THE EFFECT OF INCIDENCE ANGLE ON RESIDUAL STRESS STATE IN LASER PEENED Ti-6Al-4V PLATE

2005/24

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ABSTRACT

Residual stress was determined by neutron diffraction in laser shock peened Ti-6Al-4V ~8mm flat plate samples treated at several angles of incidence of the laser beam (namely 85°, 42° and 30°). The stresses in the two principal in-plane directions were determined non-destructively as a function of depth from the peened to the rear surface. This was possible by neutron diffraction using radial collimators to define the sampling gauge volume. The plane stress assumption was made in converting strain to stress. A preliminary scan showed that the stress tensor did not rotate as the laser incident angle was varied. The results show that laser shock peening generates a compressive residual stress to a depth of around 1.5 mm, balanced by tensile stresses beneath this region. For the sample peened at the near normal incidence (85°), the in-plane stress state is nearly isotropic. The data indicate that provided the energy input per unit area is largely the same, the stress profiles are insensitive to the angle of incidence, except at the very near surface for which the compressive stress is greater parallel to the extended footprint dimension for lower angles of incidence.

INTRODUCTION

Laser shock peening (LSP) is a mechanical surface treatment, which has been shown to introduce compressive residual stresses to depths an order of magnitude larger than those characteristic of conventional shot peening {Hammersley, 2000}. The process uses a high-energy laser pulse to vaporise locally a sacrificial ablative coating to form a plasma. An overlaying curtain of water confines the rapid expansion of the plasma. This drives a shock wave into the material, causing plastic deformation across the impact area {Peyre, 1996}. The deformation generates an indent the size of the impact footprint. The process is repeated across the desired area of the material, whereby impacts are arranged and overlaid until the desired coverage is obtained. The permanent plastic strain generates incompatibility between the plastically deformed zone and the underlying elastically deformed region. This incompatibility is the source of the compressive residual stress (RS). The compressive RS field is balanced both in depth and laterally by tensile stresses {Hill, 2003} and by elastic bending. The aim of this study was to investigate the effect of the angle of incidence of the laser pulse on the resulting residual stress state. The angle of incidence has proven important in shot peening {Ebenau, 1987}, but the effect for laser peening has yet to be reported. In the present work, the residual stress state was determined for 7.7mm thick Ti-6Al-4V plates laser peen treated at 3 different angles of incidence. Additional measurements were made to determine whether the change of the angle of incidence caused a rotation of the principal axes of the residual stress tensor.

EXPERIMENTAL

Three test-pieces were provided by Rolls-Royce plc, Derby, UK. They were flat plates of Ti-6Al-4V (dimensions 45 × 45 × 7.7 mm), which had been laser peened on one side by Metal Improvements Company. By rastering the laser, individual impacts were arranged side by side without overlapping to create an area of 6 x 6 impacts. The same pattern was then overlaid with an offset of 50% in both directions of the edges of the impact. Therefore the majority of the peened area has essentially been peened twice. The samples where treated with the laser beam at inclined to the surface at 85°, 42° and 30°. The energy of the laser pulse was 180 J. With decreasing angle of incidence the impact footprint extends in one direction (y) causing the energy to be distributed over a greater area. This was compensated for by focusing the laser beam. This meant that the total peened area for the three angles were; 85° = 18 x 21 mm, 42° = 15.5 x 21 mm and 30° = 13.5 x 24.5 mm. Therefore the total peened area elongates in the laser tilting direction, Y and narrows in the perpendicular direction X. This gives a total energy for the three samples of 85° = 48 J/cm^2, 42° = 55 J/cm^2 and 30° = 55 J/cm^2. Prior to treatment, the material had been hot rolled and creep flattened below the β-transus and exposed to a slow cooling rate, giving an equiaxed microstructure that was not affected by the LSP process.

Residual stress determination by neutron diffraction

The residual stress state of the LSP plate was determined by neutron diffraction. The residual stress state generated by laser peening can extend several mm in depth from the treated surface. Therefore, neutron diffraction is a particularly well-suited technique, since it allows non-destructive measurement of the strain tensor from the near surface (50μm beneath the surface) to the bulk of components (in our case right up to the rear surface of the plates).

The neutron diffraction measurements were made on the instrument D1A at the ILL, Grenoble, France. The experimental set-up involved radial collimator optics on the incident and diffracting beams, giving an instrumental sampling gauge cross-section of 1.2 x 1.2mm, figure 1(a). The height (10mm) of the sampling volume was determined by masking the sample with cadmium. The strain is measured in the direction of the scattering vector ***Q***. Figure 1(b) shows the volume sampled when measuring strain in the *x* direction. The *x* and *y*-directions describe the two in-plane directions parallel to the sample edges, while the *z* direction stands for the normal, out-of plane direction. The orientation of the laser beam with respect to the sample co-ordinate system is shown in Fig.1(c). The wavelength used was 2.99Å, giving a diffraction angle (2θ) of 84° for the $(10\bar{1}1)$ Ti plane. The double collimator system allows a precise definition of the gauge volume and minimises the surface effect {Pirling, 2000}. The surface effect (pseudo-strain) was experimentally determined and proved to be at most about 900με. This was corrected for experimentally by subtracting the pseudo-strain from the measured strain {Evans, 2004}.

The stress was calculated on the basis of the in-plane strains assuming a plane stress condition ($\sigma_Z = 0$). This was taken to hold at all depths, Z. We will see that this assumption is justified, since the strain in the Z direction has been found to result from the Poisson contraction caused by the in-plane residual stresses. The equation for the in-plane stresses is:

$$\sigma_i = \frac{E}{\left(1-\nu^2\right)}\left[\varepsilon_i + \nu\varepsilon_j\right] \qquad (1)$$

where i, j are the axes of the stress/strain tensors. E is the elastic modulus (115GPa for the $(10\bar{1}1)$ lattice plane), ν the Poisson's ratio (0.323) representative of the polycrystalline plane on which the strain is being measured. In order to calculate absolute values of strain, the unstressed lattice parameter d_0 must be determined. This was done by assigning d_0 globally to ensure stress balance.

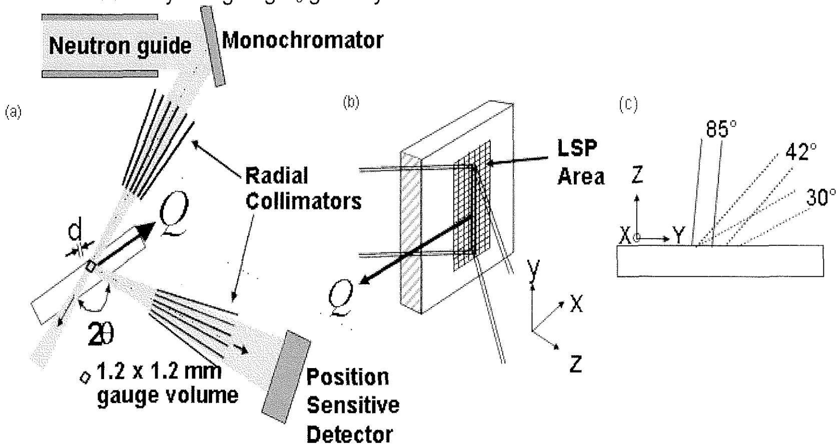

Fig. 1. (a) Schematic plane view of the experimental arrangement on D1A (b) schematic of sample gauge volume, (c) elongation of peening impact with increased angle from the normal.

For a flat plate peened normal to the surface the principal stresses can be assumed to be in the plane and normal to the plane of the plate at all depths. However, it is not so clear that this is the case when the peening takes place away from normal incidence. Indeed, locally for a row of peens a rotation of the principal axes about the x axis might be expected. In order to investigate whether this was the case, the $\sin^2\Psi$ technique was used {Noyan, 1987}. The strain can be plotted against Ψ angle (between the scattering vector and the sample normal) to reveal the direction of the principal out-of-plane strain. The samples were tilted around the X axis at a point where the centre of the gauge volume was 0.7 mm beneath the surface and hence fully immersed in the material. The 48° sample was tilted in 10 ψ offsets of 15° from -83° to 67°. The 60° sample was tilted from -70° to 185° in 12 ψ offsets.

RESULTS

Determination of the direction of the principal axes

Maxima of strain occurred at $\psi = 0$ and ψ □ 90° for both samples peened at inclined angles of incidence. This indicates that the principal directions were in-plane and normal to the surface regardless of beam incidence angle.

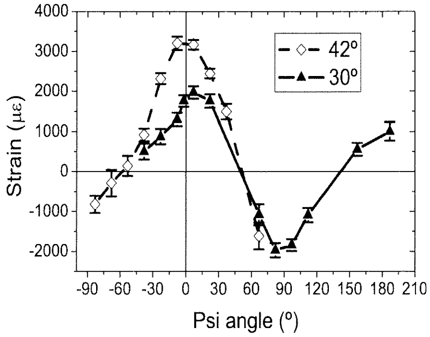

Fig 2. Residual strain in y-z plane as a function of Ψ for samples peened at 42° and 30° incidence; Ψ =0° corresponding to the z direction and Ψ =90° the y direction.

Residual stress state

The residual strain depth profiles for the sample peened near the normal (85°) to the surface are shown in Fig 3. The in-plane strain is essentially transversely isotropic at all depths (Z). The characteristic peening profile occurs to a depth of 2-3mm or so with elastic bending at greater depths. There is some evidence that the extent of bending is slightly greater in x than y. The strain normal to the surface, is mostly the result of the Poisson contraction of the in-plane residual strains, i.e it satisfies the plane stress condition, σ_z = 0. Any discrepancy is taken to arise from the plastic deformation, which can generate intergranular stress.

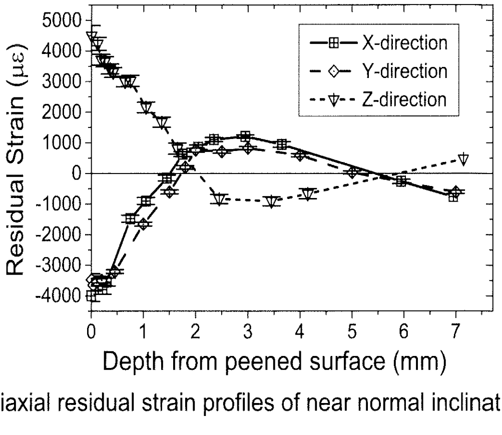

Figure 3. Triaxial residual strain profiles of near normal inclination (85°) sample

The concomitant residual stresses are shown in Figure 4(a) and (b) for the two in-plane directions for the three samples. The stresses are calculated using linear interpolations to the measured residual strain profiles. This was necessary, because the depths at which data were measured in the three directions were not precisely the same. The profiles shown in Figures 4 are in fact very similar for the x and y directions for all inclinations except near the peened surface. Near the peened surface, varying the incidence from the normal angle introduces anisotropy with the stress in the y direction becoming more compressive, and in the x direction less compressive as the angle of incidence is lowered.

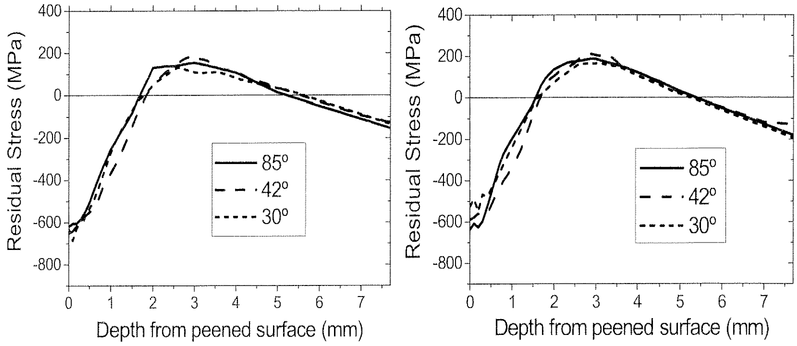

Figure 4. Residual stress profiles in a) Y direction and b) X direction.

Analysis of the peak width

The diffraction peak width gives an indication of the depth and extent of plastic deformation. While peak broadening can vary as a function of the materials microstructure, strain state and instrumental effects, in our case changes in width will be primarily due to changes in plastic deformation. The instrumental effect, which is essentially a strain gradient induced peak broadening, has been simulated based on the experimental data. The predicted maximum peak broadening is 0.04° (figure 5), which is within the experimental error. Although the data in Figure 5 exhibits some scatter, the level of broadening appears to be similar for all samples. In both directions x and y, the depth over which the peak width is broadened is around 2.5 mm. This corresponds to the depth of maximum tensile RS and the onset of the linear solely elastic bending portion of the curves in Figure 4b.

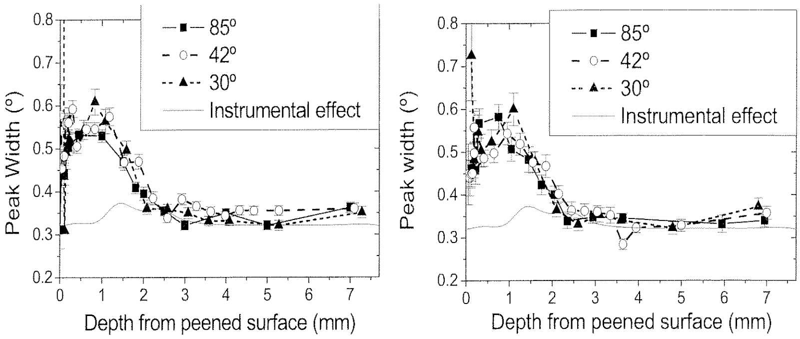

Figure 5 Peak with profiles for direction Y (a) and X (b). The expected instrumental effect is also shown.

DISCUSSION

The results indicate that if the energy input per unit area is unchanged decreasing the angle of incidence from 85° to 30°, does affect the measured residual stress state but only within 0.5mm of the peened surface. The effect is a slight decrease in the intensity of the near surface compressive stress in the direction perpendicular to the tilting of the laser and a corresponding increase parallel to it: The decrease in incidence angle from 85° to 30° has a number of effects. Firstly, it changes the shape of the impulse at the surface. It appears that within 0.5mm the shockwave is largely unaffected by this. Despite the changes in focussing, the variation in incidence does change the energy density incident on the surface, this may also affect the efficiency of transfer of that energy into the plasma and thereby to the substrate. One might expect the efficiency to be higher at higher angles of incidence. There is also a change in the shape of the peening area relative to the plate dimensions with incidence angle. The amount of underformed material increases in the X direction while it decreases in the Y direction at lower angles of incidence. These effects seem to have some influence on the residual stress state near surface, but it is clear that the long range elastic bending stresses are largely insensitive to the variation in incidence angle.

CONCLUSIONS

The effect of the laser impact incidence angle on the surface and bulk residual stress of laser shock peened Ti64 plates has been studied by neutron diffraction. Our results indicate that:

- The stress tensor does not rotate with increasing laser incidence angle at least when averaged over a number of peen footprints.
- The near-surface RS in the direction X, perpendicular to the laser tilt, decreases with decreasing angle of incidence, and increases slightly in the Y direction but otherwise has little effect on the stress profile.
- Peak width changes suggest that the work hardened region extends to the same depth irrespective of incidence angle.

These effects may be explained by means of changes in shock wave propagation and geometric effects related to the variation of the size of the impact area.

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