ABSTRACT
Recent advances in abrasive waterjet (AWJ) technology have resulted in new processes for surface treatment that are capable of introducing compressive residual stresses with simultaneous changes in the surface texture. While the surface residual stress resulting from AWJ peening has been examined, the subsurface residual stress field resulting from this process has not been evaluated. In the present investigation, the subsurface residual stress distribution resulting from AWJ peening of Ti6Al4V and ASTM A228 steel were studied. Treatments were conducted with the targets subjected to an elastic prestress ranging from 0 to 75% of the substrate yield strength. The surface residual stress ranged from 680 to 1487 MPa for Ti6Al4V and 720 to 1554 MPa for ASTM A228 steel; the depth ranged from 265 to 370 µm for Ti6Al4V and 550 to 680 µm for ASTM A228 steel. Results showed that elastic prestress may be used to increase the surface residual stress in AWJ peened components by up to 100%.

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

INTRODUCTION
Fatigue failures are one of the most critical concerns in the design of engineering components. They result from cyclic stresses that are far less than the yield strength of the material. Also, fatigue is often regarded as a surface phenomenon as failures usually initiate from the surface in the form of cracks, rather than from within. The fatigue strength of engineering components is often improved by inducing a near-surface compressive residual stress [1] using a selected method of surface treatment. Shot peening and laser peening are widely used surface treatment processes in industry [2,3]. Recent advances in abrasive waterjet (AWJ) technology have resulted in new processes for surface treatment that are capable of modifying the residual stress and surface chemistry simultaneously [4]. One potential drawback of the AWJ process is that the residual stresses are often less than that achieved by competing processes. Recent studies conducted on the surface residual stress resulting from AWJ peening indicate that an elastic prestress can be used to increase the magnitude of surface residual stress [5]. However, the effect of elastic prestress on the subsurface residual stress field resulting from this process has not been examined. Therefore, the objective of this study was to evaluate the influence of elastic prestress on the residual stress distribution resulting from AWJ peening of selected metals.

MATERIALS AND METHODS
The materials used for this investigation are titanium alloy (Ti6Al4V) and spring steel (ASTM A228). The Ti6Al4V has an elastic modulus of 111 GPa and yield and ultimate tensile strength of 1016 MPa and 1080 MPa, respectively. The spring steel has an elastic modulus of 203 GPa and yield and ultimate
tensile strength of 1570 and 1620 MPa, respectively, according to results from a uniaxial tension test. Both materials were obtained in sheet form having a thickness of 1.6 mm. Specimens were prepared from both materials for surface treatment with dimensions of 275 x 18 x 1.6 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 [6]. The specimen was loaded during surface treatment in a dedicated fixture (Figure 1(b)) and subjected to an elastic prestress varying from 0 to 75% of its yield strength in increments of 15%. 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. The residual stress resulting from AWJ peening was estimated from the curvature of the specimens using the layer removal technique.

**Determination of Residual Stress**
The residual stress resulting from treatments was estimated from the curvature of the specimens. During treatment, the specimen undergoes continuous unrestrained elastic recovery due to the residual stresses. The process results in concave deflection away from the treated surface (Figure 2).

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Figure 1: Details of the surface treatment process.

Figure 2: Schematic of a treated surface (h = thickness, ρ = radius of curvature and σ_r = residual stress).
A surface profile of the treated surface was obtained using a profilometer and the radius of curvature (ρ) was determined by fitting a profile with the equation of a circle with radius ρ. The profile traverse length was chosen to be 45 mm based on an error analysis. The subsurface residual stress profile within the specimens was determined using the layer removal technique [7-9]. Material was removed incrementally from the treated surface and the resultant change in curvature was used to infer the residual stress distribution. The method described by Treuting [7] was used to calculate the residual stress as a function of depth (z) according to

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

(1)

where, E and ν are the Young’s modulus and the Poisson’s ratio of the material, respectively. Briefly, a layer of known thickness (t) is removed from the specimen whose surface is initially at a distance \(z_0\) from the neutral axis (Figure 3). After removal, a new surface with distance \(z_1\) from the neutral axis is obtained. The specimen’s curvature is determined before and after material removal using the profilometer and the measured curvature (\(\phi_x\)) is plotted against the distance from the neutral axis (z). A quadratic curve fit is used to obtain a mathematical relationship between the curvature and distance from the neutral axis. A suitable series of such evaluations with depth permit a quantification of the subsurface residual stress distribution according to Eqn (1).

\(\sigma_r(Surface)\) ranged from 680 to 1487 MPa for Ti6Al4V and 720 to 1554 MPa for the spring steel. The depth of compressive residual stress (Z) varied between 265 to 370 μm for the Ti6Al4V and 550 to 680 μm for the spring steel. The variation in surface residual stress and

**RESULTS**

All specimens exhibited concave deflection away from the treated surface indicating the development of compressive residual stresses. The variation of curvature with respect to the distance from the neutral axis and subsurface residual stress distribution for a representative specimen is shown in Figure 4(a) and Figure 4(b), respectively. The layer removal technique was found to be very sensitive to the curve fitting technique used. Lira et al [8] reported a similar trend and it was shown that a second order polynomial provided the best estimates.
depth of compressive residual stress is plotted as a function of applied elastic prestress in Figure 5(a) and 5(b), respectively. Both the magnitude of surface stress and depth of the compressive stress field increased with increasing prestress.

![Graph showing surface residual stress and depth of compressive residual stress as functions of prestress.](image)

**Figure 5:** Effect of prestress on the subsurface residual stress distribution.

The subsurface residual stress distribution resulting from AWJ peening (Figure 5) indicates that the maximum residual stress occurs at the surface. This is advantageous for enhancing fatigue life and it is different from the distribution resulting from shot peening, where the maximum residual stress generally occurs at a particular depth below the treated surface. The difference is expected to be due to the material removal that takes place during AWJ peening and the lower degree of subsurface plastic distribution.

The magnitude of surface residual stress increased by 100% with the application of 75% elastic prestress for both the materials; the depth of compressive residual stress increased by 50%. The increase in residual stress with elastic prestress agrees with previous studies conducted in AWJ peening [5] and shot peening [11,12]. These preliminary results suggest that the residual stress does not change significantly with an increase in prestress beyond 60%. Similarly, Osgood [13], reported that a 50-65% tensile prestrain was optimum in strain peening of coil springs. Nevertheless, as evident in Figure 5(b), the depth of compressive stress shows a constant increase with an increase in prestress. At 75% prestress the spring steel showed a reduction in the depth of compressive stress when compared to the general trend. This difference is attributed to near surface yielding. Future work will address this issue.

**CONCLUSIONS**

AWJ peening was conducted on Ti6Al4V and ASTM A228 steel with elastic prestress varying from 0 to 75%. The resulting residual stress distribution was determined by layer removal method. Based on the experimental results it was found that application of elastic prestress increases the surface residual stress and the depth of residual stress. It appears that elastic prestress can be used to increase the magnitude of the surface residual stress and the depth in AWJ peening of metal components.

**FUTURE WORK**

Further work is required to explore the influence of other prestress distributions on the magnitude of surface residual stress and the subsurface distribution. Also, further work is needed to understand the parametric effect of elastic prestress in combination with other parameters that control this process.

**REFERENCES**


the International Conference on Advances in Materials and Processing Technologies, Las Vegas, Paper No. NTI2 355.


