A 3D FE model for evaluation of peening residual stress under angled multi-shot impacts

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Abstract

The finite element (FE) model for shot peening often assumes that shots impact vertically on the engineering parts to generate compressive residual stresses. However, the shots obliquely impact on the surface in actual peening. In this work, we propose a 3D FE model for evaluation of residual stress resulting from angled shot peening. Using the present FE model for angled multi-shot impacts, we examine the effects of factors such as impact angle, impact pattern and the number of shots. Plastic deformation of shot is also considered. To validate the model, we then compare the FE solution with experimental results by X-ray diffraction (XRD). The model will serve as a base of 3D multi-impact FE model for various incidence angles.

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1. Introduction

The shot peening process produces compressive residual stress by impact of numerous shots on the surface of the metallic materials, which transmits the impact energy to the materials. The shot peening helps to improve durability and reduce corrosion of the parts and is widely adopted in the automobile, power generation and aerospace industries. Because the evaluation of the compressive residual stress by peening is directly related to the evaluation of durability and reliability, its significance is increasingly stressed and thus has extensive potential for development. Generally, the experimental solution of the peening residual stress slightly varies with the measurement methods [1,2] and environment, and the measurement entails much time and cost. There have been attempts to project the peening residual stress solution with theoretical approaches to solve the issue. Al-Obaid [3] made a theoretical approach to predict the impact energy by engaging static analysis on shot peening for description of the dynamic behavior. Al-Hassani [4], Al-Obaid [5], Hills et al. [6] explored the theoretical correlation between shot peening residual stress and peening parameters. However, the theoretical approach cannot afford to consider the effect of stress interaction from multi-impacts in the actual shot peening process, interaction between peening parameters, various material properties and surface shapes. To overcome this, the evaluation of residual stress by finite element model was introduced [7–9].

To conduct FE analyses for shot peening residual stresses, there have been proposed many FE models such as 2D indentation, 2D and 3D single impacts, 3D multi-impact and 2D and 3D angled-impacts. Among them, the 2D axisymmetric FE model has been most frequently used, which mainly aims to describe the single shot impact on the surface of elasto-plastic bodies. Some studies validated the 2D FE solution by comparing it with the Hertzian solution for spherical indentation [10], experimental results [11]. Some studies considered the deformation of shot and friction [12,13] and strain hardening of material [14], and a dent produced by a single shot [15]. Those 2D FE models were further being refined for single-angled impact [16], and used as the base for 3D multi-shot impacts [17–22]. Among the issues introduced above, in the present work we focused our concern on the 3D FE model for angled multi-shot impacts, and experimental validation of FE solution.

Bagherifard et al. [23] proposed a multi-random shot-peening model, where elastic shots are chosen and shots are introduced in a confined surface region. They investigated the vertical impact with the model and subsequently verified the results with the XRD experimental results. Majzoobi et al. [20] also used the 3D FE model to simulate the actual peening process. Kim et al. [24,25] suggested the FE model involving the single and multi-shot for quantitative evaluation of the peening residual stress. However, these studies are limited by the ideal of FE models involving vertical shot. In actual peening processes, the incidence angle of shot varies with the surface orientation rather than remains vertical. The impact angle of shot is a significant factor in predicting the shot peening residual stress and largely contributes to the magnitude and distribution of the compressive residual stress of the material surface [26,27]. Baek et al. [28] conducted the 3D dynamic analysis and examined the distribution of residual stress with each...
respective incidence angle after the vertical and angled impacts. Miao et al. [29] performed multi-random shots analyses and applied the analysis result to their analytical model. In the model, the shots were set with rigid ball and angled at 60° and 90° measured from the surface. Furthermore, Hong et al. [16,30] investigated the residual stress after the angled single/multi-shot impact on the material surface of a 3D FE model. However, they only evaluated simulation results of the shot peening residual stress states for various angles but excluded the experimental verification. They also used rigid shot, ignoring the deformation in the shot and did not account for the physical behavioral characteristics of the materials. It is necessary to study angled-shot impact involving multi-shots in order to properly understand the effects of peening. To the end, we utilized the factors of the shot peening analysis model from the study by Kim et al. [24,25] in order to correlate distribution of peening residual stress with each respective incidence angle. Moreover, in the present study the correlation between impact pattern and residual stress was integrated with the angled multi-shot impact 3D FE model to make the present model adequately reflect actual shot peening process. In the end, the FE solution and XRD experimental data are compared to verify the validity of the present model.

2. FE model in 3D angled multi-shot impact and input properties

For the 3D angled multi-shot impact analysis, the commercial FE analysis program called ABAQUS Version 6.7 [31] was used. The NLGEOM (nonlinear geometry) option of the ABAQUS Explicit code was used in the FE model to reflect the deformation of both shot and peened material. The finite element mesh comprised of 3D 8-node reduced integration elements (C3D8R). Fig. 1 shows the 3D angled multi-shot impact FE model comprised of 16 shots and materials. The radius and height of the materials were set at 3 mm and 1 mm each, so that the effective stress after the impact fully vanishes at the back surface of the materials. The FE material model would then readily simulate multi-shot impact on a semi-infinite body. The plastic shot was selected, allowing the deformation in the shot in order for the FE model to adequately demonstrate the actual peening process. The shot velocity was set at \( v = 55 \times 10^3 \text{mm/s} \). The spacing between dents introduced by the shots \( S \) was fixed at the radius \( D/2 \) (\( D = 0.8 \text{mm} \)) to maximize stress interaction from multi-shot impact.

For the boundary condition, the material bottom surface was completely restrained \( (U_x = U_y = U_z = 0) \), and contact surface elements were arranged on the surfaces of the shot ball and the material to apply the penalty algorithm. The number of nodes is about 250,000 (4 shots) to 500,000 (16 shots) and the number of elements is 240,000 (4 shots) to 450,000 (6 shots) depending on the quantity of the plastic shot. The material used in the present angled shot impact FE model was AISI4340 because AISI4340 is often processed with shot peening. The material was quenched from 815 °C and tempered at 230 °C for 2 h. The tensile test provides the material properties after the heat treatment; yield strength \( \sigma_y = 1510 \text{ MPa} \), tensile strength \( \sigma_t = 1860 \text{ MPa} \), elastic modulus \( E = 205 \text{ GPa} \), Poisson’s ratio \( \nu = 0.25 \) and density \( \rho = 7.85 \times 10^{-6} \text{ kg/m}^3 \). In this work, the power law formula (Boyce et al. [32]) for plastic strain was used, which is given as:

\[
\varepsilon_p = D_m \left( \frac{\sigma_s \varepsilon_p}{\sigma_o} - 1 \right) \tag{1}
\]

where \( \varepsilon_p \) is effective plastic strain rate; \( \sigma_s \) (\( \varepsilon_p \)) is effective stress for non-zero strain rate; \( \sigma_o \) is quasi-static yield strength. Here, the constants \( D_m \) and \( n \) are \( 2.5 \times 10^6 \) and 6 respectively [24].

The properties of the shot ball for the present analysis use the ones achieved from the tensile test on a SWRH 72A wire with diameter equal to 3 mm, which is the material of CWRS (SCW/CW-32, SAE J441 [33]); yield strength \( \sigma_y = 1470 \text{ MPa} \), tensile strength \( \sigma_t = 1840 \text{ MPa} \), which belongs in the range of in the SAE J441 standard between 1840 and 2110 MPa, elastic modulus \( E = 210 \text{ GPa} \), Poisson’s ratio \( \nu = 0.3 \) and density \( \rho = 7.85 \times 10^{-6} \text{ kg/m}^3 \). The diameter \( D \) was set to 0.8 mm and the plastically deformable shot (PDS) was selected. The minimum size of the element, \( L \), was set at 0.02 mm so that the surface and maximum

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<th>Table 1 Measuring condition of residual stress [34].</th>
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compressive residual stress solution is consistent. Besides, the dynamic friction coefficient $\mu = 0.3$ was used, however rate independency (RI) was assumed so that the deformation speed was not considered [27].

Especially, in shot peening, when a shot impacts on the material, stress waves propagate across the material. The stress waves gradually diminish in amplitude with time as impact energy dissipates, and eventually disappear. In this study, the global material damping is taken into account to allow the impact energy to dissipate in a shorter computational time. In our 2D study [24], without damping, $\xi = 0$, surface residual stress was found unstable with all shots, leading to longer computation time ($t_{CPU} = 3.86 \times 10^3$ s) in PDS FE model. On the other hand, when $0.1 \leq \xi \leq 0.5$, surface residual stresses become stable in the middle of given time step. When $\xi$ increases from 0.1 to 0.5, computation time is shorter. When $\xi = 0.5$, the computation time is the shortest ($t_{CPU} = 30$ s). The value of $\xi = 0.5$, giving the converged solution in a shorter time, is used in this analysis.

3. FE analyses for angled multi-shot impacts

3.1. Residual stress based on cycle and impact pattern

The cycle-repetition can be categorized into 1 (4 shots), 2 (8 shots), 3 (12 shots) and 4 (16 shots) (the impact involving 4 shots is termed 1 cycle). From this the convergence of the peening residual stress with impact cycle can be determined. The impact locations of shots are fixed all same. There are 4 impact patterns, as illustrated in gray arrows in Case 1–4 as shown in Fig. 2. The impact angle was set at $\alpha = 60^\circ$, and the effect of the impact cycle was examined with the shot quantity. Here, the FE solution means the area-averaged solution and well agrees with the experimental data. In this work, the compressive residual stress induced by shot peening was measured by the X-ray diffraction (XRD) method, using the Raystress equipment [34]. The surface layer of material was removed by electrolytic polishing with a non-acid solution. Table 1 shows the conditions for measuring the residual stress. Fig. 2 shows 4 impact patterns of the multi-shot. The impact patterns were categorized into 4 as were in Case 1–4, and the path of the order was marked in light colored arrows. The impact order of 1-3-2-4 was marked in the black arrow, which is close to the one of the random impact from the multi-impact peening residual stress analysis by Kim et al. [24,25]; the order of 1-3-2-4 results in the best convergence with the equi-biaxial residual stress state; the equi-biaxial residual stress state with the order also best matches the experimental data.

Fig. 3 demonstrates that the distribution of residual stress for each impact pattern evolves with cycle with $\alpha = 60^\circ$. The distributions of all the given patterns merge to one line after 2 cycles. Particularly, the distribution for Cases 1 and 4 where all of the shots of each cycle are

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**Fig. 3.** Residual stresses with impact cycles at $\alpha = 60^\circ$.

**Fig. 4.** Impact types with shot sequences specified.
directed toward the center of the material agrees best with the XRD experimental data. The maximum compressive residual stress $\sigma_{\text{max}}$ for Cases 1 and 4 matches the experimental data better than those of Cases 2 and 3. The depth $z_{\text{max}}$ of $\sigma_{\text{max}}$ is also almost similar to the experimental data. However, in overall the FE solution of the residual stress in the surface layer of material $\sigma_{\text{sur}}$ is smaller than the XRD experimental data. For the discrepancy with the surface residual stress to be resolved, the residual stress distribution of the analytical model involving 4 cycles was examined with each pattern in conjunction with the multi-cycle angled impact orders, and the evolution of the stress solution of the residual stress on the surface was then predicted.

3.2. Effect of incidence angle

The incidence angle was defined with respect to the material surface. The smaller incident angles ($\alpha<45^\circ$), at which the effect of peening is weak, was excluded and instead, $\alpha=45^\circ$, $60^\circ$, $75^\circ$ and $90^\circ$ (vertical impact) were considered. Also, four impact patterns were selected to study evolution of the peening residual stress distribution based on impact pattern. Fig. 4 shows redundancy with the impact orders, which can be eliminated. If 4 shots of impact is 1 cycle, then 16 shots make up 4 cycles. The shots were introduced with the order of the cycles designed in $1324/2413/3142/4231$. The area-averaged residual stress solution after the impact was calculated, which engages the area of $(D/2)^2$ mm$^2$, and verified with the experimental data.

Fig. 5 shows the residual stress distribution for the angled multi-shot impact of the given order of the impact patterns after 4 cycles are executed. At $\alpha<60^\circ$, most FE solutions were found to be different from the experimental solutions. At $\alpha \geq 60^\circ$, however, the FE solutions better match the experimental data. This is due to the fact that with increasing $\alpha$, the vertical component of the shot velocity increases, introducing greater transmitted shot energy and thereby greater compressive residual stress at the impact. In such case, the FE solutions of Cases 1

Fig. 5. Residual stresses with the impact pattern of $1324/2413/3142/4231$ for various cases.

Fig. 6. FE solutions and XRD solution for Case 1.
and 4 of the impact patterns are relatively similar to the experimental solutions, and the residual stress in surface layer of material $\alpha_{ref}$ is almost close to the experimental solutions. At $\alpha \geq 75^\circ$, particularly, the FE solutions of Case 1 were closest to the experimental solution. On the other hand, Cases 2 and 3 of the impact patterns indicated that the FE solution of the residual stress was closer to the experimental solution at $\alpha \geq 75^\circ$, but was yet quite different from the FE solutions of Cases 1 and 4. Fig. 5(d) demonstrates that the analytical solutions of Case 1 $\alpha$ solution of the residual stress was closer to the experimental solution. At the other hand, Cases 2 and 3 of the impact patterns indicated that the FE solutions of Case 1 were closest to the experimental solution. On the other hand, Cases 2 and 3 of the impact patterns indicated that the FE solutions of Case 1 were closest to the experimental solution at $\alpha \geq 75^\circ$. In conclusion, for Cases 1 and 4 of the impact patterns are relatively similar to the experimental solution.

4. Experimental verification of finite element solution

4.1. Area averaged peening residual stress solution

Generally, XRD provides the stress averages over the area, which varies in shape and size, inspected by X-ray. Boo et al. [35] achieved the area averaged peening residual stress solution from the circular area of metal with the diameter of 0.4 mm and Hong et al. [36] achieved the XRD data from the area of 2 mm × 7 mm. Prevey and Cammett [37] characterized the relationship between shot peening coverage and the area-averaged XRD data from the areas of 5 mm × 5 mm. Kirk and Hollyoak [38] achieved the area-averaged XRD data of residual surface stress from the areas of 4 mm × 4 mm, 12 mm × 1 mm and 4 mm × 1 mm, respectively. The area-average concept used in XRD measurement was adopted in this study for consistency of comparison with the XRD data. The FE area-averaged peening residual stress solution refers to the averaged values of stresses from the nodes that comprise a finite area. In this study, the averaged residual stress solution was achieved with various areas and the relationship of averaged residual stress distribution with area engaged for the stress averaging was examined.

Figs. 6–9 show the distributions of the FE solutions of the averaged residual stress for various areas and various angles. The areas engaged for the stress averaging were $(D/4)^2$, $(D/2)^2$ and $(3D/4)^2$ mm$^2$. The FE solutions from $(D/2)^2$ and $(3D/4)^2$ mm$^2$ showed similar residual stress distribution, but the FE solutions from $(D/4)^2$ mm$^2$ is rather different. Furthermore, the FE solutions from $(D/2)^2$ and $(3D/4)^2$ mm$^2$ at every impact pattern agrees better with the XRD experimental data than...
those from \((D/4)^2\) mm². Computation time to calculate the average of the node solutions varies with area engaged for averaging. In other words, \((D/2)^2\) mm² has fewer nodes than \((3D/4)^2\) mm² and therefore solution averaging with \((D/2)^2\) mm² requires less time, suggesting that smaller areas are preferred for time saving. Of the given 4 impact patterns, Case 1 agrees best with the experimental data. For time saving and the best consistency with the experimental data, the Case 1 impact pattern and the \((D/2)^2\) mm² area was chosen for the angled multi-shot impact FE model. Fig. 10 shows the residual stress distribution for various %S (spacing between dents by the shots) with angled multi-shot impact. The FE analysis was conducted for %Sp = 55 x 10³ mm/s, Strain rate independent (RI), PDS, 4 cycles \([1324/2413/3142/4231]\) were set, and Cases 1 and 3 were selected as the impact patterns. In Fig. 11, it shows the residual stress created after the impact. For Case 1, the distribution of \(σ_x\) and \(σ_y\) are very similar at 90° and close to the perfect convergence, whereas both stresses for Case 3 were different. This demonstrates that the FE model set with Case 1 was the most adequate for the analysis. Since the convergence to the equi-biaxial stress and the consistency with the XRD experimental data of the present FE model are both achieved, it is confirmed that the present FE model readily simulates angled multi-shot impacts.

4.2. The convergence of stress field to the equi-biaxial stress state

Generally, the peening residual stress state tends to gradually converge to equi-biaxial stress state, as multiple shots create multiple impacts, producing uniform residual stress. Since the convergence to the equi-biaxial stress indicates that the uniform compressive residual stress distribution is achieved, which is observed in actual shot peening process, the convergence was examined in this study. In the analysis, the aforementioned conditions \((α=75°, v=55 \times 10³ \text{ mm/s})\), Strain rate independent (RI), PDS, 4 cycles \([1324/2413/3142/4231]\) set, and Cases 1 and 3 were selected as the impact patterns.

4.3. Meaning of FE peening coverage in angled multi-shot impact

We apply the FE peening coverage for our present model. The concept of FE peening coverage was defined in our previous impact analysis [24] where symmetry-cell was used and the effectiveness was confirmed by FE solutions. Peening residual stress depends on the area fraction of dent formed by multi-shot-impacts. The area fraction of dent is termed peening coverage denoted as C, and 100% of peening coverage C is called “full coverage”. The peening coverage generally exceeds 100% in shot peening application. Most prior FE studies overlooked the peening coverage, or represented it simply with distance between

Fig. 9. FE solutions and XRD solution for Case 4.

Fig. 10. Residual stress distributions with shot spacing.
centers of dents. Disregard of peening coverage left the prior FE solutions far apart from the actual one. Peening coverage of more than 100% represents multiples of full coverage. For example, 200% of peening coverage means the case where full coverage is repeated twice.

4.4. Model verification with multi-shot peening materials

This section is dedicated to explore the validity of our FE model with the choice of peening material. The materials chosen included AISI4340, which was used in the previous analysis [27], AISI4140 and SPS8. AISI4140 was tempered for 2 h at 450 °C after being quenched from 850 °C. The resulting material properties of AISI4140 after the heat treatment were as follows: yield strength at $\sigma_0 = 1390$ MPa; tensile strength at $\sigma_t = 1700$ MPa; modulus of elasticity at $E = 210$ GPa; Poisson’s ratio at $\nu = 0.28$; and density at $\rho = 7.85 \times 10^{-6}$ kg/m³. SPS8 went through the vacuum-heat treatment after machining to prevent oxidation and decarburization. It was quenched from 910 °C and tempered at 420 °C for 90 min. The material properties of SPS8 after the heat treatment were as follows: yield strength at $\sigma_0 = 1630$ MPa; tensile strength at $\sigma_t = 1920$ MPa; modulus of elasticity at $E = 210$ GPa; Poisson’s ratio at $\nu = 0.3$; and density at $\rho = 7.85 \times 10^{-6}$ kg/m³. The peening factors used the values obtained from the existing FE models [27] (set with Material: AISI 4340) except for the shot velocity $v$. The XRD result of AISI4340 was measured with the arc height of $H = 0.33$ mm A and coverage of $C = 200\%$ [34], which were achieved after machining, while the experimental data of AISI4140 and SPS8 were achieved after machining with $H = 0.26$ mm A and $C = 100\%$ [41], and $H = 0.37$ mm A and $C = 85\%$ [42] respectively. Generally, if the experimental coverage is between $85 \leq C \leq 98\%$, it is considered as the total coverage meaning that $C$ is set to 100% for the FE model. Therefore, $C$ was 100% for SPS8. $v$ of AISI4140 and SPS8 models were $40 \times 10^3$ mm/s and $61 \times 10^3$ mm/s respectively based on the equation of $v = C_1 H - C_2$ [25].

5. Concluding remarks

This study proposed the 3D angled multi-shot FE model. The convergence of the residual stress solution was demonstrated with shot quantity, impact angle and impact cycle. The evolution of the residual stress solutions was explored with various impact patterns...
tion depth. It was also found that the area-average FE solutions were terms of the maximum compressive residual stress and the deformation biaxial peening residual stress state. The area-averaged solution for impact angle and pattern were chosen which provides the equi...

**References**


**Fig. 13.** FE solutions and XRD solution for (a) AISI4140 (b) AISI4340 and (c) SPS materials.

and shot intervals. Base on the residual stress solutions, the optimal impact angle and pattern were chosen which provides the equibiaxial peening residual stress state. The area-averaged solution for \((D/2)^2 \text{mm}^2\) is best consistent with the XRD experimental data in terms of the maximum compressive residual stress and the deformation depth. It was also found that the area-average FE solutions were well consistent with the experimental data for AISI4340, AISI4140 and SPS8, supporting that the proposed FE model is insensitive to the choice of material and thereby reflects actual shot peening process.

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