Experiments and simulations of double side shot peened Aluminum

Siavash Ghanbari[a], Daniel J. Chadwick[b], Michael D. Sangid,[b] David F. Bahr[a],
[a] School of Materials Engineering, Purdue University, USA, sghanbar@purdue.edu, dfbahr@purdue.edu
[b] School of Aeronautics & Astronautics, Purdue University, USA, dchadwi@purdue.edu, msangid@purdue.edu

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Introduction

Shot peening is a well-established and cost effective method to induce compressive residual stresses in metallic components using a localized cold working process. Shot peening increases fatigue life in many applications via cold working a surface using a stochastic delivery of high-velocity relatively spherical media (shot), which leads to plastic deformation in the near surface region of the part. The important parameters in the shot peening process include properties of the shot itself (i.e. the shot mass, hardness and size); processing parameters such as the velocity of the shot and the angle at which the shot impacts the surface; and finally, the properties of the material being processed, such as the sample hardness (or yield strength), strain hardening behavior, and the friction between the shot and sample [1]. Many researchers have carried out numerical and experimental studies for predicting or measuring residual stresses distribution as well as the effect of the shot peening processing parameters on the resulting stress distribution [2].

Nanoindentation, also referred to as instrumented indentation since it measures load and indentation penetration depth during the indentation, can be used to measure the mechanical properties of bulk materials in small scales. The metal substrate after shot peening is affected by the residual stresses which will change yielding and plastic straining [3]. Nanoindentation parameters such as hardness [4], loading and unloading behavior and pile-up area, can be affected by residual stresses. Some researchers showed residual stresses does not always influence the hardness [5]. A method developed by Suresh et al analyzed the entire instrumented loading curve in order to estimate the residual stresses by nanoindentation method. In this method, suitable for obtaining equi-biaxial residual stresses, both stress-free and stressed samples need to be compared with each other. Lee et al suggested a new method to obtain the equi-biaxial residual stresses by using stress relaxation with the shear plastic deformation [6].

Objectives

The goals of this work were to compare experimentally measured residual stresses using a novel nanoindentation method in shot peened thin plate Al7050-T451 and compare these measurements to predictions made using dynamic finite element method (FEM) simulations. In addition to residual stresses, the indentation technique allows for localized mechanical properties before and after shot peening to be quantified. The numerical method prediction allows us to predict the effects of future modifications of the shot peening parameters such as impact velocity, ball diameter and impact angle to obtain required residual stress profiles.

Methodology

The fundamental objective of nanoindentation experiment is to obtain hardness and elastic modulus from load and unloading curves. Usually, in load-depth curves Fig. 1, the depth of the penetration is reported from zero to maximum number, then a load is returned from maximum to the zero. After unloading, the materials try to recover their original shape, but some small parts can be recovered because of the plastic deformation. The profile of nanoindentation is shown in Fig. 1. The Oliver-Pharr method [7] is developed to measure hardness and modulus from the load depth-curves. If one knows the load, P, and depth , h, and has previously calibrated the tip so that A_c is the contact area related to a given depth, S is the stiffness at the initial unloading, P_{max}, is the maximum load and β is a constant which is related to the geometry of the indenter (for example for Berkovich tip β =1.034), then it is possible to determine the reduced modulus (Er) and hardness (H), by

$$H=\frac{F_{max}}{A_c} \tag{1}$$

$$E_r=\frac{S\sqrt{\pi}}{2\beta\sqrt{A_c}} \tag{2}$$

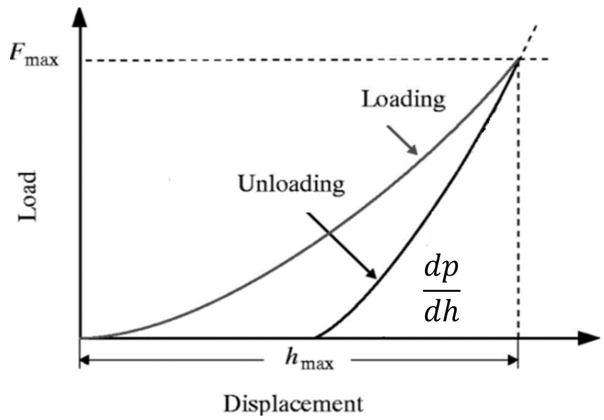

Figure 1. Schematic of loading and unloading curves, nanoindentation method.

Since modulus is an intrinsic property of a material, therefore it must be constant. So, any error in modulus measurements results from the pile-up area around the indentation. By calculating the corrected contact area, the hardness and elastic modulus are independent of the residual stresses [8]; since pile up can be difficult to determine for each indentation one convenient method is to use the constant modulus assumption and related the unloading stiffness to the maximum load; in this manner, the true hardness is found from

$$\frac{4}{\pi}\frac{P_{max}}{S^2}=\frac{H}{E_{eff}^2} \quad . \tag{3}$$

However, residual stresses can change the load-depth curves. By assuming the same indent depth, the loading curve for compressive residual stresses is "higher" than a stress-free sample. Also, oppositely the load-depth curve is lower for tensile residual stresses in comparison with free stress sample [9]. Figure 2 schematically shows loading curves for compressive and tensile residual stresses. A recent review paper covers this procedure in detail [10], calibration to materials with either an applied [9] or residual stress is needed to determine the relative "offset" in the load-depth curve, but once determined the system can provide relative differences in stresses with a fine spatial resolution. It is also possible to verify using FEM simulations of indentation with imposed biaxial stresses.

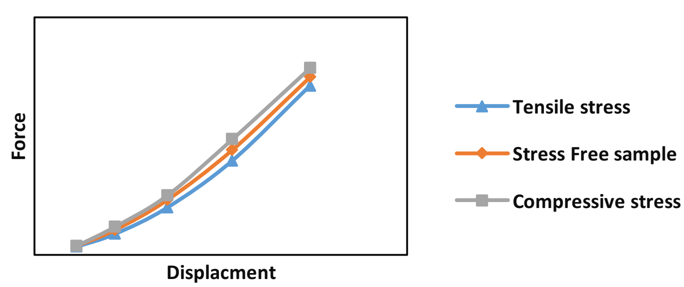

Figure 2. Schematic loading curves for tensile and compressive residual stresses compare with stress free sample.

The simulation of the shot peening process used a rigid body as an impact ball and aluminum 7050 for the substrate. ABAQUS/Explicit is used for finite element modeling. In this study a Johnson-Cook model was used to describe the deformation of the aluminum substrate. The target material was modeled as a cube 300 μm×300 μm and a depth of 1600 μm. The cube is modeled with C3D8R hexagonal elements. The shot diameter was set to 150 μm. In this simulation, we assigned rigid surface model with zirconia mass inertia.Shot peening parameters such as impact angle were between 20° up to 90° and impact velocity was set to a range of 50 m/s to 70 m/s. For doing the double sides shot peening multiple impact simulations two steps are defined. The first step's results are then transferred to the second step.

This paper has a partner paper in the current proceedings, *"Mechanism Of Shot Peening Enhancement For The Fatigue Performance Of AL7050"* by Chadwick et al. Double sided shot peening was performed by Progressive Surface (Grand Rapids MI), and full details are described in the partner paper in this volume. Nanoindentation measurements were carried out with a Hysitron TI 950 system and a Berkovich tip.

Results and analysis

Nanoindentation was carried out on the double side shot peened sample (Fig. 3). There were variations in pile up around the indentation (see inset in Fig. 3), and so rather than try to determine each indents pile up, the resulting P/S^2 method was used to demonstrate the hardness profile (Fig. 4).

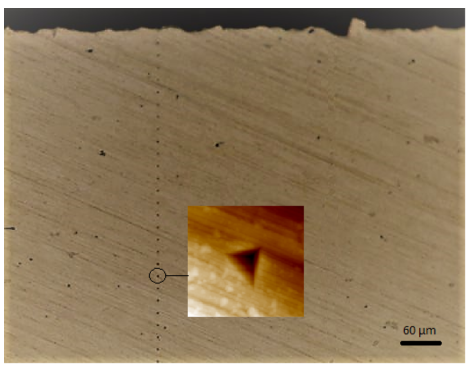

Figure 3. Nanoindentation pattern in aluminum 7050.

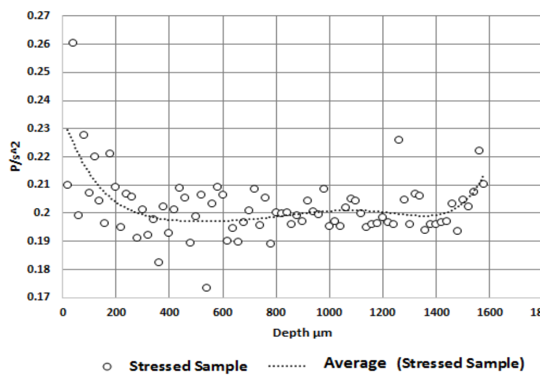

Figure 4. The variation of the maximum applied force over square of stiffness obtained from nanoindentation load-depth curve.

The FEM simulations were carried out to identify the residual stress in the samples after peening. A variety of impact conditions were modelled (various angles and velocities). A typical simulation of the residual stress profile, in this case after altering the impact angle from 90° to 45°, is shown in Fig.5, and a sample with double side shot peening is shown in Fig.6.

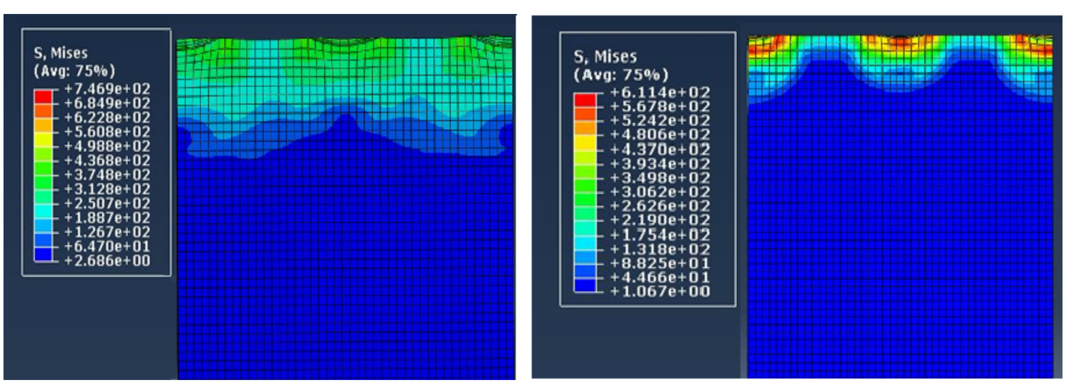

Figure 5. Residual stress profile simulations for impact angles of 90 (left) and 45 degree (right).

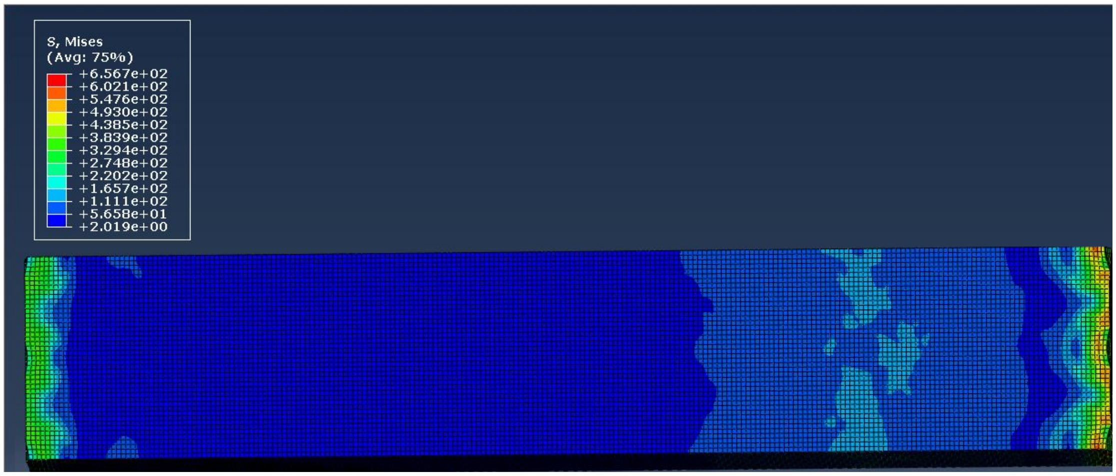

Figure 6. Double sided shot peening simulation of 1.6 mm thick Al 7050 alloy.

The indentation experiments lead to load-depth curves that follow the expectations of Fig. 2. Figure 7 shows experimental indentations in the cross section of the sample, where a compressive stress occurs, and simulations of the same indents at equivalent positions of the double sided shot peened sample (Fig. 6).

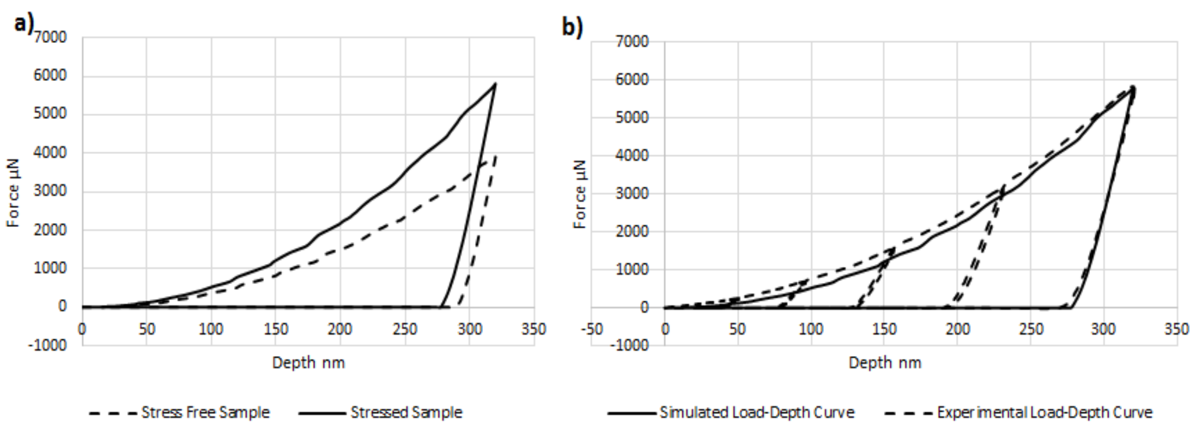

Figure 7. Load- depth curve obtained by a) finite element simulation and b) comparing nanoindentation and finite element modeling.

The residual stress profiles of the experimental measurements and simulation data are compared in Fig. 8. The experimental indentation results do show point-to-point variation (which is influenced by the polycrystalline nature of the samples), and so a 6-point smoothing was performed. As is shown in Fig. 8, the sample exhibits compressive stresses on the outside surface (with the corresponding tensile stress in the center as needed to balance stresses in the part). However, the crucial feature to note is that there is a residual stress asymmetry. This appeared in both the experimental measurements and the simulation. This increased compressive stress on one side of the sample is indicative of the double side shot peening procedure. The simulation showed that a stress wave does propagate through the sample and this leads to a slightly higher residual stress on the second peening process, and a slightly deeper region of compressive residual stress. X-ray diffraction analysis of both sides verified that there was a stress asymmetry between the sides. The XRD technique was used to measure the crystal lattice strain, with the resulting corresponding compressive stresses of 195 and 246 MPa on each side. Because the x-rays can penetrate a small skin on the surface, (on the order of 10 μm), comparing nanoindentation and x-ray results is challenging. The nanoindentation test requires an elastic-plastic response, but when the indenter is close to the surface edge, the plastic zone area is influenced by the free surface. Atar showed there is a difference between X-ray method and the Suresh model to determine residual stresses, where the indentation measurement can be us to three times higher than the x-ray method [11]. The similarity of the XRD and simulation run in this current work provides us with promising evidence that further refinement of the indentation method, coupled with accurate modelling, can in the future assess stress profiles in a wide range of materials.

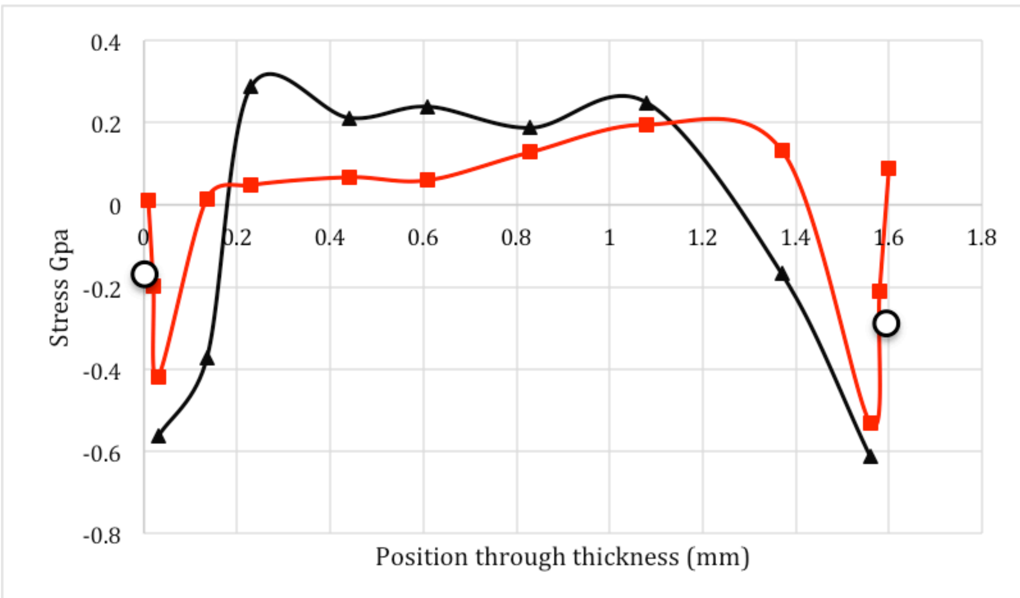

Figure 8. Residual stress profile comparing experimental measurements using indentation (triangles) and predicting by modelling (squares). A residual stress asymmetry is observed in this thin section 7050 Al alloy. X-ray diffraction measurements of the surface stresses are shown with open circles.

Conclusions

Experiments and simulation results showed residual stresses close to the edges of both sides of a double sided shot peened Al plate (1.6 mm thick) exhibit maximum compressive stresses and the middle of the sample is the tensile residual stresses. The maximum compressive residual stresses in the both sides were located approximately at the same distances from the edge, around 80 μm from the edges, but the total depth of compressive stress was slightly deeper on the second peened side. Also, nanoindentation results showed the hardness increases after peening. Moreover, an increased hardness in the shot peened sample was not uniform, hardness in the both side close to the peened surface was higher than the middle of the sample. Double side shot peening showed maximum compressive residual stresses on one side is higher than the other side due to the thin wall structure and work hardening phenomenon after the first step of shot peening for one side. After the first step shot peening because of the thin wall structure all entire depth was influenced by residual stresses, because of that during the second shot peening process, residual stress on the opposite side increases. Future work is needed to refine the indentation method for optimizing the ability to quantify the residual stress in shot peened samples.

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