A Three-dimensional Single and Multiple Shot Simulation of Shot Peening for Steel, Aluminum and Titanium Alloys

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Abstract

Three-dimensional model of single and multiple shot is developed for shot peening. Shot peening is analyzed with steel shot for three different materials, Steel, Al-7075 and Ti-6Al-4V. The diameter and velocity of shot were varied to evaluate the shot peening behavior. LS Dyna was employed to carry out the numerical simulation of shot peening process. The study examined the induced residual stresses and plastic strains produced during shot peening. The numerical results showed reasonable agreement with the existing theoretical model of shot peening. The investigation showed that velocity of shot dominates the diameter of shot.

Keywords: Shot Peening, Finite Element, Residual Stresses, Multiple Shots

Introduction

Shot Peening is widely used in the aerospace industry for parts that are subjected to high tensile stresses during their product life. These high tensile stresses make these parts prone to failure due to fatigue. Shot peening develops compressive residual stresses beneath the surface of these parts to relieve high tensile stresses in the future. In shot peening the outer surface is bombarded with small multiple spherical shots made of materials such as steel, glass or ceramic beads at relatively high velocity (40-70 m/s). This causes local plastic deformation on the top layers and elastic deformation in the sub surfaces. The velocity of shots, the diameter of shots, and the distance from it they are released (called as stand-off distance) are among the main parameters that govern quality of shot peening.

The modeling and simulation of shot peening has received attention by several researchers. Meguid et al. [1] have developed three-dimensional finite element shot peening model using Ansys program. The single and twin spherical indentions were analyzed using rigid spherical shots and metallic targets. The effect of shot velocity, size and shape, and target characteristics was examined on the residual stress distribution in the target. It was found that effects of shot peening parameters have more effect on residual stresses than the strain-hardening rate of the target. Majzoobi et. al [3] have examined multiple shot impacts and effect of shot velocity on the residual stress profile using LS-Dyna code. Their results indicated that the multiplicity of shots and impact velocity highly influence the stress distribution during the shot peening process. In the paper the primary effect of the parameters were investigated through single shot simulation with three different materials, Steel, Aluminum Alloy (Al-7075), and Titanium alloy (Ti-6Al-4V). Two types of models on multiple shot peening are studied. The first model examines the relationships between intensity, coverage, residual stresses and the number of shots. In the second model the manual shot peening of multiple shots was simulated from the experimental data.

Finite Element Model

Shot peening simulations were performed using the finite element code for non-linear dynamic of structures LS-Dyna. The target was modeled as rectangle plate. The depth of plate is along Z direction, while X and Y directions represents length and width of the plate respectively. The bottom face of the plate was constrained in all directions while the side faces were constrained in X and Y directions. The target plate and shot were meshed using the solid elements. The node to surface contact was chosen between the shot and target.

Single Shot Model

The finite element (FE) model consisted of a steel ball impact on center of target plate with 5mm x 5 mm x 3 mm dimensions. The area of 3 mm x 3 mm x 2 mm was selected for studying the results (Figure 1). The mesh size of the element is 0.05 mm in the contact area. The mesh size of ball was matched with the plate. The target plate was modeled as bilinear isotropic material for Steel and as piecewise linear plasticity model in Al-7075 and Ti-6Al-4V, while the shot was modelled as a rigid type. The piecewise linear plasticity model of Al7075 and Ti-6Al-4V was defined with true stress strain curve (Table1). The material properties of steel shots and steel plate - Mass density: 7.8 g/cm^3, Elastic modulus: 200 GPa, Poisons ratio: 0.28. The bilinear elasto plastic behavior for steel plate was assumed with an initial stress of 1450 MPa and a tangent modulus of 2500 MPa. Al-7075 and Ti-6Al-4V plates had mass density of 2.83 and 4.43 g/cm^3, Elastic modulus of 71 GPa and 114 GPa, Poisson's ratio of 0.34 and 0.28, and Yield stress of 441 MPa and 1030 MPa respectively. The static coefficient friction between the target and shot contact was 0.25.

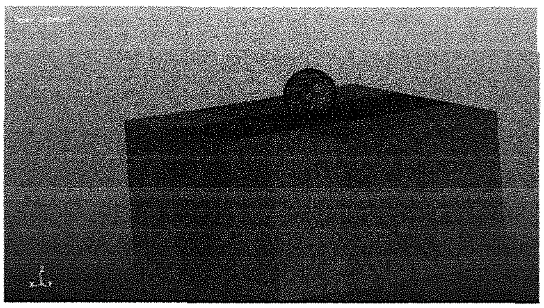
Figure 1: Single Shot FE Model

Table 1.Material Curves: Al-7075 and Ti-6Al-4V

Effective Plastic Strain	True Stress (MPa)	Effective Plastic Strain	True Stress (MPa)
0	0	0	0
7.08E-05	381.22	0.00183	1000.09
2.59E-03	452.11	0.01272	1055.61
1.07E-02	491.11	0.018194	1072.62
3.93E-02	541.81	0.019017	1072.54
1.28E-01	632.28	0.02624	1079.76
1.49	3041	0.02926	1081.49
3.47	4543	0.037806	1075.36

Multiple Shot Models

In the first model the peening coverage was analyzed by increasing number of shots in four steps = {6, 12, 24, and 36}. In the second model, number of multiple shots in manual shot peening were calculated from the measured mass flow rate data.

In Model A, the dimensions and mesh properties of the target plate were same as of the single shot model. The target was an aluminum plate with bilinear isotropic material behavior defined using piecewise linear plasticity (Elastic Modulus: 71.7 GPa, Poisson's ratio: 0.33, Yield Stress: 503 MPa, and Tangent Modulus: 3300 MPa). The material properties of shot were same as those applied in single shot model. The shot diameter was 1 mm whereas the velocity of it was 50 m/s. The X, Y, and Z coordinates of the center of shot were generated using Perl program. The equations used for them were: X=-0.75+1.5*rand(1,1) , Y=-0.75+1.5*rand(1,1) and Z=-0.5-(N-1)*0.5*rand(1,1). Figure 2 shows FEA model for the four cases. The coefficient of friction of 0.2 was used between the contact algorithm.

In Model B, the aluminum specimen used in this study was modeled as a flat block. The geometry configuration are 4 mm in X and Z directions and 2 mm in Y direction, respectively (Figure 2). The shot material was hard steel and of the specimen was an aluminum alloy 7050-T7451. The steel shot was a spherical shape with 0.29 mm in radius. The appropriate mesh size of 100 µm was determined by number of single impact simulations. The stress-strain response of target plate was characterized as piecewise linear plasticity shown in Figure 2. The material properties of shot and target plate were Yield Strength: 572 MPa and 469 MPa, Poisson's ratio: 0.27and 0.33, Elastic Modulus: 204 GPa and 71.7 GPa, and Density: 7916 kg/m^3 and 2823 kg/m^3 respectively. The master-slave contact was applied with the coulomb friction model of 0.2. In order to investigate the random impact effect, shot locations were chosen randomly. The shot velocity and the impingement angle were kept constant at 50 m/sec and 90° with 20 impacting shots. The origin of the coordinate system was located at the center of aluminum block's surface. The initial coordinates of these shots were generated with MATLAB program. 25 location points were generated by positioning each center at every 0.145 mm distance in axial and tangential direction. An algorithm to pick 20 shot locations from 25 location points the shot location randomly uses the uniformly distributed pseudorandom generation without replacement.

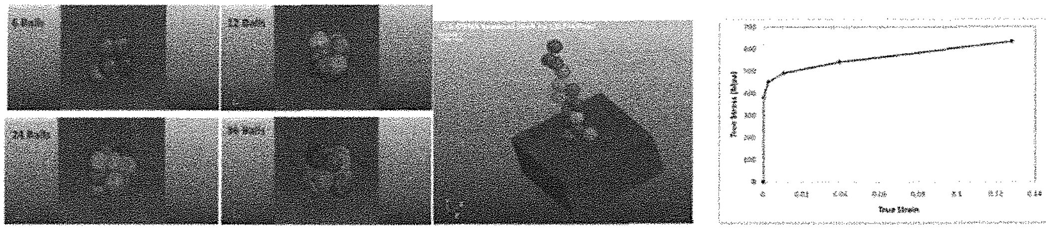

Figure 2: FE of Multiple Shot Models (A and B)

Results and Discussions

The stresses and strain results were compiled after the simulation results got stabilized over the time. Of particular interest for this study were the indent depth, residual stresses and strains from single and multiple impacts, and the peening coverage due to multiple impacts. The stresses are the left over stresses after the impact hence can used to study the trends of residual stresses. Z stresses represent trend of residual stresses along the impact depth.

Single Shot Simulation

The effect of shot diameter is studied by varying the diameter range from 0.4 mm to 1.2 mm by maintaining constant velocity at 60 m/s, while the effect of velocity was studied by changing it from 20 m/s to 80 m/s keeping diameter constant with 1.2 mm. The indent depth was plotted against the distance from the center of the impact; the stresses and the plastic strain were plotted along the depth of the impact. Figure 3 shows typical profile of impact depth in z direction and distribution of stresses and strain along x-y section of model.

Effect of Shot Diameter

A similar pattern of indent depth was created by the shot on the impact surfaces of Steel, Al-7075, and Ti-6Al-4V. It can be noted as the diameter of the ball increases from 0.4 mm to 1.2 mm, the indent radius both along the depth as well as along the width also increases for all the three materials. The increase in diameter of the shot caused slight increase in the Z stress for Steel and Ti-6Al-4V. Z stress in Al-7075 remained unaffected for the change in diameter. In all the three cases when the diameter is increased from 0.8 mm to 1.2 mm, there was minimal increase in the maximum value of the plastic strain. The interesting point to note is that the depth where the plastic strain becomes zero is the same depth where the stresses become zero (Figure 4).

Effect of Shot Velocity

When the velocity is increased from 20m/s to 100m/s the indent depth and the indent radius increases. However for the same velocity Al-7075 covered higher indent depth than Ti-6Al-4V and Steel. The radius of Z stresses profile also increased with the increase in the velocity of shot for Steel and Ti-6Al-4V. The velocity of shot has more impact on Z stresses as compared to diameter of shot. Though more depth is covered by the shot in Al-7075, it was seen that Z stress did not change much with respect to the velocity. The plastic strain increases with the increase in velocity of the shot for all the three materials. The increase in plastic strain was less for the higher range of velocity (Figure 4).

Diameter vs. Velocity of Shot

The independent effect of diameter and the velocity on the formation of indent and residual stresses was examined using the function of correlation coefficients in excel. The diameter was varied from 0.4 mm to 1.4 mm by keeping the velocity constant at 60m/s. The velocity was changed from 30 m/s to 130 m/s by keeping the diameter constant at 1.2 mm. The correlation coefficient for stresses and plastic strain as a function of diameter and velocity of shot are displayed in Table 2. As Y Stresses have same magnitude of X Stresses, therefore they are not represented. The negative sign present in the correlation is due to negative stresses, being compressive in nature. The absolute value of correlation coefficient is considered to compare influence of parameters on the shot. A good correlation of shot diameter and velocity with residual stresses and strains is obtained. In Z Stresses, the diameter coefficient is higher than the velocity coefficient for two (Steel and Ti-6Al-4V) out of the three cases. The diameter and velocity coefficient of Z Stress were found similar for Al-7075. The velocity coefficients were higher than the diameter coefficients for X Stress and Plastic Strain. In most of the cases, velocity coefficients are greater than diameter coefficients of the shot. Therefore velocity of shot has more influence than diameter of shot.

Table 2.Shot Diameter and Velocity Correlation Coefficients for Steel, Al7075 and Ti6Al4V

Correlation	Z Stress			X Stress			Plastic Strain		
Coefficient	Steel	Al7075	Ti64	Steel	Al7075	Ti64	Steel	Al7075	Ti64
Diameter	-0.981	-0.909	-0.977	-0.821	-0.517	-0.887	0.832	0.962	0.894
Velocity	-0.967	-0.902	-0.931	-0.925	-0.939	-0.918	0.999	0.996	0.999

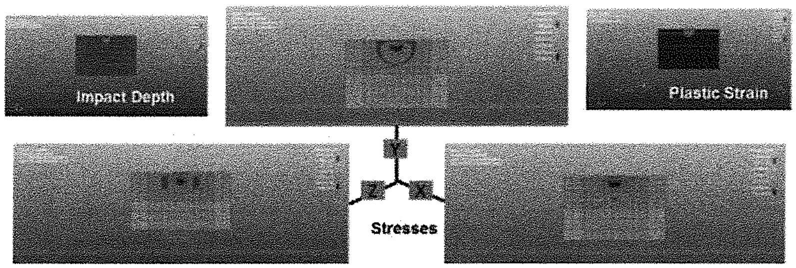

Figure 3: Single Shot FEA Plots: Impact Depth, Residual Stresses and Strain

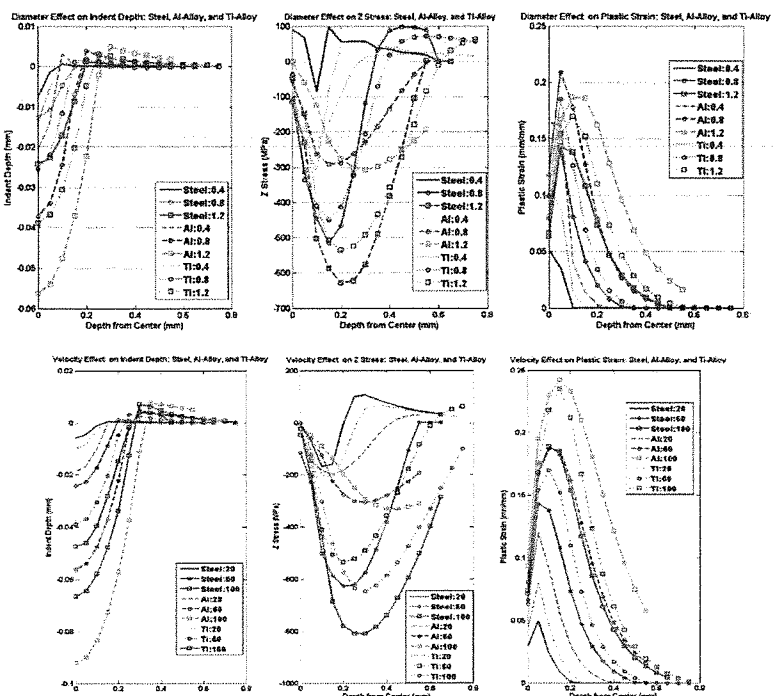

Figure 4: Effect of Shot Diameter and Velocity on Shot Peening (Steel/Al-7075/Ti-6Al-4V)

Material influence on Single Shot Peening

The shot peening process was studied on three materials, Steel, Al-7075, and Ti-6Al-4V. It is observed that higher yield stress produce higher compressive residual stresses. Steel and Ti-6Al-4V yielded higher residual stresses than Al-7075. The compressive residual stresses along the impact depth, the Z stress, increases with the increase in the diameter and the velocity of the shot Steel and Ti-6Al-4V. The compressive residual stresses, Z and X Stresses remain unchanged with respective to diameter and velocity of shot for Al-7075.

Model Validation

The model was validated by comparing the depth of plastic zone obtained from the numerical results with Al-Hassani's theoretical model of shot peening [4]. The depth of plastic zone defined in Al-Hassani's model is given by Eq. (1). The numerical results are in good agreement, except in case of Al7075, where the numerical estimates are higher than theoretical predictions (Figure 5).

$$h_h = 2.57R\left(\frac{2}{3}\right)^{0.25}\left(\frac{\rho V^2}{p}\right)^{0.25} \qquad \text{Eq. (1)}$$

$$p = \frac{2}{3\pi}(2.5\pi\rho)^{0.2}\left[\frac{E}{1-\mu^2}\right]^{0.8}(\mu)^{0.4} \qquad \text{Eq. (2)}$$

(h_h: Depth of plastic zone, R: Radius of indenter, V: Velocity, ρ: Density of target material, p: Pressure, μ: Poisson's ratio of target, and E: Elastic Modulus of target)

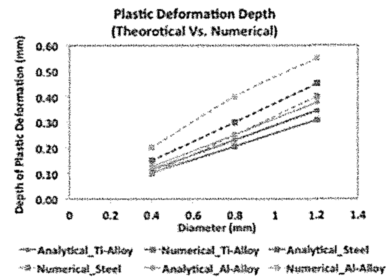

Figure 5: Numerical Results Validation with Theoretical Model

Effect of Multiple Shots

Peening Coverage

In the first step result of single shot simulation was compared with the previous work of Hong [5]. The maximum depth and the plastic strain results from the simulation were checked with his findings. The plastic strain value at 0.02 mm from the center of impact in Hong's findings was 0.027 whereas in the study was 0.034. This can be attributed to numerical modeling differences present between his work and the study. The meshing of the ball was carried out in a different way. Multiple impact simulations were then run with time of 7588 s, 42207 s, and 49509 s required completing 12, 24 and 36 impacts respectively. The peening coverage was studied in 1 mm by 1 mm area of the target plate. The plastic strain was checked for all 441 nodes present within this area. If the plastic strain value was found to be 0.034 or greater (plastic strain at the indent radius in single shot), then it was assumed that the peening has occurred. The peening coverage percentage was found with number of nodes with peening. The coverage increased with the increase in the number of impacts. Figure 6 shows the effect of number of shots on peening. Nearly 96% coverage was reached with 36 random impacts in the center area of the target plate. The results of stresses and plastic strain were studied along center area at nine locations: three at the middle (one in the center, and other two equidistant from it), similarly three at 0.5 mm above and other three at 0.5 mm below the middle line. Figure 7 shows results of residual stresses for three cases of random impact simulations (12 balls, 24 balls, and 36 balls) at the left corner of middle line of 1 mm by 1 mm area and the stress distribution due to maximum number of impacts (# 36) along its middle line respectively. In the random impact simulation the stresses and strains are produced at numerous locations. Depending on locations of the impact, the stresses and strain concentration takes place. The magnitude of stresses is higher in Y and X than Z direction. The difference between residual stresses for various locations was less for 24 and 36 balls as against 12 and 24 balls. Therefore an increase in impacts results in stabilizing distribution of stresses and strains underneath peened surface.

Manual Peening

It is shown that the series of shot impacts create negative plastic deformation in Ydirection and circular contours in X and Z directions (Figure 8). It is found that maximum depth of plastic deformation was about 30 μm in Y direction. The depth of the plastic deformation was also compared with measured surface roughness, R_t. The plastic deformation is closely matched with experimental measured, R_t which is 25 μm. The residual stresses at the impact surface are -292 MPa, , -231 MPa, and 23 MPa in X, Z and Y direction respectively. The compressive residual stress zone is formed from surface to about 0.17mm in depth.

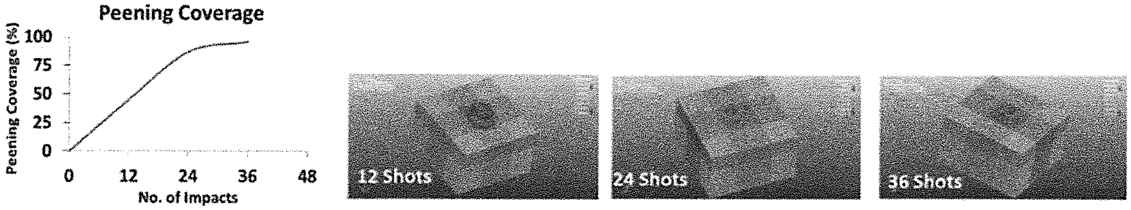

Figure 6: Peening Coverage and Impact surface with 12, 24 and 36 shots

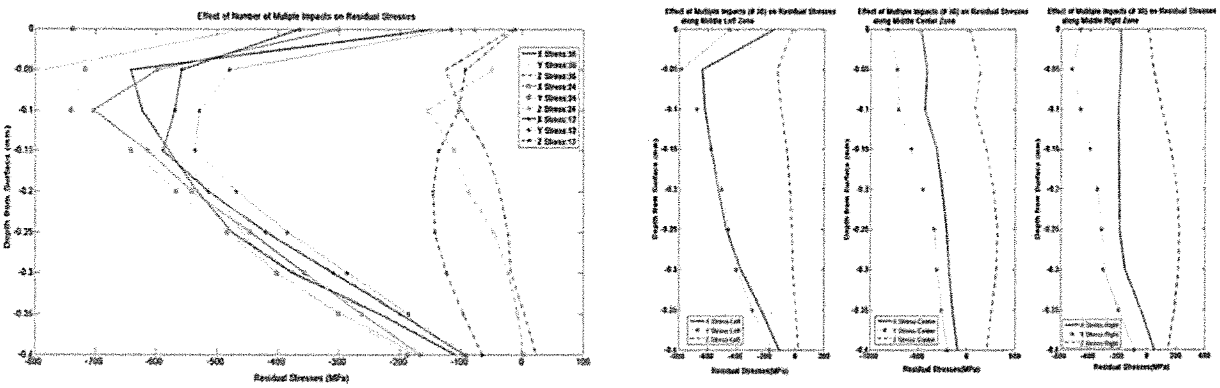

Figure 7: Effect of Number of Impacts on Residual Stresses, Residual Stress Distribution along Middle Zone due to 36 Impacts (Left-Center-Right Side)

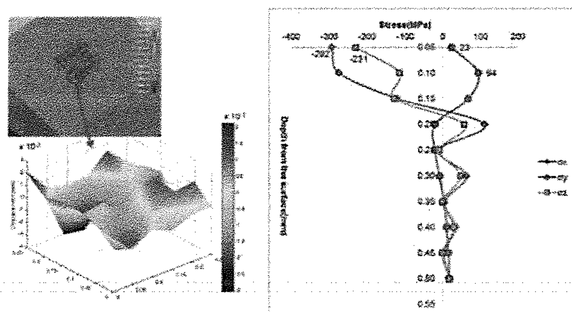

Figure 8: Depth of Surface Plastic Deformation, and Stress Profiles in XYZ directions

Conclusion

The study encompasses the residual stress distribution of single shot impact on Steel, Al-alloy (Al-7075), and titanium alloy (Ti-6Al-4V). The results of these materials showed similar basic trends of the indent depth, residual stresses and the plastic strain in the shot irrespective to the material, velocity and the diameter of the shot. Higher yield stress produced higher compressive residual stresses. Steel and Ti-6Al-4V showed similar trends of induced residual stresses and plastic strains. From the above results, it was evident that both the diameter and the velocity of the shot have influence on the impact depth and compressive residual stresses produced during the shot peening. The velocity of shot was found to have more effect than diameter of shot on shot peening. The numerical results of single shot model were in good agreement with the existing theoretical model. The effect of multiple shots on the residual stress distribution was modeled to include the coverage effect on the shot peening process.

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