Shot peening DEM-FEM simulation considering shot stream expansion, peening intensity and target materials

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Introduction

Finite element (FE) simulation of shot peening has been widely applied to investigate the influence of the shot peening parameters on peening results like residual stresses and roughness [1-8]. Shot-shot interactions, shot-target interactions should both be considered in the shot peening simulation to yield physically realistic results. Discrete element model (DEM) - Finite element model (FEM) coupling methods have been shown to effectively predict the shot stream and shot peening effects by accounting for shot-shot and shot-target interactions [9, 10].

Objectives

The objective of this work was to develop a DEM-FEM coupling model for simulating the shot peening process on three materials: Inconel 718, 300M steel and AA7050-T7451. The model accounted for the shot stream expansion, shot-shot interactions as well as the distribution of shot impact locations. Almen intensities of 4A and 8A obtained with three different shot types (CW14, S230 and Z425) were simulated and the predictions were compared against experimentally measured residual stresses and roughness.

Methodology

The DEM-FEM sequential coupling method introduced by Murugaratnam et al. [10] and further improved by Tu et al. [9] was adopted to simulate the shot peening process. First, the shot stream was simulated in an open-source DE software Yade to obtain the shots impacting velocities and spatial coordinates before they were about to impact the metal part. A conical shot stream accounting for shot stream expansion, as shown in Figure 1, was developed. The extracted shots impacting velocities and positions were then imported into ABAQUS/Explicit for computing the target's responses. The target was described by periodic cell in ABAQUS/Explicit.

Application of the process and measurements

Shot peening was performed on IN718, 300M and AA7050-T7451 with Almen intensities of 4A and 8A until full coverage. Table 1 lists the shot peening parameters used in the experiments. Shot peening velocities were measured by a Shotmeter G3 supplied by Progressive Technology. The X-Ray Diffraction (XRD) technique was adopted to measure the macroscopic residual stress profiles after shot peening. A Proto iXRD diffractometer (Proto Manufacturing Ltd.) equipped with two linear detectors and relying on the $sin^2\psi$ method was used to measure residual stresses in IN718. A Pulstec μ-X360n diffractometer (Pulstec Industrial Co., Ltd.) equipped with one image plate detector and bases on $cos\alpha$ method was used to measure residual stress for the three materials.

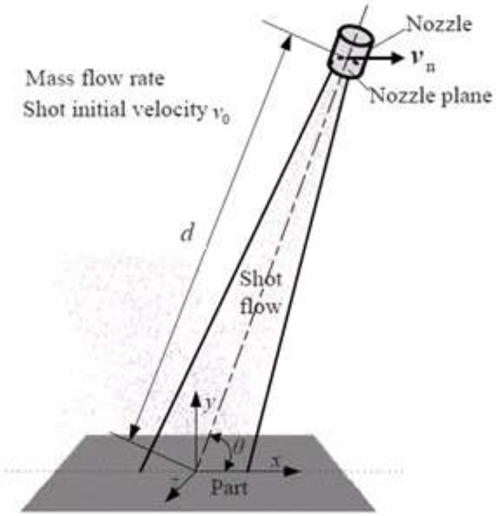

Figure 1 DEM model accounting for shot stream expansion.

Table 1 Shot peening conditions for the DEM-FEM simulations

Material	Almen intensity	Shot type	Shot diameter (mm)	Shot density (kg/m^3)	Shotvelocity (m/s)	Mass flow rate (kg/min)
IN718	4A	CW14	0.3556	7800	32	6.8
IN718	8A	CW14	0.3556	7800	75	6.8
300M	4A	CW14	0.3556	7800	32	6.8
300M	8A	CW14	0.3556	7800	75	6.8
AA7050	4A	S230	[0.5, 0.84]	7800	12	13.6
AA7050	8A	S230	[0.5, 0.84]	7800	25	13.6
AA7050	8A	Z425	[0.425,0.6]	3850	65	4.5

Table 2 Material properties of In718, 300M and AA7050 in FEM model

Material	Young's Modulus (GPa)	Poisson's ratio	Density (kg/m^3)
IN718	205	0.32	8100
300M	197	0.28	7800
AA7050	70.7	0.33	2800

Surface roughness after different shot peening conditions was measured using Mitutoyo SV- C400. Tensile test and strain-controlled cyclic tests were carried out on a MTS uni-axial test machine to obtain the mechanical properties of the three materials. Table 2 lists the experimentally measured Young's modulus and Poisson's ratio for the three materials, along with their densities extracted from [11]. For the cyclic tests, strain amplitude $\Delta\varepsilon$=2%, 2% and 1%, and strain ratio R_ε=-1, 0 and -1 have been applied to IN718, 300M and AA7050, respectively.

DEM-FEM model

In the DEM model, the shot stream was simulated in an open source DE software Yade to acquire the shots impacting velocities v_{imp} and locations immediately before hitting the target. Shots were simulated as spherical DE particles while the target was simulated as a rigid square surface with dimensions of 40mm×40mm. Assuming that the nozzle's plane center was at (x_n, y_n=d, z_n), a shot's initial positon was randomly generated as:

$$\begin{cases} x = x_n + (2(r_n - r_s)\mathrm{rand}(0,1) - (r_n - r_s)) \\ y = d \\ z = z_n + (2(r_n - r_s)\mathrm{rand}(0,1) - (r_n - r_s)) \end{cases} \tag{1}$$

where r_n is the radius of the nozzle and was 6.35mm, $r_s = d_s/2$ is the shots radius, rand(0,1) is a uniform distribution random number generator delivering numbers in the range of [0,1], d is the stand-off distance between the nozzle and the targets and was 300mm. For S230 and Z425 shots, in order to consider the diameters range, the shot's radius was randomly set as per:

$$r_s = r_{smin} + (r_{smax} - r_{smin})\mathrm{rand}(0,1) \tag{2}$$

where r_{smin} and r_{smax} were the minimum and maximum shot radii. The generated shot lied inside a circular nozzle through the contraint:

$$(x - x_n)^2 + (z - z_n)^2 \leq (r_n - r_s)^2 \tag{3}$$

In order to consider shot stream expansion, all of the shots lied in a conical stream, assuming that $\frac{|x-x_n|}{r_n} = \frac{r_1}{r_i}$, where r_1 was the distance from the impacting locaiton of the origin O and $r_i = \frac{d_i}{2}$ was the radius (half of the width) of impacting zone on a sample. The initial volcity vector was obtained as:

$$\begin{cases} v_{0x} = v_0 \dfrac{x - x_n}{|x - x_n|} \dfrac{r_1 - |x - x_n|}{\sqrt{(r_1 - |x - x_n|)^2 + d^2}} \\ v_{0y} = -v_0 \dfrac{d}{\sqrt{(r_1 - |x - x_n|)^2 + d^2}} \\ v_{0z} = v_0 \dfrac{z - z_n}{|x - x_n|} \dfrac{(r_1 - |x - x_n|)}{\sqrt{(r_1 - |x - x_n|)^2 + d^2}} \end{cases} \tag{4}$$

Young's modulus and Poission's ratio as listed in Table 2 were used in the DEM simulation. A constand Coefficient of Restituaiton(CoR)=0.4 was used for shot-shot interaction as introduced in [9].
Shots were considered as rigid spherical surfaces to reduce the compuation cost. 8 node reduced intergartion 3D elements (C3D8R) were used to simulate the target material. An explicit periodic cell model introduced by Yang et al. [8] was applied to simualte the residual stress after shot peening. The size of periodic cell was set to $2r_s \times h \times 2r_s$, where the height $h = 4.1r_s$, r_s is the shto radius. From the contact surface till depth of $2.5r_s$, the fine element size was set to $\frac{r_s}{16} \times \frac{r_s}{16} \times \frac{r_s}{16}$, and the corse element till $4.1r_s$, the coarse element size was set to $\frac{r_s}{16} \times \frac{r_s}{5} \times \frac{r_s}{16}$. The degrees of freedom of the bottom nodes were set to 0. Each pair of corresponding side nodes were submitted periodic boundaries conditons through multiple point constrains (MPC) using *EQUATION commnd in ABAQUS. To simulate random impingement with the period cell model, the shot whose impacting position was close to periodic cell boundaries must be carefully treated as explained in [8].
A combined isotropic and kinematic hardening model was adoped to simulate the plastic behavior of the material during cyclic loading. A single elment simulation of the strain-controlled cyclic tests were simulated and compared with experiments. Figure 2, Figure 3 and Figure 4 compare the simulated stress strain relationship with experimental measurement for IN718, 300M and AA7050, respectively.

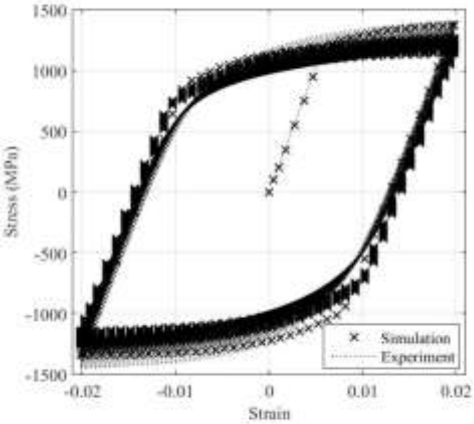

Figure 2 Comparison between the cyclic test data and a single element simulation for IN718 (strain amplitude $\Delta\varepsilon$ = 2%, strain ratio R_ϵ= -1).

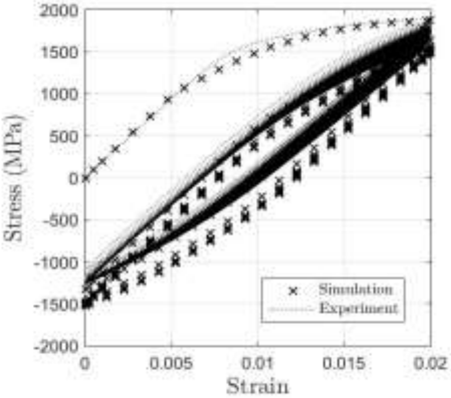

Figure 3 Comparison between the cyclic test data and a single element simulation for 300M (strain amplitude$\Delta\varepsilon$= 2%, strain ratio R_ϵ= 0).

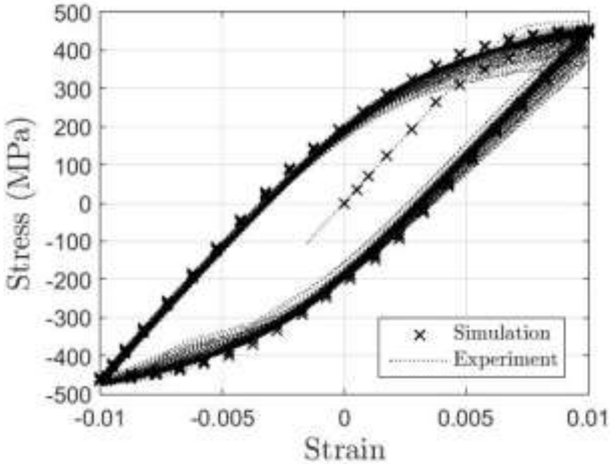

Figure 4 Comparison between the cyclic test data and a single element simulation for AA7050 (strain amplitude$\Delta\varepsilon$= 1%, strain ratio R_ϵ= -1).

Results and analysis

For each shot peening cases, five DEM-FEM simulations were carried out to calculate the average residual stress. Coverage assessment method based on the outward normal of a shot peened surface introduced in [9] was used to define the number of shots to reach full coverage. Figures 5, 6 and 7 present the simulated and experimental measured residual stresses at different shot peening conditions for IN718, 300M and 7050AA, respectively. From these figures, it can be seen that for all the studies and materials and intensity ranges, the maximum compressive residual stresses are insensitive to the peening intensity, while the depth of the compressive stresses becomes deeper with the increase of intensity.

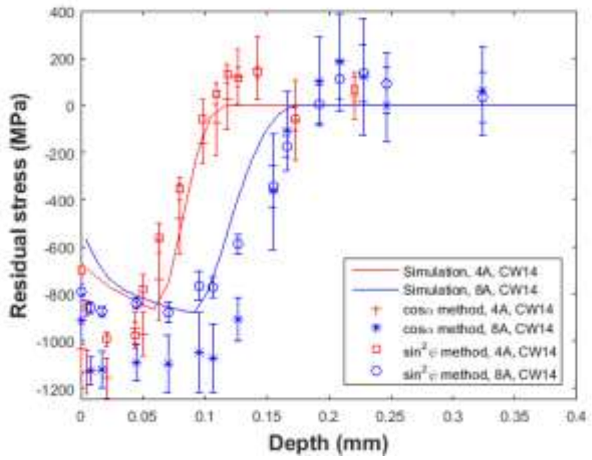

Figure 5 Residual stresses at full coverage for IN718 peened with intensities of 4A and 8A intensities.

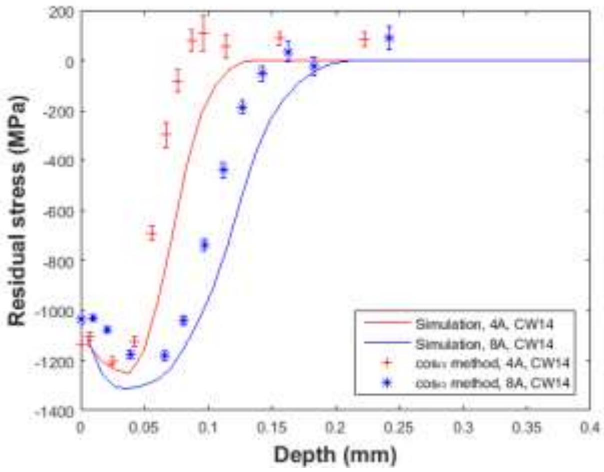

Figure 6 Residual stresses at full coverage for 300M peened with intensities of 4A and 8A intensities.

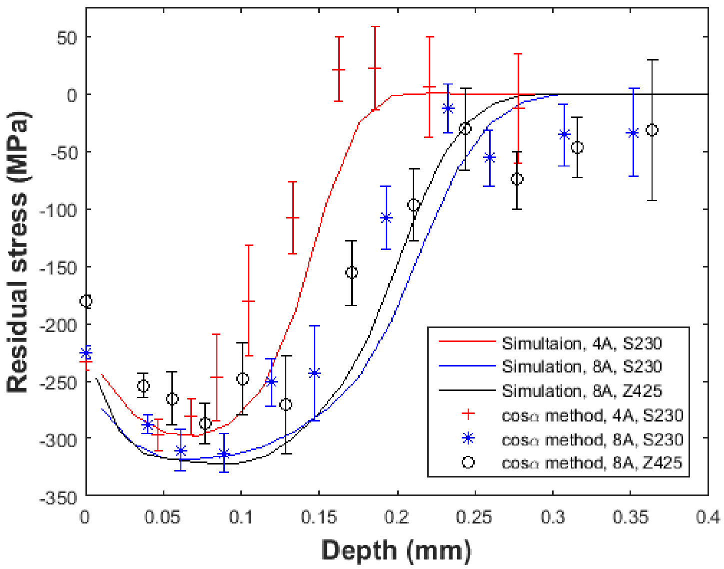

Figure 7 Residual stresses at full coverage for AA7050 peened with intensities of 4A and 8A (S230 and Z425 shots) intensities.

Figure 6 compares the simulated surface peak and valley roughness (R_{PV}) with the experimental measurements for each shot peening conditions. 25 sampling lines were used to extract surface roughness on shot peened surface from experiments, and 66 sampling lines were used to extract R_{PV} from numerical simulation. For IN718 and AA7050, the simulated surface roughness is underestimated by less than 12% compared with experiments. For 300M, the simulated roughness is overestimated around 19%.

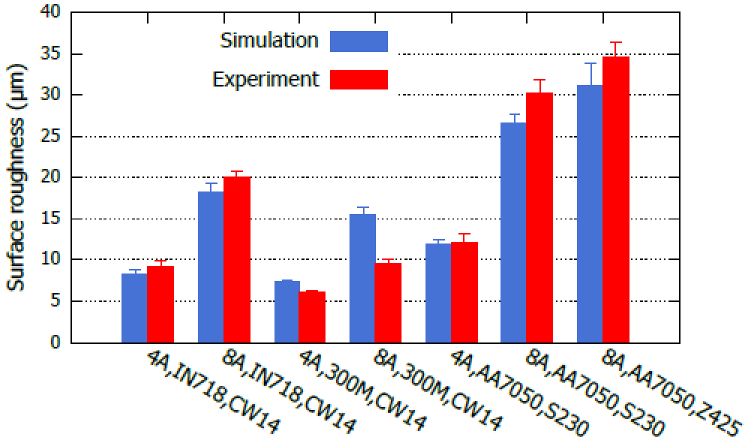

Figure 6 Surface roughness for different peening conditions: 8A and 4A, IN718, 300Mand AA7050.

Conclusions

A DEM – FEM coupled model in which conical shot stream accounting for shot stream expansion was simulated in DE and shot-target impacts were simulated by a periodic cell FE model, was proposed for shot peening simulation. The influences of target material (IN718, 300M and AA7050), impact intensities (4A and 8A) and shot type (CW14, S230 and Z425) on the distribution of residual stress profile and surface roughness were investigated. The predicted results were comparable with X-ray diffraction and surface roughness measurements.

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