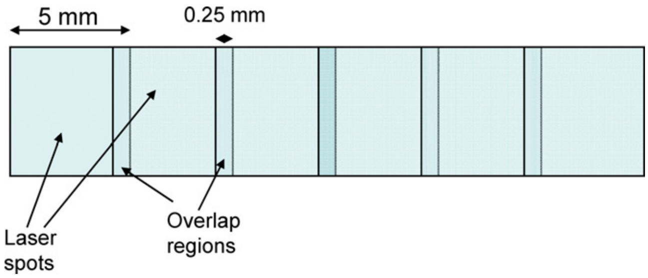

Fig. 1. Laser spot raster morphology. The example shown represents an overlap of 5% on a single row.

[7,9,11,12] and aluminium alloys [1,3,4,13–23], and broadly similar conclusions are found for each. The maximum compressive residual stresses are generally of the order of 0.5–0.6σ_y, the yield stress of the treated material, and extend 1–2 mm into the depth of the sample. There are reports [12] that peening with repeated overlaps at a pulse density of 2500 pulses/cm^2 with pulses of 1.5 mm diameter can produce compressive stresses up to 1600 MPa in a 6061 aluminium alloy with a yield strength of 250–300 MPa. These figures are obviously significantly in excess of the nominal yield strength of the alloy. Fatigue performance is invariably enhanced by the laser peening treatment: fatigue endurance as measured by S–N curves is significantly improved, and fatigue crack growth rates are reduced.

Measuring the effects of the peen residual stress field on fatigue strength requires a degree of experimental ingenuity, as the compressive residual stress field will be balanced by tensile residual stresses on the surface adjacent to the peened area and also in the interior of the sample. Unless the compressive residual stresses are located in regions of the sample with greater applied stress than the regions containing tensile residual stress, fatigue failure will occur preferentially in the regions with tensile stresses and the full potential of the laser peen improvement will not be realised. Some researchers overcame this problem using stress concentrators in the form of notches and holes in the region of compressive residual stress [3]; others – e.g. Luong and Hill [18] – used trapezoidal samples tested in 4-point bending in which the region of greatest alternating fatigue stress was the smallest side of the trapezoid and this was treated with peening; the balancing tensile regions being located at other regions of the sample with reduced alternating stresses.

There have been some investigations and theoretical predictions of residual stresses and fatigue performance of peened thin (<2 mm) sheet material [5,10,21]; all other investigations of the fatigue performance of peened components have used samples of at least 5–6 mm thick. Residual stresses in thin sheet are predicted [5] to be significantly different from those found in thick material, and in addition, there may be other effects associated with stress relaxation and sample distortion. Thin sheets have also been used to study mechanical property and microstructural changes after laser peening [22,24,25].

In order to investigate the benefits of laser peening in thin sheet material, this paper reports on an investigation into fatigue performance and residual stress development in 2 mm thick 2024 T351 clad aluminium alloy treated with laser peening. Fatigue cracks were encouraged to develop in the peened region by use of scribes with a high stress concentration located in the peened area.

Fig. 2. (a) Clad 2024 T351 section showing cladding on outer layers; (b) Grain structure of 2024 T351; section on L–ST plane.

2. Materials and experimental techniques

2.1. Material

The material chosen for the study was 2 mm-thick clad 2024 T 351 aluminium sheet. Typical mechanical properties of the bulk material are shown in Table 1.

The clad layer is of soft unalloyed aluminium with an estimated proof strength of approximately 120 MPa. Metallographic sections of the alloy show that the clad layer is about 70 μm thick. Fig. 2a shows the clad layer as the light etching constituent on the outer surfaces of the sheet. Fig. 2b shows that the substrate grain structure is a typical “pancake” structure, with grain diameters in the longitudinal direction of 100–200 μm and in the through thickness direction of 20–30 μm.

In order to remove potential complexities associated with the clad layer on the residual stress generation, some samples were prepared with the clad layer removed by chemical milling. These samples therefore had a slightly reduced thickness of 1.8 mm.

2.2. Fatigue test sample design

The fatigue test samples were dogbone shaped as shown in Fig. 3, with an overall length of 400 mm and a width of 80 mm at the minimum diameter. The fatigue performance of this sample geometry has been studied extensively in previous research exploring the fatigue performance of 2024 T351 [27]. In order to initiate a fatigue crack at a defined location, a scribe perpendicular to the longitudinal axis of the sample was inserted at the point of minimum diameter using a diamond-tipped tool with a 5 μm root radius. The scratches or scribes were of accurately controlled dimensions and were either 50 or 150 μm deep ±3 μm extending over the entire minimum sample width. Procedures for creating the scribes are described in detail in [28]. A typical transverse section of a 50 μm scribe can be seen in Fig. 4.

Table 1
Typical mechanical properties of clad 2024 T351 [26].

Material	Young modulus *E* (MPa)	Yield stress ($\sigma_{0.2}$, MPa)	Ultimate stress (σ_u, MPa)	Elongation at fracture (%)
Al 2024-T351	72,000	360	481	19