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Proceedings of IMECE2007
2007 ASME International Mechanical Engineering Congress and Exposition
November 11-15, 2007, Seattle, Washington, USA

IMECE2007-43281

INDUCING RESIDUAL STRESS IN BONE USING ABRASIVE AIR-JET SURFACE TREATMENT

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ABSTRACT

Based on past research, the growth and repair of bone is a function of physical activity (i.e. stresses) and bone chemistry. As such, the rate of recovery of an individual that has undergone total joint arthroplasty could be influenced by the introduction of changes in bone chemistry and “apparent” stress state in the bone that results from the surgical procedures and/or treatments. This preliminary study explored the opportunity for introducing residual stresses in hard tissues using an air-jet surface treatment. Cortical bone was obtained from bovine femurs and treated with an abrasive jet process. The radius of curvature of the bone specimens was estimated before and after treatment and used in estimating the magnitude of surface residual stress. An SEM analysis was also performed to examine structural changes in the bone caused by the surface treatment. Results showed that it is possible to impart residual stress within bone using an air-jet surface treatment. The magnitude of surface residual stress was 16 ± 0.8 MPa. Residual stresses appeared to result from a combination of near-surface deformation and embedded particles.

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

INTRODUCTION

Residual stress is considered a state of stress that exists within a structure or component without application of an external load. In metals, compressive residual stress has been used for improving the fatigue life and resistance to stress corrosion cracking [1,2]. In biological hard tissues like bone, the growth and repair of the tissue is a function of physical activity (i.e., stress) and bone chemistry [3-5]. The rate of recovery of an individual that has undergone total joint arthroplasty could be influenced by the introduction of changes in bone chemistry and apparent stress state that has resulted from surgery or a specific treatment. Surprisingly, no study has been reported on the opportunity for introducing residual stresses in bone or other hard tissues using a surface treatment. Most commercial techniques for introducing stresses within engineering components are not appropriate for introducing stresses within biological targets. Therefore, the objective of this investigation was to explore the potential for introducing residual stresses within cortical bone using an air-jet surface treatment.

MATERIALS AND METHODS

Twenty specimens were obtained at various locations with reference to the femoral canal of a bovine femur (Figure 1) having a young’s modulus of 19.8 ± 1.6 GPa [6]. The specimens were obtained in the form of rectangular beams having dimensions of 35 mm x 3 mm x 1mm and treated on a selected side using an abrasive air-jet. The specimens were dehydrated in air for 24 hours before subjecting them to the surface treatment. Hydration changes occurring during treatment and subsequent analysis complicated the evaluation of residual stress and prevented treatment of fully hydrated samples.

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. Treatments were carried out using Aluminum oxide abrasives with machine parameters fixed at a jet pressure of 200 kPa, effective particle diameter of 25 μm, stand off distance of 0.025 m and a traverse speed of 0.4 m/min. 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.

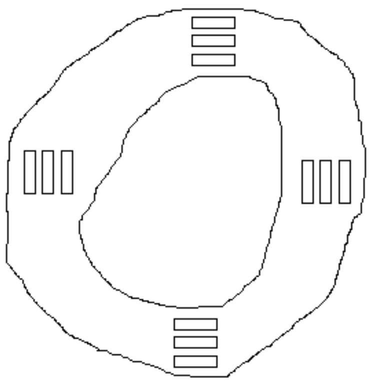


Figure 1: Orientation of specimens obtained from the mid-diaphysial sections of bovine bone.

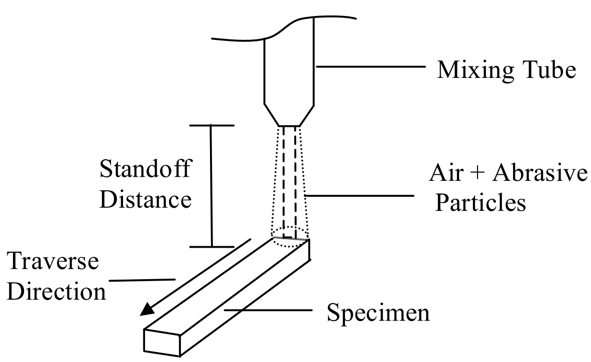


Figure 2: Details of the surface treatment process.

Determination of residual stress
Residual stress in the surface of the beams 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 (ρ) was determined by fitting the profile with the equation of a circle with radius ρ (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 be a result of a uniform moment distributed over the length of the beam. Using the moment relation for beam curvature, the longitudinal residual stress (σ_r) at the surface of the beam is given by

$$\sigma_r = \frac{Et}{2\rho} \tag{1}$$

where E is the Young's modulus, t is the beam thickness and ρ is the radius of curvature.

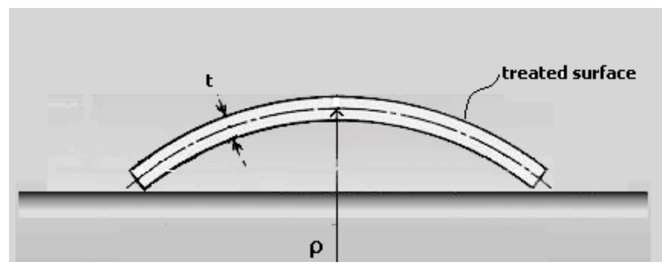
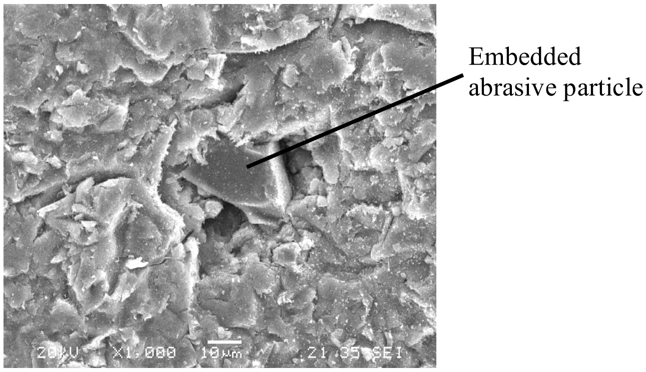


Figure 3: Schematic diagram of beam deflection and pertinent variables.

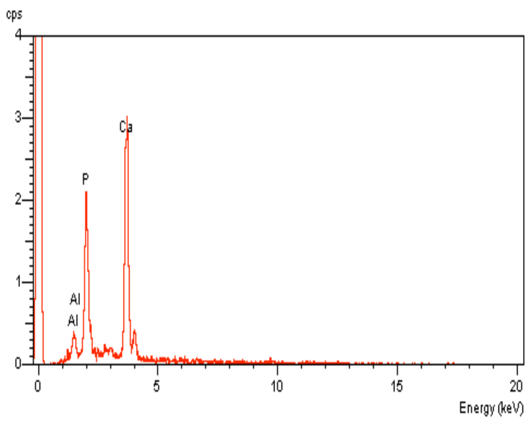
Determination of surface chemistry
The treated surfaces were examined using a JEOL JSM-5600 scanning electron microscope (SEM) equipped with an Oxford Link ISIS system for conducting energy dispersive X-ray analysis (EDXA). An accelerating voltage of 20 kV was used for all measurements. The EDXA enabled 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 twenty specimens exhibited concave deflection away from the treated surface, indicating the presence of compressive residual stresses and the consequence of elastic recovery. The average surface residual stress (σ_r) for the three samples was found to be 16 ± 0.8 MPa. Results of the SEM and EDXA analyses showed that the surface underwent near surface deformation due to abrasive impact and that there were particles embedded within the treated surface. A micrograph of an embedded particle and the surrounding treated surface is shown in Figure 4(a) and the corresponding energy spectrum obtained from EDXA is shown in Figure 4(b). An assessment of the area fraction of particles showed that Aluminum oxide particles covered 6% of the treated surface. While Aluminum oxide particles would be considered a contamination of the bone, their presence indicates that the air jet process could potentially be conducted with alternative particle formulations that may be more favorable for stimulating bone growth (e.g. apatitic formulations).



a) A micrograph of the treated surface



b) EDXA chemical spectrum

Figure 4: Analysis of a treated surface.

DISCUSSION

Results from the experimental evaluation distinguished that that the air-jet surface treatment of bone resulted in the development of a near-surface compressive residual stress. The magnitude of the estimated surface residual stress is relatively low, nearly only 20% of the effective yield strength of cortical one. It is important to emphasize that the estimates represent a first order approximation and assumed that the stress is linearly distributed from the neutral axis. A more accurate estimate of the surface stress could be obtained using the layer removal technique or x-ray diffraction, both of which would be subject to additional complications. Future work is planned to examine the parametric treatment space in more detail and to adopt a more rigorous approach in quantifying both the surface and sub-surface residual stress distribution.

Results of the SEM evaluation provided some insight towards the mechanisms responsible for the formation of residual stress. Unlike metals, bone does not undergo near surface "plastic" deformation due its unique structure and behavior of the constituents (apatite mineral crystallites and collagen fibril network). However, as evident from Figure 4(a), there was a component of inelastic deformation resulting from abrasive impact, which is undoubtedly comprised of the redistribution of near-surface mineral crystals amongst the surrounding organic matrix. The SEM analysis also revealed that abrasive particles were embedded in the surface, which also potentially contributed to the development of residual stress due to the densification. Additional work is required to obtain a more thorough understanding of these mechanisms and their relative contribution.

To the author's knowledge the present study represents the first exploration of residual stresses in bone resulting from a surface treatment. While important, there are a number of obvious limitations to the study that are worth highlighting. The low number of samples included in the evaluation, treatment of samples in the dehydrated state, and simple approach for estimating the residual stress are perhaps the most obvious limitations. Also, the treatments considered only one set of treatment parameters and there was no attempt to address the potential for improving the choice of parameters for increasing the level or stress imparted. Despite these concerns, 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 study was conducted to identify if residual stresses could be induced in cortical bone through an abrasive air-jet surface treatment. Results of the investigation showed that it is possible to impart residual stress within the treated surface and that the residual stress results from a combination of near-surface deformation and embedded particles. Residual stresses in the surface reached nearly 20 MPa.

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