ABSTRACT

Abrasive Waterjet Peening (AWJP) has emerged as a potential surface treatment process for metal implants and prosthetic devices. An elastic tensile prestress has been shown to increase the magnitude and depth of residual stress that can be obtained. In the present investigation, the subsurface residual stress fields resulting from AWJ peening of Ti6Al4V with load control and displacement control elastic prestress were compared. Prestress ranged from 0 to 75% of the material’s yield strength and the subsurface residual stress distribution was quantified using the layer removal technique. Results showed that the surface residual stress was dependent on the boundary conditions for prestress levels less than 60% of the material’s yield strength. The magnitude of surface residual stress and the stored elastic energy were up to 50% and 100% larger respectively when load controlled boundary conditions were used. However, the boundary condition did not affect the depth of compressive residual stress.

Keywords: Abrasive Waterjet, Boundary Conditions, Elastic Prestress, Layer Removal Technique, Residual Stress.

INTRODUCTION

The surface texture of machine components generally plays an important role on the functionality and fatigue strength. Apparent stress concentrations arising from the surface texture often serve as initiation sites for fatigue cracks [1-3], which may propagate under cyclic loading and facilitate failure. A smooth surface is generally desired to maximize the fatigue life of components. However there are applications where fatigue strength and high surface roughness are desired. Dental and orthopaedic implants are one such application where surfaces must be rough enough to support fixation of the device through mechanical interlock and have high fatigue strength. Yet, the surface texture should not sacrifice the fatigue strength of the implant. Conventional surface treatment processes cannot meet this unique requirement.

Advances in Abrasive Waterjet (AWJ) technology have resulted in a new surface treatment process capable of producing a rough surface and preserving the fatigue strength [4,5] due to the introduction of near-surface compressive residual stresses. Strain peening or peening while subjecting the surface to an elastic tensile prestress has been shown to increase the magnitude and depth of residual stress [6-8]. However, the effect of boundary conditions related to application of the prestress on the resulting residual stress field has not been studied. In the present investigation the residual stress distributions resulting from Abrasive Waterjet Peening (AWJP) of Ti6Al4V were evaluated as a function of load control and displacement control prestress. Investigations were carried out to determine the effect of boundary conditions on the resulting residual stress field and the stored elastic energy.
MATERIALS AND METHODS

The investigations were carried out on a Titanium alloy (Ti6Al4V) having an elastic modulus of 111 GPa and yield and ultimate tensile strength of 1016 MPa and 1080 MPa, respectively. The material was obtained in sheet form having a thickness of 1.6 mm and rectangular specimens were prepared with dimensions of 18 x 275 mm.

Equipment and Procedures

The surface treatments were conducted using an OMAX Model 2652 abrasive waterjet. The machine is capable of discharging a mixture of water and abrasives at pressures within the range of 150-300 MPa. The nozzle assembly consisted of a 0.36 mm diameter sapphire orifice and a tungsten carbide mixing tube of 0.9 mm internal diameter and 89 mm length. A schematic diagram of the peening process is shown in Figure 1(a). Treatments were carried out using Aluminum Oxide abrasives with machine parameters fixed at a jet pressure of 262 MPa, abrasive particle size of #54 mesh, stand off distance of 0.25m and traverse speed of 2.54 m/min. These levels were chosen to maximize the magnitude of residual stress development based on a previous study [4]. Treatments were conducted using these jet conditions according to the pattern in Figure 1(b) to achieve 100% surface coverage over the target surface area. The specimens were loaded in a dedicated fixture (Figure 1(c)) and subjected to prestress during the surface treatment that varied from 0 to 75% of the yield strength (1016 MPa) in increments of 15%.

A dedicated fixture was used to subject the specimens to either load control or displacement control flexure. In both conditions, the elastic prestress was achieved by subjecting the specimen to a constant bending moment between the fixed ends as shown in Figure 1(c), thereby resulting in a uniform prestress along the treatment area. In load control, the treatment was carried out with dead weights maintained on the weight platforms. In this manner, the specimen was subjected to a constant flexure stress throughout the treatment. In displacement control, the specimen was loaded to the appropriate level of prestress and then the loading pins were locked in place and the dead weights were removed. As such the specimen was subjected to a constant displacement that corresponded to the level of original prestress. However, as a result of elastic recovery during the treatment there was a reduction in the magnitude of surface prestress.

Determination of Residual Stress

The residual stress distribution resulting from AWJP was estimated from the curvature of the specimens and by employing the layer removal method [9-11]. Layer removal was performed by etching the specimen in a solution prepared from 20 H2O:1 H2O2:1 HF [12]. The untreated side of the specimen was masked using a photomask to prevent material removal and to ensure that the resulting change in curvature resulted from material removed from the treated surface only. Incremental layer removal was continued until there was no change in curvature with further material removal. In each increment the change in curvature was used to infer the apparent residual stress distribution as a function of depth (σr(z)) according to [9,10]

\[
\sigma_r(z) = \frac{-E}{6(1-\nu^2)} \left[ (z_0 + z_1)^2 \frac{d^2\phi_x(z_1)}{dz_1^2} + 4(z_0 + z_1)^2 \phi_x(z_1) \right.
\]

\[
\left. -2 \int_0^z \phi_x(z) dz \right] \tag{1}
\]

where, E and υ are the Young’s modulus and the Poisson’s ratio of the material, respectively and z is the depth below the surface. Briefly, a layer of known thickness (t) was removed from the specimen whose surface is initially at a distance z0 from the neutral axis (Figure 2). After removal, a new surface with distance z1 from the neutral axis is obtained. The specimen’s curvature was determined before and after material removal using a profilometer and the measured curvature (ϕx) was plotted against the distance from the neutral axis (z). A second order polynomial was used to obtain a mathematical relationship between the curvature and distance from the neutral axis. A suitable series of such evaluations with depth permitted a quantification of the residual stress distribution according to Eqn (1). The distributions were examined to identify the surface residual stress (σr), the maximum residual stress (σr,max) and the depth of the residual stress (Zmax).

Determination of Stored Elastic Energy

The elastic energy stored in the surface as a result of AWJP was determined from the results of the experiments. Specifically, the subsurface residual stress distribution was plotted with the depth and a quadratic curve was fit to mathematically describe the distribution. The specific energy stored (U) was obtained from the subsurface residual stress distribution by integrating it over the depth of compressive residual stress (Zmax) according to

\[
U = \frac{1}{E} \left[ \frac{1}{Z_{\text{max}}} \int_0^{Z_{\text{max}}} \sigma(z) dz \right]^2 \tag{2}
\]

where E is the elastic modulus of the substrate.
RESULTS

All specimens exhibited concave deflection away from the treated surface indicating the development of compressive residual stresses and corresponding shape change induced by elastic recovery. As a result of successive layer removal with etching the curvature decreased, which was quantified using profilometry until the specimens returned to their stress free state. The variation of curvature with respect to the distance from the neutral axis for a representative specimen is shown in Figure 3(a). The corresponding subsurface residual stress distribution for the specimen is shown in Figure 3(b). For clarity, the surface residual stress ($\sigma_{r,s}$) and the depth of compressive residual stress ($Z_{\text{max}}$) are highlighted in this figure.

The influence of boundary conditions on the surface residual stress and depth of compressive residual stress are shown in Figure 4(a) and 4(b), respectively. The surface residual stresses measured in specimens treated under load control treatments showed a higher magnitude. For treatments conducted with 15% prestress, the magnitude of surface residual stress increased by 50% with load control. In contrast, there was no distinct influence of boundary condition on the depth of compressive residual stress.

The variation in stored elastic energy is plotted as a function of applied elastic prestress in Figure 5 for both boundary conditions used. Similar to the trend in surface residual stress, the load control treatments resulted in higher stored energy. At 15% prestress, the load control treatments resulted in a 100% increase in stored energy. However, the increase in stored energy reduced with the magnitude of applied prestress. In both loading configurations the stored energy increased with increasing prestress over the entire range of prestress applied.
DISCUSSION

The responses in Figure 4(a) suggest that the maximum residual stress increased with prestress up to approximately 60% of the materials yield strength. There were minimal changes thereafter. This suggests that there is a threshold elastic tensile prestress beyond which any increase in prestress will result in minimal changes. Previous studies indicated that saturation is seen around 50% for Ti6Al4V, spring steel and inconel 718 treated under load control flexure [8]. The current study indicates the same trend for displacement control flexure. Similarly, Osgood [2] reported that a 50-65% tensile prestrain was optimum in strain peening of coil springs. Therefore, the saturation is independent of the target material and the boundary conditions applied.

The load controlled boundary condition resulted in larger surface residual stress than that resulting from displacement
control and the effect of boundary conditions on the maximum compressive stress appears to be most important at lower levels of prestress (less than 50%). This behavior was expected since the load control boundary conditions maintained the specimens under a constant tensile surface stress despite continuous elastic recovery of the specimen during AWJ treatment. Once the treatment was completed, the release of this tensile prestress resulted in a superposition with the surface stress that was induced by the abrasive impingement and near-surface deformation. Treatments conducted under displacement control prestress resulted in far lower superposition of a surface stress due to elastic recovery. Under displacement control flexure the lowest level of prestress (15%) did not result in a superposition of residual stress after treatment. Instead, the continuous elastic recovery of the specimen during treatment caused a decrease in radius of curvature that approached the radius of curvature of the specimen in the original loaded state. As such, the displacement boundary condition inhibited unrestricted elastic recovery during the later stages of treatment and reduced the magnitude of tensile prestress during treatment. The magnitude of prestress constantly decays with elastic recovery and this perhaps the primary contributor to the lower level surface residual stress resulting from displacement control flexure. In fact, at lower levels of prestress one can potentially subject the surface to a compressive prestress after a period of treatment. The possible reversal of prestress into the compressive region also reduced the depth of compressive residual stress, which is evident from the response in Figure 4(b). The response in Figure 4(b) show that boundary conditions are not important on $Z_{max}$ except at the lowest level of prestress (15%).

Results presented in Figure 5 showed that the stored energy resulting from AWJ treatments increased with an increase in prestress. At levels of prestress less than 50% of the yield strength the boundary conditions were important to the magnitude of stored energy. These results suggest that there is potential for using AWJ technique to peen form materials and induce permanent shape changes. Furthermore, there may be further benefits to the residual stress distribution or stored energy achieved by treating components with prestress distribution resulting from uniaxial tension or a superposition of bending and tension. Future studies should be performed to evaluate these opportunities for optimizing the residual stress field in AWJP or alternative methods of surface treatment with prestress.

CONCLUSION

Surface treatments were conducted to evaluate the effect of boundary conditions on the residual stress field and stored energy resulting from AWJP of Ti6Al4V with prestress. Either load control or displacement control flexure was used to achieve a tensile elastic surface stress ranging from 0 to 75% of the yield strength of the targets. Treatments conducted with both boundary conditions resulted in an increase in the magnitude and depth of residual stress with increase in prestress. The load control boundary conditions resulted in up to 50% and 100% larger residual surface stress and stored energy than those resulting from displacement control conditions.

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REFERENCES


