A preliminary study was conducted to evaluate the parametric dependence of the residual stress distributions in bone that result from an abrasive air-jet surface treatment. Specifically, the influence of particle size and shape used in the treatment on the residual stress, propensity of embedding particles and material removal were studied. Rectangular beams of cortical bone were prepared from bovine femurs and treated with aluminum oxide and glass particles with different treatment angles. Residual stresses within the bone were quantified in terms of the radius of curvature of the bone specimens measured before and after the treatments, as well as a function of time to quantify decay in the stress. The sub-surface distribution was also examined using the layer removal technique. Results showed that the particle size and shape could be used to control the amount of material removal and the magnitude of residual stress within the treated surfaces. An increase in size of the glass particles resulted in an increase in the residual stress and a decrease in material removed during the treatment. The magnitude of residual stress ranged from 22 MPa to nearly 44 MPa through modulation of the particle qualities (size and shape). A microscopic examination of the treated surfaces suggests that the residual stresses resulted primarily from near-surface deformation.

**Keywords:** Residual Stress, Cortical Bone, Stress Distribution

**INTRODUCTION**

The stress that remains within a deformable body after all external forces have been removed is regarded as "residual stress" and it can be either compressive or tensile in nature. In engineering materials a compressive residual stress has been found to be effective in retarding the initiation and propagation of surface cracks, which often facilitate component failures by fatigue [1-4]. Living tissues respond to mechanical stress by undergoing growth and potential changes in volume [5]. X-ray diffraction measurements conducted on rabbit tibiofibula indicated that a residual stress of 0.1 MPa is present in the bone in its natural state [6]. Tanaka et al. [7] reported a residual stress of 2 MPa in bovine coccygeal vertebrae in its natural state. Surprisingly, no study has examined on the opportunity for introducing residual stresses in bone or other hard tissues using a surface treatment with the objective of accelerating the healing process or enhancing bone growth.

Most commercial techniques for introducing stresses within engineering materials are not appropriate for introducing stresses within biological targets. The air-jet technique is a newly conceived process that can
potentially introduce residual stress in biological tissues. Preliminary studies conducted using this approach showed that compressive residual stress as large as 22 MPa can be introduced within cortical bone [8]. However, the technique currently lacks fundamental understanding of the process parameters and their interactions. Therefore, the objective of this investigation was to conduct a parametric analysis by using a design of experiments (DOE) to explore the effect of process parameters on the residual stress, propensity of embedding particles and rate of material removal.

MATERIALS AND METHODS

A parametric study was conducted with 96 rectangular beams of cortical bone, which were prepared from mid-diaphysial region of bovine femurs. The specimens were prepared according to the schematic diagram in Figure 1 with dimensions of 35 mm x 3 mm x 1 mm and treated on a selected side using the abrasive air-jet. After sectioning, the specimens were kept hydrated (HBSS) at 4°C to prevent dehydration and to maintain the mineral content. Sectioning of the specimens was performed within 5 days of obtaining the bone and the time of treatment, as well as the characterization of residual stress was performed shortly thereafter.

![Figure 1: Schematic diagram showing specimens obtained from the mid-diaphysial sections of bovine bone. The primary axis of the specimens is parallel to the femoral canal.](image)

Equipment and Procedures

The surface treatments were carried out using a Comco Inc., MicroBlaster. A schematic diagram of the treatment process is shown in Figure 2. A modified 5 factor 2 level Plackett-Burman screening design of experiments (DOE) was conducted with 3 repetitions for each run. Process parameters chosen for the DOE and their appropriate low and high levels included the jet pressure (100, 500 kPa), the effective particle diameter (10, 300 µm), the traverse speed (0.1, 0.5 m/s), the nozzle angle (30°, 90°) and abrasive particle shape (spherical, crushed). The particle flow rate and standoff distance were held constant at the level of (0.1 g/sec) and (0.025m) for all preliminary treatments to get a uniform treated surface in each run. The high and low levels were determined by the equipment capabilities and the abrasive particle type. All treatments were performed using either crushed or spherical Aluminum oxide and glass particles. The specimens were loaded into the abrasive jet enclosure and treated using a single pass along the primary length. Owing to the relatively large standoff distance, the treatment was essentially uniform over the exposed surface area. The residual stress obtained from this treatment was measured from the resulting change in curvature.

![Figure 2: Details of the surface treatment process.](image)

Determination of Residual Stress

Residual stress in the surface of the beam was determined from the change in curvature resulting from elastic recovery. Surface profiles of the untreated side were obtained with a Hommel T8000 stylus surface profilometer using a traverse length of 15 mm. The radius of curvature was determined by fitting the profile with the equation of a circle with known radius (r0) (Figure 3).

The curved beam was assumed to have a constant radius of curvature over the entire length due to uniform surface treatment. Also, the beam curvature was assumed to result from a uniform moment distributed over the length of the beam according to

\[
\frac{1}{r_0} = -\frac{M_s}{EI}
\]

where \(M_s\), \(I\) and \(E\) are the restoring moment, moment of inertia and elastic modulus (19.8 GPa [9]), respectively.
To determine the residual surface stress it was necessary to determine the moment distribution necessary to restore the beam from the state of curvature to that present before treatment. Using the restoring moment theory [10-13], the longitudinal residual stress ($\sigma$) at the surface of the beam is given by

$$\sigma(\theta) = \frac{4M_0}{wb^2} \left(1 - \frac{r}{\bar{r}}\right) \left(\frac{\bar{r}}{r}\right) \left[\log r + \log \bar{r} - \log \frac{\bar{r}}{r}\right]$$

(2)

where \(\bar{r} = \frac{r}{b}\), and \(\bar{a} = \frac{a}{b}\)

(3)

and where the radius of curvature and the quantities \(a\), \(b\) and \(w\) are defined in Figure 3.

![Figure 3: Schematic diagram of beam deflection and pertinent variables.](image)

Layer Removal Technique

The layer removal technique was performed on 5 specimens that were treated using conditions that promoted the largest surface residual stress. Bone was removed from the treated surface to a desired depth using a 34% by weight phosphoric acid (Dentsply-CAULK Tooth Conditioner Gel). Before etching and treatment, the side opposite to that intended for treatment was covered using a very thin (≈10 µm) layer of nail polish to protect it from etching. The phosphoric acid was applied approximately 10 minutes in each increment, resulting in approximately 20 µm of material removed. Before and after etching the radius of curvature was measured to determine the difference in curvature using the profilometer as previously described. The surface residual stress after each increment of removal was calculated using the restoring moment approach described by Eqns. 1 to 3.

Determination of surface chemistry

The treated surfaces were examined using a JEOL JSM-5600 scanning electron microscope (SEM) equipped with an Oxford Link ISIS system for conducting energy dispersive X-ray analysis (EDXA). An accelerating voltage of 20 kV was used for all measurements. The EDXA enabled identification of the surface chemistry and was implemented to evaluate the concentration of embedded particles (i.e., the fraction of treated surface area covered by abrasive particles) on the treated surface.

RESULTS

All 96 specimens exhibited concave deflection away from the treated surface, indicating the presence of compressive residual stress. The surface residual stress ($\sigma$) and rate of material removal varied from 10 MPa to 44 MPa and 0.01 mm$^3$/s to 0.26 mm$^3$/s respectively over the range in treatment conditions. Results of the DOE indicated that the air-jet pressure and particle type were the main effects on residual stress. The air-jet pressure and nozzle angle were the main effects for the rate of material removal. The relative contributions of the variables and interaction effects are shown in Figure 4. Overall, the air-jet pressure was the primary contributor to the response accounting for 65% of the residual stress and 70% of the rate of material removed.

![Figure 4: Scree plot showing relative contributions of treatment effects on total variation of residual stress and rate of material removal (P = Pressure, A = Nozzle angle, B = Particle Type, D = Particle Size, T = Traverse Speed)](image)
The reduction in residual stress with material removal for a selected specimen is shown in Figure 5. The layer removal technique showed that the residual stress decreased with depth below the surface and that the depth of residual stress extended approximately 150 µm beneath the surface.

Five specimens were maintained in the HBSS solution over a period of 30 days after treatment to observe the decrease in surface residual stress in the bone (Figure 6). There was a decrease of approximately 25% over a period of 8 days after the treatment. Within the next 5 days there was over a 50% reduction, followed by a period of stabilization. After 5 days stabilization there was a decrease again until the specimen recovered to nearly a stress free state.

Results of the SEM and EDX analyses showed that the surface underwent near surface deformation due to abrasive impact and that there were particles occasionally embedded within the treated surfaces. Representative, micrographs of the surface treated with spherical particles (Figure 7 (a)) and crushed particles (Figure 7 (b)) are presented for review. Both the surfaces were treated with a pressure of 500 kPa, traverse speed of 100mm/s, nozzle angle of 90°, particle size of 300µm. These micrographs show a large difference in the level of plastic deformation and emphasize the influence of particle shape on the surface characteristics.

![Image](image1.png)

**Figure 5:** Sub-surface residual stress distribution. The specimen was treated with P = 200 kPa, A = 90°, B = Crushed, D = 25 µm, T = 400 mm/s, S (standoff distance) = 20mm

![Image](image2.png)

**Figure 6:** Decay in residual stress over a 30 day time period

![Image](image3.png)

*a) Spherical particles*
b) Crushed particles

Figure 7: Representative micrographs of the treated bone surfaces.

DISCUSSION

Results from the experimental evaluation distinguished that the air-jet surface treatment of bone resulted in the development of a near-surface compressive residual stress. An analysis of variance performed with the residual stress indicated that the jet pressure is the primary contributor and that the magnitude of surface stress increased with pressure. This is expected since the jet pressure influences the kinetic energy of the particle; a higher kinetic energy results in a larger degree of surface deformation. Similarly, the rate of material removed is also influenced primarily by the air-jet pressure. Similar studies conducted on Abrasive waterjet peening [14] and shot peening [15] have shown that pressure was a main factor in the residual stress resulting from those treatments as well. One interesting aspect of the treatments was that the spherical particles resulted in a very low degree of material removal when compared to the crushed particles. Crushed particles have a high effective rake angle (less negative) that promotes material removal, particularly for the oblique (30°) angle of impingement. Overall the residual stress decreased with the reduction in angle of impingement, whereas the rate of material removed increased.

Results of the SEM evaluation provided some insight towards the mechanisms responsible for the formation of residual stress. The degree of near-surface plastic deformation is highly influenced by the shape of the abrasive particles impinging the surface. As evident from Figure 7(a), the spherical particles created acute craters on the surface, whereas the surrounding areas were far smoother. This indicated that the particles impinged the surface and bounced off, leaving regions that are plastically deformed. On the other hand, the crushed particles (Figure 7(b)) resulted in a more uniform and rough surface, which would be expected from the material removal. There were no signs of particles embedded on the surface as seen in a previous study conducted using aluminum oxide abrasives [8]. This suggests that the particle size and other physical characteristics influence the ability for embedding particles during treatment.

One potential contribution to changes in the radius of curvature of the bone specimens was dehydration caused by forced convection of the air-jet. It was expected that deflection of the beams resulted from impingement of particles and near surface deformation as well as effects of air on the collagen fibrils. To address this concern, a separate set of treatments was performed with air only (i.e. no particles) and then the change in radius of curvature of the beams was measured. These treatments caused curvature of the beams towards the jet, the opposite of that which resulted from treatments with particles. The separate pilot experiment showed that the “air-only” treatments resulted in a residual stress of 0.4-0.6 MPa depending on the treatment pressure. Therefore, the total residual stress resulting from the air-jet treatment was the net sum of tension induced by the air and compression resulting from the deformation. However, the component associated with dehydration is nearly a factor of magnitude smaller and was neglected.

One interesting aspect of the residual stress was that relaxation took place after treatment (Figure 6). Relaxation either resulted from the time dependent response of the constituents or from a potential loss in mineral within the highly stressed region. Demineralization could be possible as a result of pH changes in the HBSS solution. But separate experiment performed on 5 specimens showed that the pH level (7.1-7.5) taken from the HBSS supplier did not contribute to the time dependent changes over the 30 day time period. One possible reason for the decrease could be associated with stress relaxation in collagen fibrils; this mechanism needs to be examined in more detail. A recent study [16] showed that stress relaxation due to demineralization for compact bone showed similar behavior, but the rate of relaxation was far greater than that observed in the present study.

To the author’s knowledge the present study represents the first parametric study of effects from treatment parameters on the residual stress introduced in bone. The study represents an important first step in identifying new and interesting technologies for the surgical environment that may provide supplemental methods of treating hard tissues with potential for fostering more expedient recovery.

CONCLUSIONS
An experimental investigation was conducted to study the influence of treatment parameters on the introduction of residual stress in using an abrasive air-jet surface treatment. According to results of the study, the following conclusions were drawn:

1. It is possible to impart compressive residual stress within the surface of cortical bone using air-jet surface treatment. The maximum surface residual stress identified was approximately 44 MPa over the range in treatment parameters used.

2. Air-jet pressure and particle type were main effects on the residual stress induced in the bone. However, for the rate of material removal, the air-jet pressure and nozzle angle were the main effects.

3. Using the layer removal techniques it was found that the residual stress decreased through the thickness from and extended to a depth of approximately 150µm.

4. The surface residual stress underwent a decrease in magnitude with time. There was a 25% decrease after approximately 10 days and a complete relaxation of the surface stress after approximately 25 days from the time of treatment.

ACKNOWLEDGEMENTS
The author gratefully acknowledge that support for the investigation was received from Maryland Technology Development Corporation (TEDCO).

REFERENCES