3D Multi-impact FE Solution for Peening Residual Stress in AISI4340 Steel

Taehyung Kim 1[a], Hyungyil Lee 1[b], Seong-Kyun Cheong 2

1 Department of Mechanical Engineering, Sogang University, Seoul 121-742, Korea ([a]kthmax@sogang.ac.kr, [b]hylee@sogang.ac.kr)
2 Department of Mechanical Engineering, Seoul National University of Technology, Seoul 139-743, Korea (skjung@snut.ac.kr)

ABSTRACT
In this paper, we evaluate the residual stress of AISI4340 steel under multi-impact shot peening via 3D Finite element (FE) model with combined physical and kinetic factors. The physical parameters in 3D FE model are elastic-plastic deformation of shot, material damping coefficient, dynamic friction coefficient. The kinematical parameters are impact velocity and angle, shot diameter. Multi-impact FE model consists of 3D FE symmetry-cell. With the symmetry-cell model, we investigate FE peening coverage, dependency on the impact sequence, effect of repeated cycle. We also obtain the residual stress averaged at full-nodes in the surface of symmetry-cell. In contrast to rigid and elastic shots, plastically deformable shot produces residual stress closer to the XRD experimental solution. Consequently, we confirmed that the 3D FE model with peening factors and plastic shot successfully evaluate the residual stress by multi-shot peening in AISI4340 steel.

KEY WORDS
Multi-impact, Finite element coverage, Impact sequence, Repeated cycle, Averaged residual stress, Plastic shot

INTRODUCTION
In relation to evaluation of durability, it is significant to quantitatively estimate the compressive residual stress produced by shot peening. The residual stresses are generally measured by X-ray and neutron diffraction techniques, hole drilling, chemical etching, curvature/strain measurement and beam bending method [1]. Each of these methods, however, has a shortcoming in the light of accuracy, sensitivity, resolution, specimen preparation, convenience, material types and geometry of structure. Theoretical approach of Al-Obaid *et al*. to peening residual stress [2] did not consider the stress interference due to multi-impacts, interaction among peening parameters, various material properties and surface morphology. To overcome the problems associated with finite element analysis (FEA) of single impact, many FE analyses of 3D multi-impacts were performed. Guagliano [3] derived the relationship between arc height of Almen strip and peening residual stress solution via FE analysis of random multi-impacts. Kim *et al*. [4] attempted to simulate the peening coverage by arbitrarily varying the central distances between shot balls. Those FE analyses of simple and arbitrary multi-impacts, however, fail to provide the homogeneous solution for equi-biaxial peening residual stress, featured by location

independency. Meguid *et al.* [5] contrived a 3D symmetry-cell FE model under multi-impacts to generate the location free residual stress solutions. But, they omitted the plastic deformation of shot ball, which turns out to be fatal in this work. As stated above, prior works examined only the separate effect of a limited set of peening parameters, but never systematically integrated the physical factors of material and the kinematical peening parameters. Kim and Lee [6] proposed a 2D single impact FE model which considered the material and kinematical parameters in an integrated manner. In this study, to move a step forward from the 2D FE model, we first investigate the effects of FE peening coverage, impact sequence, repeated cycles on the peening residual stress with a 3D FE model. We then suggest an inclusive 3D FE model providing the converged solution for homogeneous residual stress in multi-impact shot peening.

3-D FE MODEL FOR MULTI SHOT IMPACT

Figure 1 shows a 3D FE model for evaluation of shot peening residual stress. The left side simulates the phenomenon that numerous shots, depicted by four basic rows, impact on the top surface. The gap between each raw is equal, and each raw remain horizontal. Shots of four rows impact on the top surface in series without bumping each other. The symmetry-cell FE model in the right side of figure represents the whole body of shot-peened surface of material. It can simultaneously embody the actual equi-biaxial peening residual stress.

We use the commercial finite element code ABAQUS [7] in this work. To analyze large deformation of elasto-plastic specimen, we adopt NLGEOM option in ABAQUS Explicit code. FE mesh is composed of 3D eight-node reduced integral elements C3D8R (ABAQUS) [7]. As boundary conditions, we fix the bottom of symmetry-cell ($U_x = U_y = U_z = 0$), and impose symmetric displacement conditions on the four sides of symmetry-cell ($U_x = 0$ or $U_z = 0$). Considering the maximum capacity of shot peening equipment, we select initial impact velocity $v = 75$m/s for experimental verification of FE solution. To apply the penalty algorism to impact, we place contact surfaces at both material and shot ball surfaces.

Fig. 2 show the elatic / plastic properties of material and shot used for FEA. Material adopted for FE model is AISI4340 which is often subject to shot peening process. Material was tempered for 2 hours in 230°*C* after quenching in 815°*C*. Yield strength of material is $\sigma_o = 1510$MPa, tensile strength $\sigma_t = 1860$MPa, elastic modulus $E = 205$ GPa, Poission's ratio $\nu = 0.25$, density $\rho = 7850$kg/m^3. For FE model of shot, we select

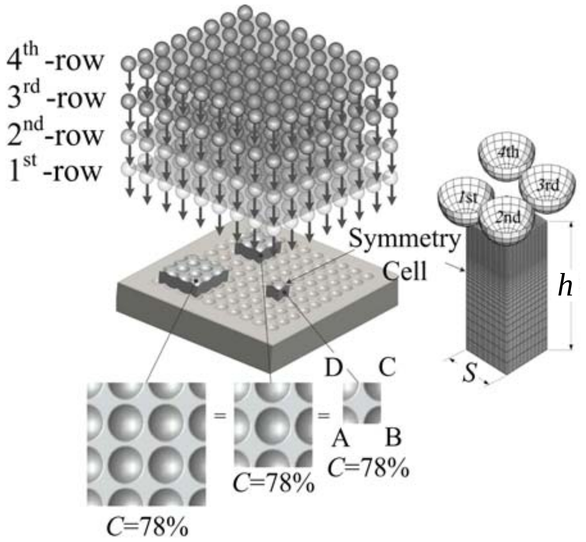


Fig. 1 FE symmetry cell model

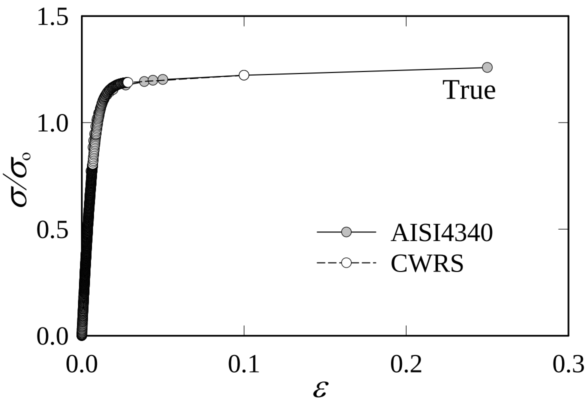
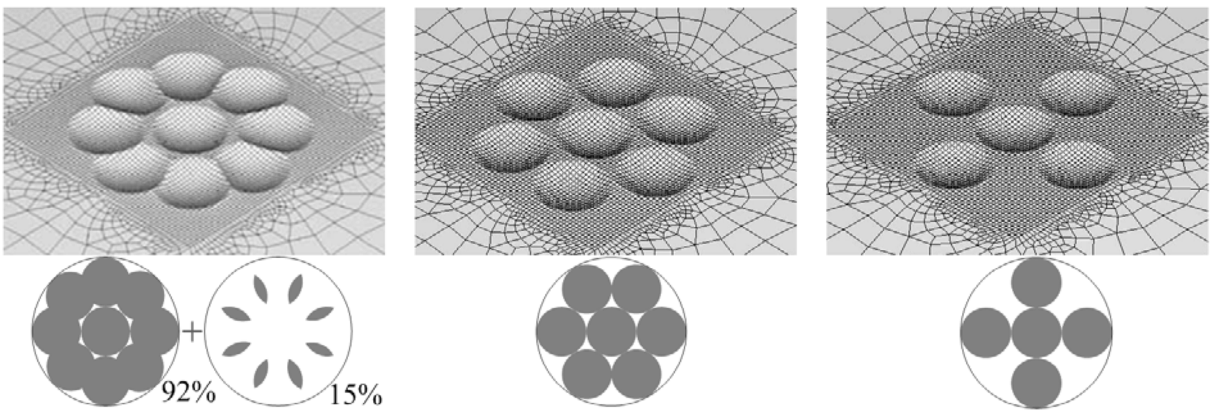


Fig. 2 Material curves for FEA

the cut wire rounded shot widely used in peening process. Yield strength of shot ball is σ_o = 1470MPa, tensile strength σ_t = 1840MPa, elastic modulus E = 210GPa, Poisson's ratio $\nu = 0.3$, density $\rho = 7850\text{kg/m}^3$, hardness $H_v = 670$ and diameter D = 0.8mm. We consider rigid shot (RS) without deformation and elastic shot (EDS) and plastic shot (PDS) with deformation in impact. We adopt proper height h from the proposed 3D symmetry-cell model under multi-impacts. The abscissa is depth d measured from the surface of symmetry-cell, and the ordinate is equivalent stress σ_e normalized by material yield strength. The letters A-D denote four nodal locations impacted by shot balls on the top surface of symmetry-cell (Fig. 1). As the stress value approaches to zero from about 1mm depth, we select h = 1.5mm over which no deformation occurs.

DEFINITION OF FE PEENING COVERAGE

Shot peening residual stress solution depends on the density of dent created by impacts of shot balls. The dent density is called peening coverage C, and about 100% dent density is called full coverage. The peening coverage generally exceeds 100% in most shot peening applications. We thus need to define FE peening coverage ahead of FE analysis to obtain FE peening residual stress solution comparable to real multi-impact solution. Fig. 3 shows the definition of FE peening coverages based on real peening phenomenon. Fig. 3 (a) is regarded as 107% peening coverage after consecutive impacts by 9-shots, since it is overlap area 15% is



(a) 107% (b) 82% (c) 58%

Fig. 3 Definition of FE peening coverages

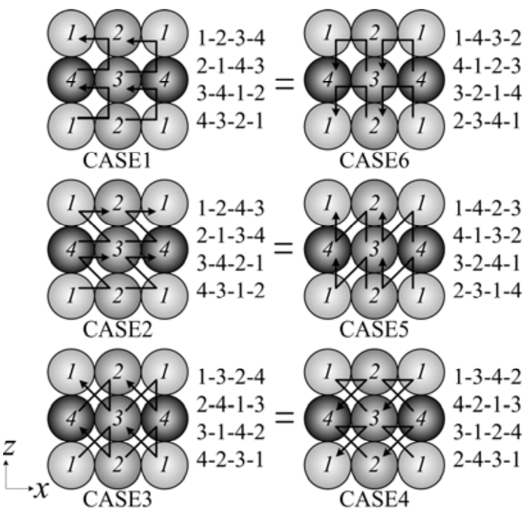


Fig. 4 Similar impact types

Table 1. Impact sequences with multi cycles

Case	Cycles (Shots)	Impact sequence
1	1 (04)	(1-2-3-4), (2-1-4-3), (3-4-1-2), (4-3-2-1)
	4 (16)	(1-2-3-4 / 2-1-4-3 / 3-4-1-2 / 4-3-2-1) × 1
	8 (32)	(1-2-3-4 / 2-1-4-3 / 3-4-1-2 / 4-3-2-1) × 2
	16 (64)	(1-2-3-4 / 2-1-4-3 / 3-4-1-2 / 4-3-2-1) × 4
2	1 (04)	(1-2-4-3), (2-1-3-4), (3-4-2-1), (4-3-1-2)
	4 (16)	(1-2-4-3 / 2-1-3-4 / 3-4-2-1 / 4-3-1-2) × 1
	8 (32)	(1-2-4-3 / 2-1-3-4 / 3-4-2-1 / 4-3-1-2) × 2
	16 (64)	(1-2-4-3 / 2-1-3-4 / 3-4-2-1 / 4-3-1-2) × 4
3	1 (04)	(1-3-2-4), (2-4-1-3), (3-1-4-2), (4-2-3-1)
	4 (16)	(1-3-2-4 / 2-4-1-3 / 3-1-4-2 / 4-2-3-1) × 1
	8 (32)	(1-3-2-4 / 2-4-1-3 / 3-1-4-2 / 4-2-3-1) × 2
	16 (64)	(1-3-2-4 / 2-4-1-3 / 3-1-4-2 / 4-2-3-1) × 4

added to projected indent area of 92%. Fig. 3 (b) is regarded as 82% peening coverage after impacts by 7-shots, and Fig. 3 (c) is regarded 58% as peening coverage after impacts by 5-shots. Stress interference due to overlap in peening coverage affects the residual stress solution. In order to make the FE peening solution close to real residual stress, the definition of FE peening coverage and reflection of it to FE model is indispensable.

DEPENDENCY ON IMPACT SEQUENCE

The FE peening solution gradually converges into equi-biaxial homogeneous stress not by simple impact or single cycle, but by numerous impacts with repeated cycles. We investigate the value of residual stress and convergency for various impact sequences along the depth at the four-nodes of top surface in symmetry-cell model. Figure 4 illustrates 3 identical impact types. There are 6 basic Cases 1- 6. Each case is subdivided into 4 types of single cycle with distinct first impact. Here the Cases 1and 6 are equal, and Case 2 = Case 5 and Case 3 = Case 4. The reason is that 90^{o} rotations of Cases 1- 3 produce the same types of Cases 6 - 4 respectively. Table 1 sums up the impact sequences with multi-cycle of Cases 1-3. We examine the effect of repeated cycles by repeating four single-cycles in each case. We group them as 1

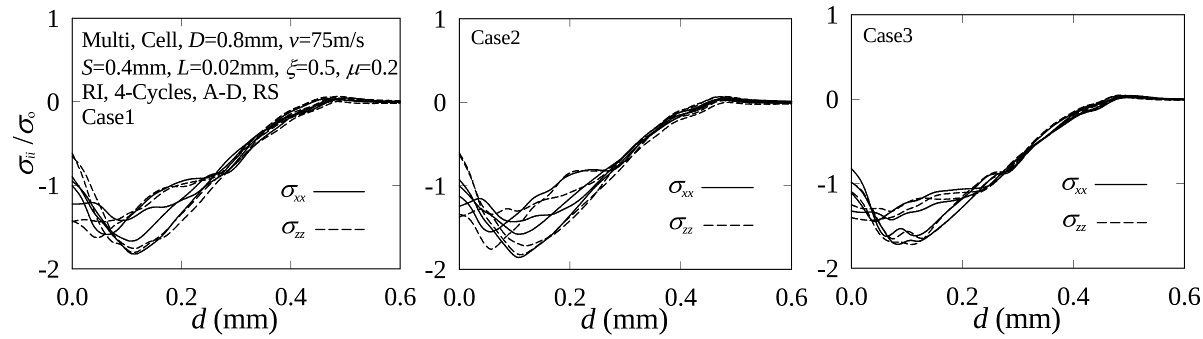
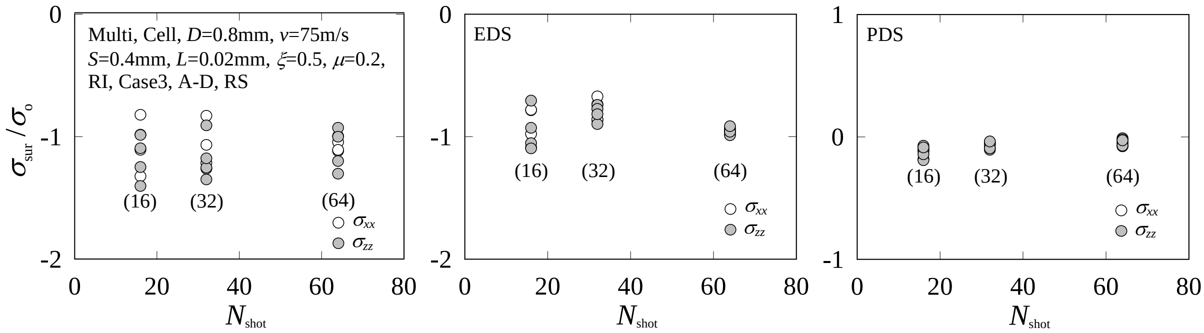
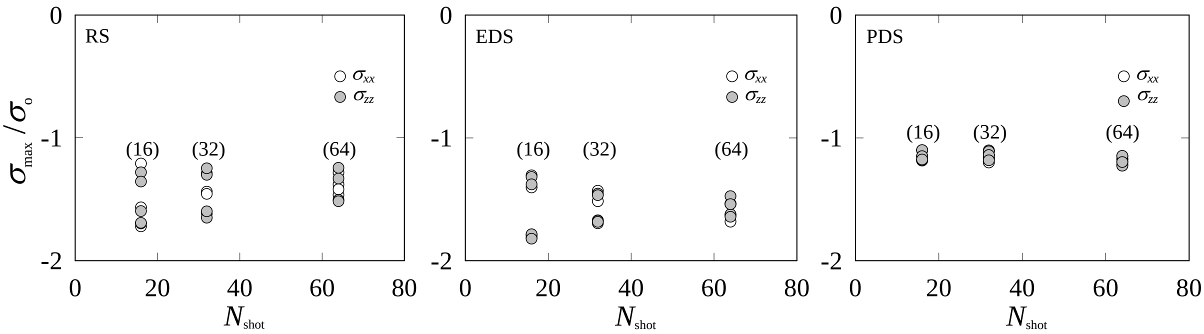


Fig. 5 Convergence to equi-biaxial stress in rigid shot FE model with 4-cycles



(a) σ_{sur}



(b) $\sigma_{\max}$

Fig. 6 Convergence on equi-biaxial residual stress with respect to increase of shot ball

(4 shots), 4 (16 shots), 8 (32 shots), 16 (64 shots) cycles. Figure 5 shows convergency of residual stress to equi-biaxial state in Case 3 after 4 cycles (16 shots) of rigid shots. Convergency to equi-biaxial stress of σ_{xx} and σ_{zz} in Case3 is the best. We then perform the multi-impact FE analyses with repeated cycles in Table 1. Figure6 reveals the effects of rigid, elastic, plastic shots on the convergence of stresses to equi-biaxial state in repeated cycles of 16, 32, 64-shots in Case3. As repeated cycle increase, the stresses σ_{xx} and σ_{zz} approach to each other. Plastic shot model gives the best convergency. On this observation, we select the Case3 as the basic FE model for its excellent convergency to equi-biaxial stress state and closeness to random impact.

COMPARISON OF RESIDUAL STRESSES BY FE AND XRD

Deformation of shot ball is additionally considered in this work. We study on rigid shot without deformation and elastic and plastic shots with deformation. We compare FE solution from the shot models with XRD experimental solution. The reference XRD experimental solution was obtained from the specimens with coverage of 200% and arc height of 0.36mmA [9]. If these factors correspond to saturation curves in Fig. 7, we can calculate input impact velocities for FE analyses. As shown in Fig. 7, the relationship of FE peening coverage, arc height and impact velocities is written as $v^C = C_1 H - C_2$ where $C_1 = 153.4$, $C_2 = 0.82$ when $C = 200\%$. The velocity $v = 55$m/s is obtained by substituting arc height 0.36mmA into the equation. We adopt it in our FE analysis. Figure 8 compares FE solutions with XRD experimental solution. FE solutions of rigid and elastic shot models lie far below the experimental solution. On the

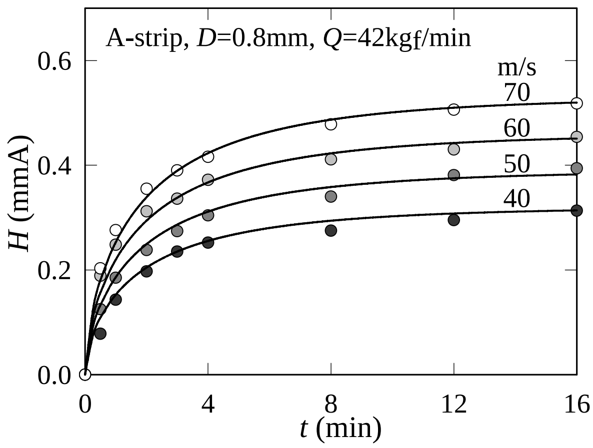


Fig. 7 Saturation curves

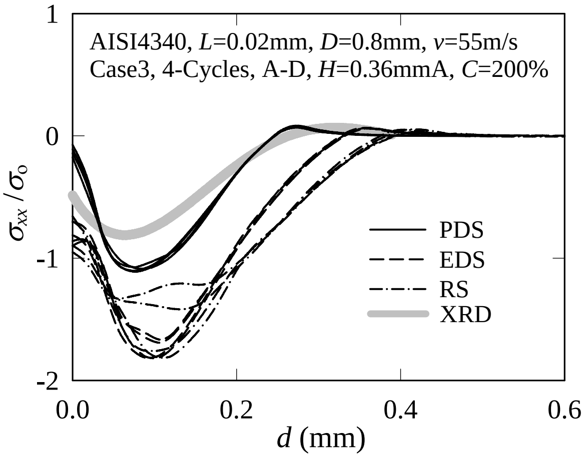


Fig. 8 Comparison of residual stresses

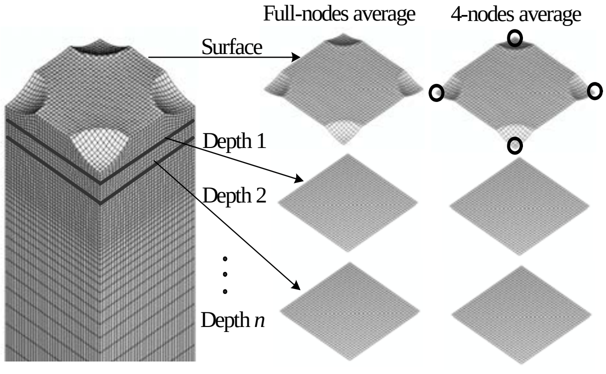


Fig. 9 Full-nodes and 4-nodes

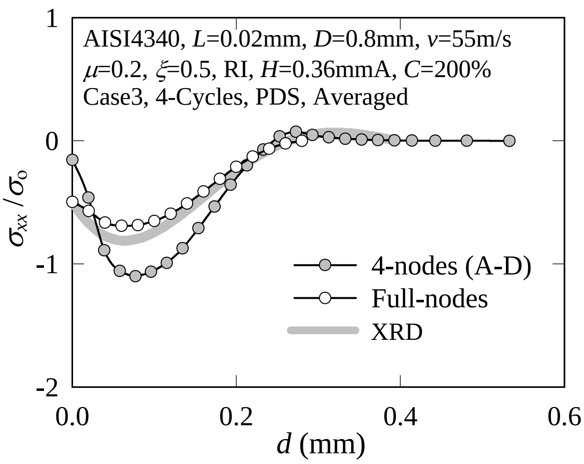


Fig. 10 Averaged FE residual stresses

other hand, plastic shot model gives quite better solution, although it lies a bit above the experimental solution. We confirm that the plastic FE model is more useful due to the better convergency to equi-biaxial stress state and proximity to the XRD solution. Generally XRD solution gives the value of area averaged residual stress at X-ray irradiated region. Considering this, we take an average of residual stresses at all-nodes forming the cross-sections (0.4mm x 0.4mm) at each depth. We also take an average of residual stresses at the 4-nodes of A-D locations. No prior study on multi-impact FE analyses attempted the average approach to our knowledge. Figure 10 shows the all- and 4-nodes averaged solutions along with the XRD solution. Contrary to 4-nodes averaged solution, full-nodes averaged solution is quite close to experimental solution.

CONCLUDING REMARKS

In this study, we contrived a 3D symmetry-cell FE model under multi-impact for quantitative evaluation of shot peening residual stress. We validated the model by comparison of FE and experimental solutions. Essential physical factors of material were applied to FE model, and kinematical peening parameters were combined additionally. We also examined the deformation of shot ball. Plastic shot model gives quite better solution. We achieved the convergency to equi-biaxial stress state by considering FE peening coverage, multi-impact sequence and repeated cycles. All-nodes averaged solution is quite close to experimental XRD solution.

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