Shot Peening Optimization using the Discrete Element Method

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Abstract
The aim of this study is to develop a Discrete Element Model (DEM) capable of simulating the main shot peening (SP) processes of industrial interest. By means of this model, shot - shot interaction, shot - target interaction and the overall shot flow were investigated in detail with limited computational effort. A new technique to dynamically change the coefficient of restitution (CoR) for repeated impacts of shots on the same spot was implemented to take into account the effect of material hardening. It emerges that changing the CoR for subsequent impacts has a significant influence on the predicted overall peening effect.
Keywords Shot Peening, Finite Element Method, Discrete Element Method, Coefficient of restitution, optimization.

Introduction

Shot peening (SP) is governed by several parameters, for instance: shot size, nozzle-to-treated surface distance, shot initial velocity and angle of attack (see Figure 1). The aim of the undertaken research is to develop a combined Discrete Element/Finite Element Model (FEM) to simulate the shot peening process that can assist understanding of the relationship between SP parameter and the residual stress distribution generated in the peened material.

Modeling shot peening (SP) processes is very complex since it involves the interaction of a metallic surface with millions of shots. Experimental studies can require high costs to optimize a new set of peening parameters. Numerical simulations can assist one to understand the influence of the individual peening parameters on the field of residual stresses and to achieve a prescribed peening target [1-4]. SP parameters are customarily chosen on the basis of either empirical laws or past practice. The relationship between the desired peening effect, particularly the residual stress distribution of the treated surface, and the peening parameters is still unknown and needs to be investigated. Different values of peening parameters may give rise to very different fields of residual stress distribution [5,6].

The objective of this work is to develop a numerical model that can acceptably simulate the SP process so that parameters may be selected on the basis of mechanical considerations. A new technique to dynamically change the coefficient of restitution for repeated impacts of shots in the same spot was implemented. Then, the DEM code EDEM was coupled with the Finite Element code Abaqus to run combined DEM/FEM analyses.

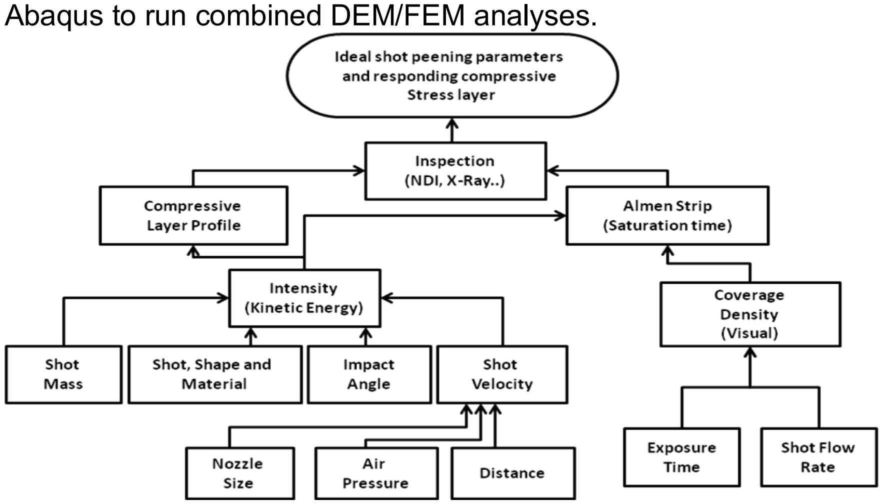

Figure 1: Parameters affecting the peening process.

1. DEM Contact Model

The Hertz-Mindlin contact law was used to model shot - shot and the shot - target surface interactions. The implementation of the contact law in the DEM code is based on the work of Mindlin [7] and Tsuji [8]. Viscous damping is applied during contact so that a prescribed coefficient of restitution is enforced at each interaction.

Coefficient of restitution for repeated impacts

The CoR depends on both the impact velocity, and the impact angle θ_i. Therefore, the values of the CoR in the normal and tangential directions should be determined for a set of values of v_i and θ_i where v_i is the initial velocity and θ_i the angle of impingement. The CoR for the shot – surface interaction will substantially vary depending on previous hits and plastic deformation of the component. Bhuvaragham et al. have performed a FE analysis and have retrieved values for the CoR for subsequent hits on the same location (Table 1).

Table 1: CoR for shot interaction after Bhuvaragham et al.[1].

Impact No	Input velocity m/sec	Rebound velocity m/sec	CoR
1	100	40.27	0.396
2	100	54.04	0.540
3	100	58.28	0.583
4	100	76.31	0.763

To change the CoR during the DEM simulation for repeated impacts we need to keep track of the location and the number of impacts per location. In this way, the CoR is assigned dynamically as a function of the number of previous impacts in a given location. Figure 2 shows the process diagram.

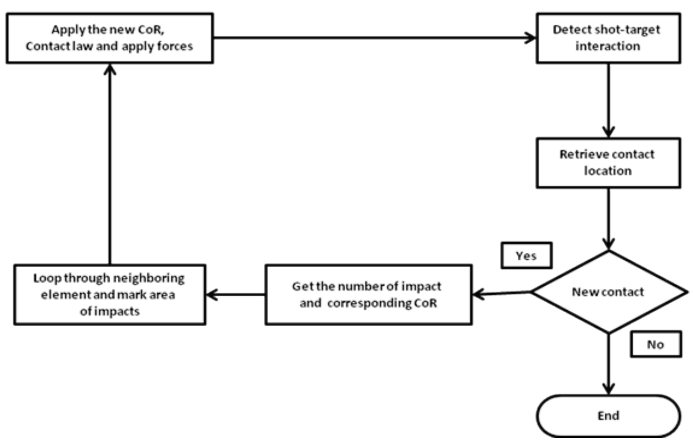

Figure 2: Process for changing the CoR for subsequent impacts.

Concerning the CoR for shot - shot interaction, e_{s-s} is different from the sphere-flat surface interaction e_{s-p}. In the absence of precise experimental data, e_{s-s} = 0.5 was assumed for both normal and tangential directions independently of the angle of impact and the relative velocity between colliding shots.

In order to validate our model, a comparison with early works of Bhuvaraghan et al. and Hong et al. [1,4] was carried out. The parameters employed in the simulation were the same as those selected by Hong et al. [4]. The time step for the DEM simulations was taken as the minimum between the 20 - 40% of the Rayleigh time step.

2. DEM Simulation: model setup

The Discrete Element Model was developed using the commercial code EDEM [9]. Shots were modeled as spherical particles generated from a circular nozzle and delivered onto a flat target surface. The nozzle was modeled using an inner diameter d_n and the distance between nozzle and target surface d with an angle of attack θ. The number of shots delivered from the nozzle in a time period is a function of the mass flow rate employed in the peening process. The initial velocity of the shots, v_i, depends on the air pressure in the nozzle. Drag forces and other fluid effects were neglected in the present model since their effect was deemed negligible. During each simulation, the time, position and velocity of the shot impacting the target surface were recorded.

The parameters employed in the DEM simulations are the following: shot diameter d_{shot}= 0.58 mm, density ρ = 7800 kg/m^3,E= 200 GPa and Poisson's ratio ν= 0.3. The target was a 30 x 30 x 30 mm cube with the following properties: elastic modulus E= 200 GPa and Poisson's ratio ν= 0.3 and density ρ = 7800 kg/m^3 respectively. The diameter of the nozzle was d_n= 8 mm with mass flow rate of $\dot{m}$= 9.25 kg/min and initial velocities v_i =50, 75 and 100 m/s. The distance from nozzle to target was d = 20 mm with various angles of attack employed: θ= 35°, 45°, 62.5°, 67.5° and 90°.

3. DEM – FEM Coupling

The DEM is unable to model plastic deformations and residual stresses induced on the treated surface. Hence, the FEM tool is to determine the compressive residual stresses on the peened component. A User Defined Library (UDL) is created within the EDEM program to log forces and locations. This information is then implemented into the Abaqus input file. Figure 3 shows the process flow diagram between the commercial DEM code EDEM and FEM code Abaqus [9,10].

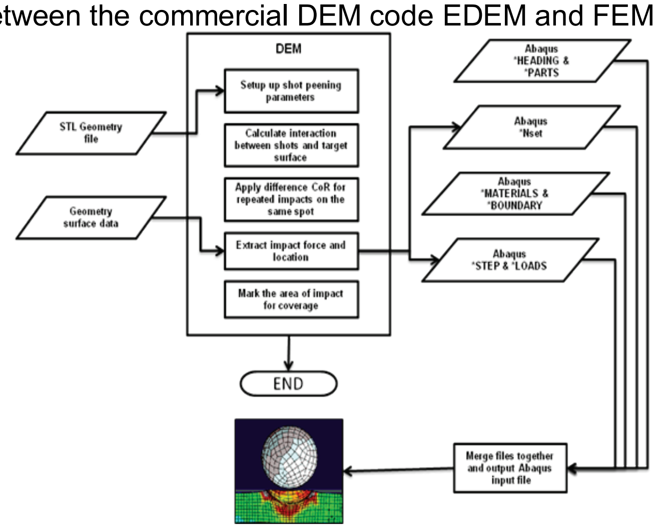

Figure 3: The diagram shows the DEM - FEM coupling process.

The coupling can be outlined in the following steps:

1. The *.stl geometry file is loaded into Abaqus and the material properties are selected. The input file is created and separated into dynamic and static parts. These are parts of the main input file that need to be populated and parts of the file that will remain unchanged regardless of the number of impacts, location etc. The main input file is divided into four separate files. The dynamic parts are discarded and the static parts are saved to be used in step 6.
2. The same *.stl file is loaded into the commercial EDEM program along with a file containing the geometry surface data from FEM.
3. The SP model is set up with the individual peening parameters.

4. The DEM SP simulation is run, applying the CoR for repeated impacts. For each new shot - target contact the highest force is recorded along with the impact location.
5. When the simulation ends, two separate files are created containing the *Nset, *Step and *Loads parts of the Abaqus file. Impacts that are further away from each other are grouped together and are computed simultaneously in the same time step. This reduces the computation time and the output size of the file.
6. The two output files created from the EDEM simulations are then merged together with the two files from step one to generate the main Abaqus input file.
7. The input file is then loaded into Abaqus to obtain the residual compressive stresses.

Depending on the target geometry size and number of impacts, the input file can become very large. Running a set of programs to translate the DEM output file to generate a computable FE input can be very time consuming. Generating the FE input file within the DEM application is more efficient and less time consuming as the sorting and population process is performed within the DEM program.

4. Results and Discussion

DEM Simulation - Individual shot parameters

SP parameters were investigated using the new developed DEM model. An important step in the analysis is to identify the steady state for the flow of shots. About 64% of shots hit the target surface with initial velocity ($v_{imp} = 0.9{\sim}1.0\ v_i$) in the first 50 impacts, indication that they had no or only little interaction with other shots before impact. Figure 4 shows the effect of impact numbers. The impact velocity distribution reaches steady state after 4000 impacts. Next the distance between nozzle and target surface was investigated. Figure 5 shows the number of shot – target interactions for different values of nozzle distances, d, ranging from 5mm to 40mm. It merges that the number of shot – target collisions remain almost constant when d > = 20 mm. Therefore, a distance $d =$ 20 mm was employed throughout this study.

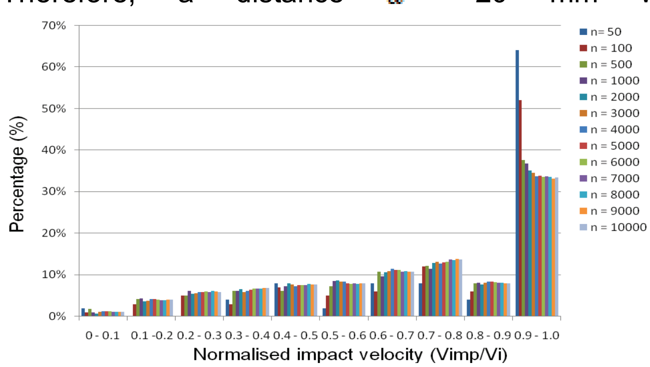

Figure 4: Effect of impact number.

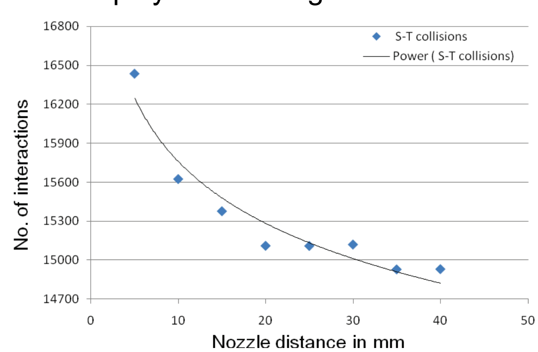

Figure 5: Effect of nozzle distance.

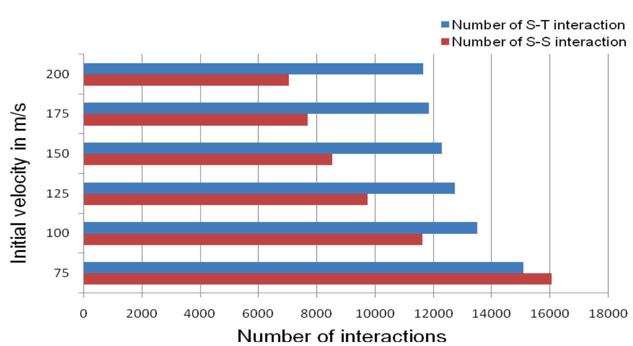

Figure 6: Shot interaction at different initial velocity.

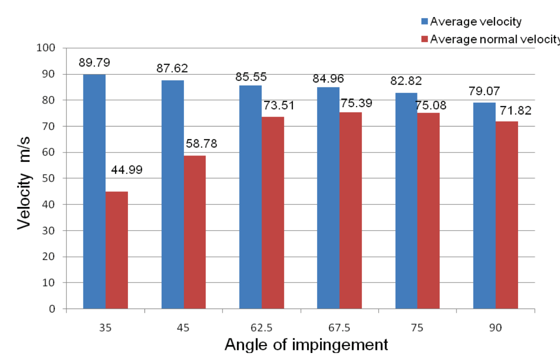

Figure 7: Impact velocity for different angle of attack.

Figure 6 shows the number of shot interactions at different initial velocities v_i and constant mass flow rate r_m. Results show that number of shots – target and shot – target interaction increase with a lower initial velocity. After the first target collision, the shots lose about 40% of their initial velocity and hence rebound at a much lower velocity. When shots rebound at a lower velocity, the probability of hitting the incoming shots is much higher.
To investigate the effect of angle of attacks, the normalized impact velocity v_{imp}/v_i for the different angles of attack was recorded. Figure 7 showing the average and normal shot- target velocity at impact. Results show that for θ=35°, about 74% of shots retained their initial velocity and for θ=90° only 50% shots retained their initial velocity. This is due to the high number of rebounding shots colliding with the incoming shots. And results for θ=45° was 72%, θ=62.5° 66%, θ=67.5° 64% and θ=75° 60%. However, for generating the compressive residual stresses, the normal impact velocity v_n is more significant than that of the tangential impact velocity v_t. v_n contributes to the depth of the normal stresses σ and v_t the component parallel to the plane, the shearing stresses τ. Looking at v_n, θ=62.5° is most effective with a large number shots retaining initial velocity and highest average normal velocity at impact with 62.83 % followed closely by θ=67.5° with 62.33% retaining their initial velocity.
All the results derived from the DEM simulations agree well from a qualitative point of view, with the experiments performed by Hong et al. [4].

Effect of a variable CoR for subsequent impacts
The effect of the CoR on shot - shot and target - shot interaction for repeated impacts was investigated. Figure 8 shows the energy dissipation for shot – target interaction with a fixed CoR and the energy dissipation for shot – target interaction with changing CoR. In practice the region of influence will depend on the impact velocity, angle of impact and the shot size. The indentation area is affected by shot size, the impact velocity (the higher the velocity the larger the dimple) and the angle of impingement (an oblique angle generates an elliptical dimple). For simplicity, the region of influence was chosen as the average shot diameter (0.58mm). When applying the CoR dynamically the energy dissipation decreases with the increase of indentation radius. Table 2 shows the results for constant and variable CoR for 10,000 impacts. A target location that is being hit for the first time has a low CoR, resulting in high energy dissipation. The next shot hitting a location that was hit previously and plastically deformed the target surface has a higher CoR, resulting in lower energy dissipation. Subsequent shots hitting the target surface will rebound with a higher velocity than the first shot and retaining more of their kinetic energy.
Results show that shot – shot interaction decreases and shot – target interaction number increases. More importantly the average normal velocity at impact increases, which is important for the generation of compressive residual stress. Changing the CoR for repeated impacts will result in a more intense compressive residual stress distribution.

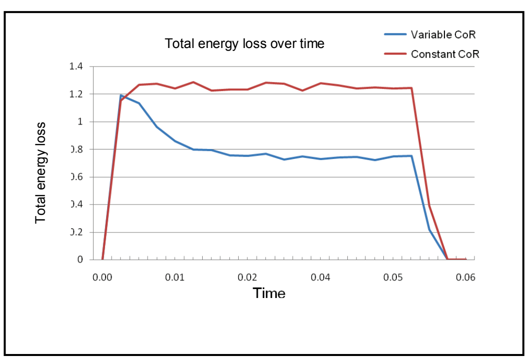

Figure 8: Showing the energy dissipation for shot – target with a constant CoR 0.4 and the energy dissipation for shot - target interaction with changing the CoR for the case with indentation radius 0.58.

Table 2: Shows the results for indentation radius d_{shot}.

	Constant CoR	Variable CoR with indentation radius 0.58
Shot - Shot collision	6485	5912
Shot - Target collision	13959	15615
Total Energy Loss through shot - target collision in J	21.99	13.1993
Average velocity at impact in m/s	78.29	79.3572
Average normal velocity at impact in m/s	62.38	63.7258

5. Conclusion

A computational model of the shot peening process based on a combined discrete element – finite element method has been presented. The DEM model provides a rapid method to investigate the individual peening parameters. A simulation with SP process having 10 000 impacts can be achieved in only a few minutes. This simulation of the SP process is far from a complete SP model, but it can assist to understand the shot peening process further and contribute to the development of new models. Future work is focusing on the optimization of the DEM - FEM coupling process and the validation of the FE model to analyze the residual stress profile resulting from different peening parameters.

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