A NUMERICAL SIMULATION TO RELATE THE SHOT PEENING PROCESS PARAMETERS TO THE INDUCED RESIDUAL STRESSES

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ABSTRACT

This paper presents a computational modelling of the shot peening process, in which the finite element (FE) method was employed to study the elastic-plastic dynamic process of the shot impact on a metallic target, and the discrete element (DE) method was used to study the multiple particles dynamics. The results obtained from the DE simulation demonstrated the capability of the method to capture realistic behaviour especially the interaction between the incoming shots with rebound shots. Careful statistical analyses of the shot impact data reveal the relationships between peening process parameters and peening quality, which are very useful for identifying those parameters which need to be controlled and regulated in order to produce a more beneficial compressive residual stress distribution within the target.

KEYWORDS: shot peening, finite element analysis, discrete element method, compressive residual stress

1. INTRODUCTION

Shot peening is a very complex process, involving dynamic analysis of a huge number of shot impacts on a metallic target which can often have complex geometry. There are a significant number of parameters involved in shot peening which may be regulated to produce a more beneficial compressive residual stress distribution within the target. With the availability of greatly increased computing power and the widespread use of commercial programs in recent years, the use of numerical methods in simulating shot peening processes is becoming an increasingly attractive alternative. Most of the previous studies employed FE method to simulate single/multiple shot impacts and examined the effect of several parameters on the resulting residual stress distribution (e.g. Meguid, 1999, 2002; Rouhaud, 2002). The FE method provides a powerful method for establishing quantitative relationships between shot and target parameters and residual stress characteristics. The dynamic impacting of single or multiple shots with high velocity and the double non-linearity of the problem due to the contact of two bodies and the elastic-plastic behaviour of the target can all be taken into account in an appropriate FE analysis. As mentioned above shot peening is a very complex process in which a huge number of shots (more than 10^6) are involved in industrial applications. FE cannot model a stream of so many shots impacting on a target. The discrete element (DE) method (Cundall, 1979) for modelling particle dynamics is now being applied to a wide range of engineering problems. A combined finite/discrete element simulation of the shot peening process was developed by Han et al (2000a,b; 2002). They did not model the nozzle geometry or investigate the process parameters in the simulation, so the pattern of shot impacts on the target was specified rather than predicted.

This paper presents a computational modelling of the shot peening process, in which the finite element (FE) method was employed to study the elastic-plastic dynamic process of the shot impact on a metallic target, and the discrete element (DE) method was used to simulate the stream of shots delivered onto a target and drained from the area of impact. The DE model developed was used to study the effect of process parameters on peening quality. Careful statistical analyses of the shot impact data reveal the relationships between process parameters and peening quality, which are very useful for identifying those parameters which need to be controlled and regulated in order to produce a more beneficial compressive residual stress distribution within the target.

2. FINITE ELEMENT ANALYSIS AND RESULTS

2.1 Finite element model

The three-dimensional FE model was developed using the commercial finite element code ABAQUS Explicit 6.3. Figure 1 shows the FE mesh that was used to investigate single/multiple shot peening. Only one half of the circular plate was analysed by exploiting symmetry. The circular plate was restrained against all displacements and rotations on the bottom end and was given the following geometric properties: radius $R=8d_{shot}$, height $H=3d_{shot}$ where d_{shot} is the shot diameter. Eight-node linear brick elements with reduced integration were used with element size $0.05d_{shot} \times 0.05d_{shot} \times 0.05d_{shot}$ in the impact region. Shot chosen for industrial application is at least as hard as the impacted target material. For simplicity, a rigid sphere was chosen to model the shot. In ABAQUS Explicit, rigid bodies can be defined with an analytical rigid surface. So, a fully spherical surface with a mass positioned at its centre was used to model a shot as shown in Fig. 1. Convergence tests were conducted using different meshes and element types to ensure the numerical results were not affected by the choice of mesh or element types.

2.2 FE results

Following numerical validations, a parametric study was conducted to investigate the effect of shot and target parameters on the residual stress pattern including shot size, impact velocity and angle; target material properties (initial yield stress, strain hardening, strain rate dependent material); shot impact with overlap; and peening coverage (Hong et al, 2005). The aim is to build a better understanding of the shot peening process from a comprehensive set of residual stress predictions arising from the key parameters. With the space constraint in the paper, a small set of results is presented here. In this study, the target is assumed to be a linear elastic strain-hardening plastic material and the properties are: elastic modulus E=200GPa, Poisson's ratio $\nu=0.3$, density $\rho=7800\text{kg/m}^3$, initial yield stress $\sigma_0=760\text{MPa}$ and linear strain-hardening parameter $H^1=500\text{MPa}$. For the shot, the reference value of the impact velocity is 75m/s and the diameter d_{shot} is 1mm. Using a steel density of 7800kg/m^3, the mass of the shot m=4.085mg. Coulomb's law, with a friction coefficient $\mu=0.20$, is used for contact modelling.

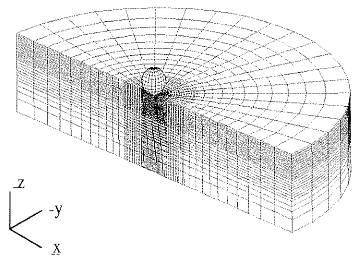

Fig. 1 Three-dimensional FE mesh

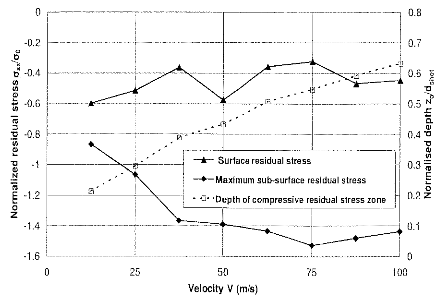

Fig. 2 Influence of shot impact velocity (normal impact)

First the influence of shot velocity for normal impact was investigated. The variations of the surface residual stress, maximum sub-surface residual stress and depth of the compressive residual stress zone with shot velocity are shown in Fig. 2. The impact velocity appeared to have little effect on the surface residual stress, but showed significant effect on the maximum sub-surface residual stress and depth of compressive residual stress zone. As the strain-hardening material was used, the maximum compressive residual stress reached $1.5\sigma_0$, which is higher than the initial yield stress of the target.

Then oblique impact was considered. The impact velocity of shot is v=75m/s with an impact angle α, so the components of velocity along three coordinates are v_x=vcosα, v_y=0 and v_z=-vsinα. Figure 3 shows the relationships between the surface residual stress, maximum sub-surface residual stress and depth of the compressive residual stress zone as functions of the impact angle α. As expected, normal or close to normal impact with $\alpha \rightarrow 90^0$ produces the most beneficial compressive residual stress regime within the target. However with a continuous stream of shots in practice, the interaction between incoming and rebounding shots increases for normal impact, so significant impact energy may be lost in the process.

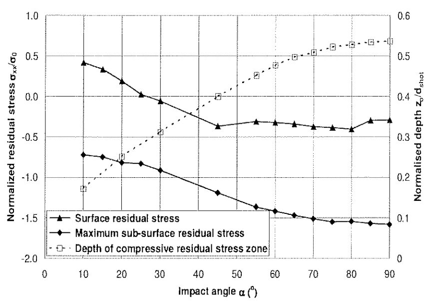

Fig. 3 Influence of impact angle α (v = 75m/s)

3. DISCRETE ELEMENT SIMULATION AND RESULTS

3.1 DE modelling of shot streams

Whilst FE can successfully model the complex interaction between the material non-linearity with the non-linear contact in shot peening, it cannot model a stream of many discrete shots impacting on a surface. The DE method was used to simulate the stream of shots delivered onto a target and drained from the area of impact. The DE method tracks the motion of each individual particle and its interaction with other particles and boundary surfaces using Newton's laws of motion and constitutive laws for the contact and body forces. The contact law is commonly based on a spring-damper type model. The spring stores the displacement strain energy, and the damper represents the dissipation of energy during deformation of the contact.

The three-dimensional DE model was developed using the commercial discrete element code EDEM (DEM Solutions Ltd). As shown in Fig. 4, shots are delivered from a straight circular nozzle, to impact the surface of a target. Inner-diameter of the nozzle is d_n, the distance between nozzle and surface is d, and angle of inclination to the horizontal surface is θ. In this simulation, shot is treated as a rigid sphere, and all shots are identical. Using the Particle Factory Function in EDEM, shots were generated at the nozzle cross-section randomly. In practice, the number of shot delivered from the nozzle in a period depends on the mass flow rate used in the peening process. The initial velocity of shot delivered from the nozzle depends on the air pressure set in the nozzle. The drag and other fluid effects are neglected in the present model but can be included in a later stage. Nonlinear Hertz-Mindlin contact law is used to model the interactions between shot-shot and shot-target. Energy dissipations associated with shot-shot and shot-target collisions are accounted for using the coefficients of restitution $\xi_{s\text{-}s}$ and $\xi_{s\text{-}t}$ respectively. Figure 5 shows a snapshot of the DE simulation.

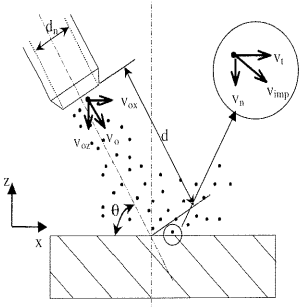

Fig. 4 DE simulation of shot peening

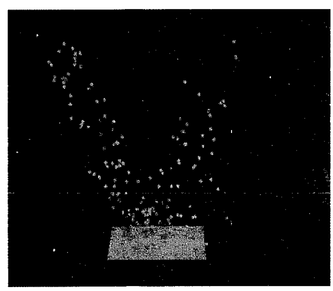

Fig. 5 Snapshot of DE simulation animation

It is well known that the peening quality (compressive residual stress distribution within the target) depends significantly on the energy transfer from the shot stream into the plastic deformation in the target. One direct way to evaluate the impact energy is to determine the velocity of shot just before impact. In the present study, when an interaction between a shot and the target is detected, the data (including time of impact, spatial position, translation velocities and rotating velocities) of the shot just before impact on the surface are recorded and used for statistical analyses. As shown in Fig. 4, the velocity of shot delivered from the nozzle is termed as initial velocity v_o, the components of this velocity along three coordinates are v_{ox}, v_{oy}, and v_{oz} respectively. The total kinetic energy of all shots generated in the nozzle E_o can be obtained using the initial velocity and total number of shots generated. This would not be the same as the kinetic energy of the shots impacting on the target E_{imp}, which relates to the number of shots and velocity just before impact. The velocity of the shot just before impact on the target is termed as impact velocity v_{imp}. The components of the impact velocity along normal and tangential direction to the surface are referred to as normal impact velocity v_n and tangential impact velocity v_t, and the kinetic energy corresponding to these two velocity components are E_n and E_t respectively.

3.2 Effect of peening process parameters

In practice, there are a significant number of parameters involved in shot peening which need to be controlled and regulated in order to produce a more beneficial compressive residual stress distribution within the target. Here, the effect of process parameters such as mass flow rate, initial velocity (nozzle air pressure) and angle of incidence is investigated. The properties of the shot and the target are kept constant in the following simulations. The shot is elastic, with diameter d_{shot}=0.58mm, density ρ=7800kg/m^3, elastic modulus E=200GPa and Poisson's ratio ν=0.3. The target material is: elastic modulus E=200GPa, Poisson's ratio ν=0.3, density ρ=7800kg/m^3. The nozzle geometry is: inner-diameter d_n=8mm, and the distance from the surface d=20mm. Several values of the distance were used, the effect of the distance on peening quality is found to be not significant as long as d is greater than 20mm. Using this model, a matrix of simulations covering a range of mass flow rate, angle of incidence and initial velocity were performed. The values adopted for these parameters are: mass flow rate r_m=5.5, 9.25, 13kg/min; angle of incidence θ=35°, 62.5°, 90°; and initial velocity v_0=50, 75, 100m/s. For simplicity, the component of initial velocity along y-direction is assumed to be zero in this study. A small variation of initial velocity is assumed, so that the initial velocity components randomly distributed between the bounds: $v_{ox}=v_0\cos\theta\pm\Delta v$, $v_{oy}=0\pm\Delta v$ and $v_{oz}=v_0\sin\theta\pm\Delta v$, in which Δv=1m/s. The coefficients of restitution for shot-shot $\xi_{s\text{-}s}$=0.5 and shot-target $\xi_{s\text{-}t}$=0.4 are deduced from the FE results of two-shot collision and single shot impact on target. The friction contact is considered for shot-shot and shot-target interactions, friction coefficient μ=0.20 is used for both interactions.

The effect of mass flow rate is investigated first. Figure 6 shows the distribution of the normal impact velocity for three different mass flow rates. The normal impact velocity v_n is normalised with v_{oz} the component of initial velocity along the same direction. The results are obtained from a statistical analysis of the data for the first 10000 impacts. A study of the impact velocity distribution for different time intervals has shown that the velocity distribution reaches a steady state after the initial period of about 3000 impacts. So, the results from 10000 impacts as presented in this paper can be taken as the steady state outcome for each set of parameters.

The differences between the results for different mass flow rates are significant. For a lean flow rate with r_m=5.5kg/min, more than 65% of the impacts maintained the initial normal velocity from the nozzle ($0.9v_{oz}$ ~$1.0v_{oz}$). This means that for these shots, little or no energy has been dissipated on their path from the nozzle to the target. For the high flow rate of r_m=13kg/min, less than 35% of the impacts maintained the initial velocity when they impact on the target. The increasing interaction between shots for a higher flow rate has caused a larger energy dissipation. It is also interesting to note that the velocity of the impact the second or third time round is much smaller than its initial velocity. The result thus suggests that a lower mass flow rate is better with a smaller energy dissipation associated with shot-shot collisions.

The effect of initial velocity is examined next. In practice, the air pressure in the nozzle controls the initial velocity. In this numerical study, the velocity corresponding to air pressure used typically in shot peening is studied. The effect of initial velocity is shown in Fig. 7. As the initial velocity increases, the probability of interactions between shots decreases because each shot moves quickly and has less time to interact. This results in a higher percentage of shots impacting with their initial velocities. The FE predictions (Fig. 2) already showed that a more beneficial compressive residual stress profile can be obtained with a moderately high normal impact velocity of shot. This study thus indicates that a high air pressure is beneficial in a peening process.

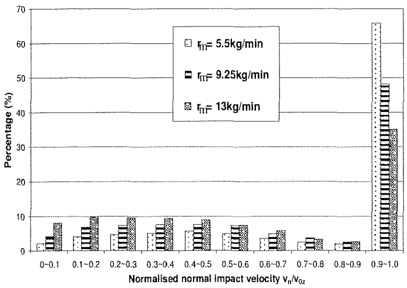

Fig. 6 Effect of mass flow rate (v_0=75m/s, θ=62.5°)

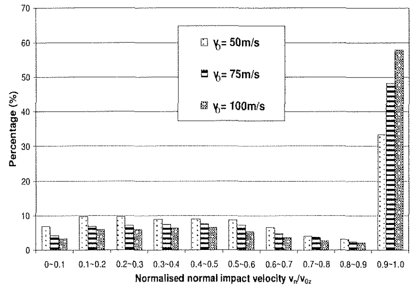

Fig. 7 Effect of initial velocity v_0 (r_m=9.25kg/min, θ=62.5°)

Finally the effect of angle of incidence was investigated. For clarity, the results are plotted in Fig. 8 with the direct values of the normal impact velocity in m/s. For θ=35° case, a very high percentage (close to 70%) of shots retain their initial velocity due to fewer interactions between shots. However the value of normal impact velocity is reduced considerably because of the low angle of incidence. When θ=90°, the shot-shot collisions increased considerably since the track of rebound shots coincides with that of incoming shots, resulting in less than 20% of shots retaining their initial velocity on impact. These shots naturally impact with much higher normal velocity ($v_{0z}\approx$75m/s) than the θ=35° case. The results for θ=62.5° are in between those of θ=35° and θ=90°, with about 45% shots retaining their initial normal velocity of $v_{0z}\approx$67m/s. For further clarity, some ratios of energy have been calculated and listed in Table 1. For the case of θ=35°, although ~95% of the total kinetic energy input is available on impacting the target, only 27% of this total energy is the energy from normal impact which is a key factor in generating residual stress. For θ=90°, the shot-shot collisions dissipate a much larger proportion of the total kinetic energy (36%), but the remaining 64% is almost all normal impact energy, directing contributing to generating residual stress. Broadly speaking, the ratio of the normal impact energy to the total energy E_n/E_0 is probably the best indicator and this shows that θ=62.5° case is the most effective at 57%.

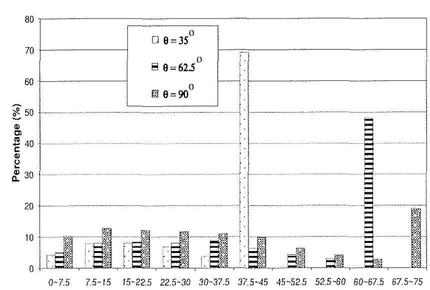

Fig. 8 Effect of angle of incidence θ (v_0=75m/s, r_m=9.25kg/min)

Table1 Ratios of Energy (after 10000 impacts)

	shots	E_n/E_0	E_t/E_0	E_{imp}/E_0
$\theta = 35^o$	9079	0.27	0.68	0.95
$\theta = 62.5^o$	8150	0.57	0.25	0.82
$\theta = 90^o$	6374	0.55	0.09	0.64

4. CONCLUSIONS

A computational modelling of the shot peening process has been presented. Using this numerical model, a parametric study was conducted to investigate the effect of several shot, target and process parameters on the induced residual stress profile within the target. The FE calculations can be used to evaluate the influence of the shot and target parameters on the residual stress profile. The DE simulations have been shown to be able to model the actual peening process. The statistical analysis of the impact data shows the characteristics of the impact velocity arising from the peening process. Further study is being undertaken including exploring the spatial distribution of the impacts and how that influences the residual stress pattern.

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REFERENCES

Meguid, S. A., Shagal, G., Stranart, J. C., Daly, J. (1999), Three-dimensional dynamic finite element analysis of shot-peening induced residual stresses, *Finite Elements in Analysis and Design*, 31, pp.179-191.

Meguid, S. A., Shagal, G., Stranart, J. C. (2002), 3D FE analysis of peening of strain-rate sensitive materials using multiple impingement model, *International Journal of Impact Engineering*, 27, pp.119-134.

Rouhaud, E., Deslaef, D. (2002), Influence of shots' material on shot peening, a finite element model, *Materials Science Forum*, 404-407, pp.153-158.

Cundall, P.A., Strack, O.D.L. (1979), A discrete numerical model for granular assemblies, *Geotechnique*, 29, pp.47-65.

Han, K., Peric, D., Crook, A.J.L., Owen, D.R.J. (2000a), A combined finite/discrete element simulation of shot peening processes Part I: studies on 2D interaction laws, *Engineering Computations*, 17, pp.593-619.

Han, K., Peric, D., Owen, D.R.J., Yu, J. (2000b), A combined finite/discrete element simulation of shot peening processes Part II: 3D interaction laws, *Engineering Computations*, 17, pp.680-702.

Han, K., Owen, D.R.J., Peric, D. (2002), Combined finite/discrete element and explicit/implicit simulation of peen forming process, *Engineering Computations*, 19, pp.92-118.

Hong, T., Ooi, J.Y., Shaw, B.A. (2005), Three-dimensional finite element analysis of residual stress induced by single/multiple shots impact", *Internal Report*, School of Engineering & Electronics, University of Edinburgh.