*Applied Mechanics and Materials* *Online: 2007-12-06*
*ISSN: 1662-7482, Vols. 10-12, pp 493-497*
*doi:10.4028/www.scientific.net/AMM.10-12.493*


# Optimising Shot Peening Parameters Using Finite Element and Discrete Element Analysis

T. Hong[1,a], D.H. Wen[1,b] and J.L. Yuan[1,c]

[1]Precision Engineering Laboratory, Zhejiang University of Technology,

Hangzhou, Zhejiang, China (310014)

[a]hz6770@hotmail.com, [b]wdh_74@163.com, [c]jlyuan@zjut.edu.cn

**Keywords:** Shot peening, Finite element, Discrete element, Compressive residual stress

**Abstract.** Shot peening is a cold-work process in which a stream of small spherical shot is blasted against a metallic component to generate a high compressive residual stress regime at the surface of the target. 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. Statistical analyses of the shot impact data reveal the relationships between peening process parameters and peening intensity, which can be used to optimise these process parameters to produce an improved outcome.

## Introduction

Shot peening is a complex process that involves a huge number of shot (small spherical ball, 0.2~1mm) with high velocity typically in the range of 50-100 m/s, impacting on a metallic target that may have a complex geometry. The use of computational methods to simulate shot peening is becoming an attractive alternative. Most of the previous studies employed FE method to simulate single/multiple shot impacts and examined the effect of some parameters on the resulting residual stress distribution (e.g. [1]~[3]). 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. However FE cannot realistically model the huge number of shots (more than say $10^6$) that are involved in typical industrial applications. The discrete element (DE) method [4] for modelling particle dynamics is increasingly 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 [5, 6]. However 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 FE method was employed to study the elastic-plastic dynamic process of the shot impact on a metallic target, and the 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 intensity. Statistical analyses of the shot impact data reveal the relationships between process parameters and peening intensity, which can be used to optimise the process parameters to produce an improved outcome.

## Finite Element Analysis and Results

**FE Model.** The three-dimensional FE model was developed using the commercial finite element code ABAQUS. Figure 1 shows the FE mesh that was used to investigate single shot impacted on a target. 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 = 8$d_{shot}$, height H = 3$d_{shot}$ where $d_{shot}$ is the shot diameter. Eight-node linear brick elements with reduced integration were used with element size 0.05$d_{shot}$ × 0.05$d_{shot}$ × 0.05$d_{shot}$ in the impact region. Shot chosen for industrial application is often as hard as the impacted target material. For simplicity, 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.

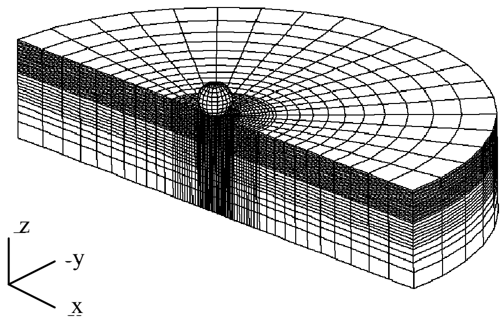


Fig.1 Three-dimensional FE mesh

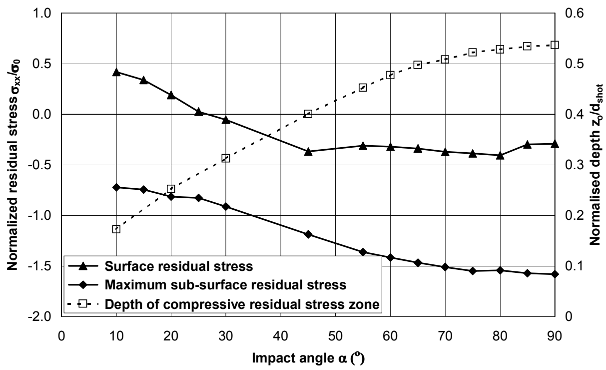


Fig.2 Influence of impact angle α (v = 75m/s)

**FE Results.** Following numerical validation, 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); multiple shot impacts; and peening coverage [7,8]. 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. 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 ν = 0.3, density ρ = 7800kg/m$^3$, initial yield stress $\sigma_0$ = 760MPa and linear strain-hardening parameter $H^1$ = 500MPa. The diameter of shot $d_{shot}$ is 1mm. Using a steel density of 7800kg/m$^3$, the mass of the shot m = 4.085mg. Coulomb's law, with two different friction coefficients μ = 0.2, were used for contact modelling.

The influence of shot oblique impact was investigated here. 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 2 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 α→90$^o$ 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.

## Discrete Element Simulation and Results

**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 three-dimensional DE model was developed as shown in Fig. 3, shots were delivered from a straight circular nozzle, to impact the surface of a plane target. Inner-diameter of the nozzle is $d_n$, the distance between nozzle and target surface is d, and angle of inclination to the horizontal surface is θ. In this simulation, 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. Nonlinear Hertz-Mindlin contact law was used to model the interactions between shot-shot and shot-target. Energy dissipations associated with shot-shot and shot-target collisions were accounted for using the coefficients of restitution $e_{s-s}$ and $e_{s-t}$ respectively.

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 was detected, the data (including time of impact, spatial position, translation and rotating velocities) of the shot just before impact on the surface were recorded and used for statistical analyses. As shown in Fig. 3, the velocity of shot delivered from the nozzle is termed as initial velocity $v_o$, the components of this velocity along the 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.

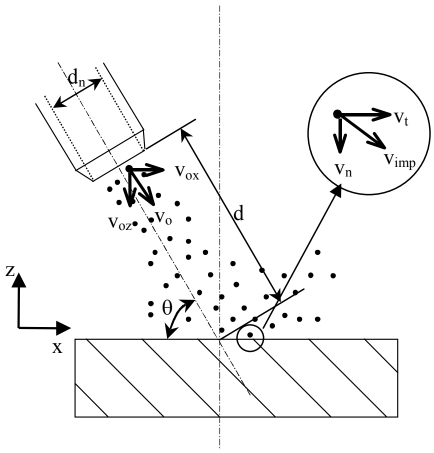

Fig. 3 DE simulation of shot peening

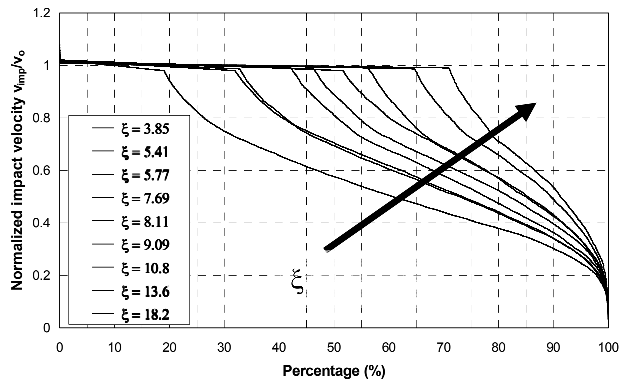

Fig. 4 Effect of parameter ξ (m/kg) (θ = 62.5°)

**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 nozzle geometry is: inner-diameter $d_n$ = 8mm, and the distance from the surface d = 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 $\theta$ = 35°, 45°, 62.5°, 67.5°, 90°; and initial velocity $v_o$ = 50, 75, 100m/s. A small variation of initial velocity was assumed, so that the initial velocity components were randomly distributed between the bounds: $v_{ox} = v_o\cos\theta \pm \Delta v$, $v_{oy} = 0 \pm \Delta v$ and $v_{oz} = v_o\sin\theta \pm \Delta v$, in which $\Delta v$ = 1m/s. The coefficients of restitution for shot-shot $e_{s-s}$ = 0.5 and shot-target $e_{s-t}$ = 0.4 were deduced from the FE results of two-shot collision and single shot impact on target. The friction contact was considered for shot-shot and shot-target interactions, with friction coefficient $\mu$ = 0.2 used for both interactions.

The effect of mass flow rate $r_m$ and initial velocity $v_o$ was investigated first. To demonstrate the results, a parameter is defined as $\xi = v_o/r_m$. Figure 4 shows the distribution of the impact velocity for several different values of ξ (m/kg). The impact velocity $v_{imp}$ is normalised with the initial velocity $v_o$. As shown in Fig. 4, the differences between the results for different values of $\xi$ are significant. For the biggest value of $\xi = 18.2$ m/kg, more than 70% of the impacts maintained the initial velocity from the nozzle ($\sim 1.0v_o$). This means that for these shots, little or no energy has been dissipated on their path from the nozzle to the target. For the small value of $\xi$ such as $\xi = 3.85$ m/kg, only about 20% of the impact maintained the initial velocity on impact. As the initial velocity increases, the probability of interaction 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. As the mass flow rate increases corresponding to the parameter $\xi$ decreasing, the interaction between shots increases resulting in an increase in dissipated energy. A lower mass flow rate is thus better with a smaller energy dissipation associated with shot-shot collisions. The FE prediction showed that a more beneficial compressive residual stress profile could be obtained with a moderately high normal impact velocity. This study thus suggests that a high air pressure (initial velocity) together with a lower mass flow rate, giving a large value of parameter $\xi$, is beneficial for peening process.

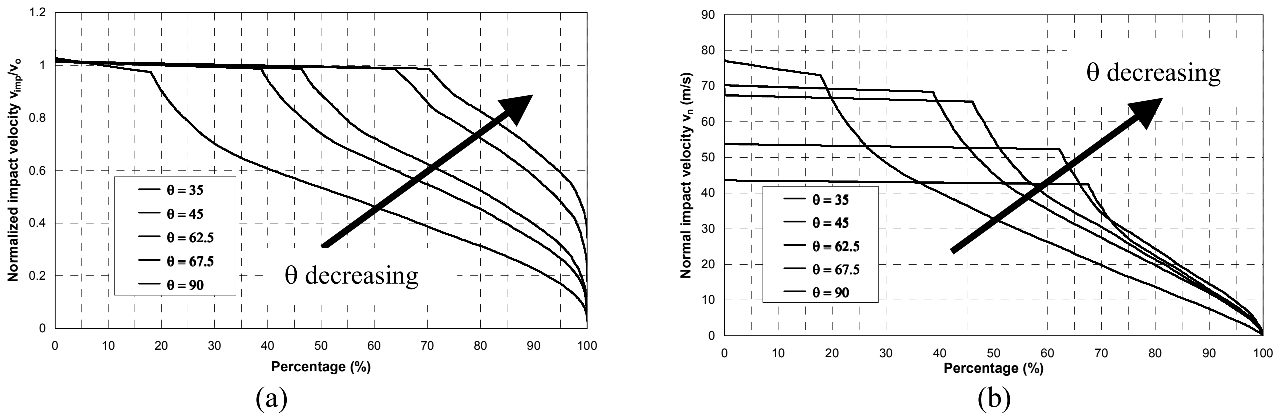


Fig. 5 Effect of angle of incidence $\theta(^o)$ ($\xi = 8.11$m/kg)

The effect of angle of incidence was investigated next. Figure 5a shows the distribution of the impact velocity for five different angles of incidence. For $\theta = 35^o$ case, a very high percentage (about 70%) of shots retain their initial velocity due to fewer interactions between shots. When $\theta = 90^o$, the shot-shot collisions increased considerably since the track of rebound shots coincides with those of incoming shots, resulting in only about 18% of shots retaining their initial velocity on impact. The results for $\theta = 45^o$, $62.5^o$, $67.5^o$ are in between those of $\theta = 35^o$ and $\theta = 90^o$, with about 64%, 46%, 39% shots retaining their initial normal velocity ($\sim 1.0v_o$). Since the normal component of the impact velocity is much more important than the tangential component for generating compressive residual stress, the distribution of the normal impact velocity $v_n$ as a function of the angle of incidence is explored further in Fig. 5b. For $\theta = 35^o$ case, a very high percentage (about 67.5%) of shots have normal impact velocity $v_n \approx 43.5$m/s, however this value is much smaller than the initial velocity $v_o = 75$m/s because of the low angle of incidence. When $\theta = 90^o$, less than 20% of shots retaining their initial velocity on impact, but these shots naturally impact with a much higher normal velocity ($v_n \approx 75$m/s) than the $\theta = 35^o$ case. For further clarity, some ratios of energy have been calculated and listed in Table 1. For the case of $\theta = 35^o$, 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 $\theta = 90^o$, 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, directly contributing to generating residual stress. Broadly speaking, the ratio of the normal impact energy to the total energy $E_n/E_o$ is probably the best indictor and this shows that $\theta = 62.5^o$ case is the most effective at 57%.

Table 1 Ratios of Energy (after 10000 impacts)

| | shots | $E_n/E_o$ | $E_t/E_o$ | $E_{imp}/E_o$ |
|---|---|---|---|---|
| $\theta = 35^o$ | 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 |

## Conclusion

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 two consecutive shots, 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.

## References

[1] S.A. Meguid, G. Shagal, J.C. Stranart and et al: Finite Elements in Analysis and Design Vol.31 (1999), pp.179-191.

[2] S.A. Meguid, G. Shagal and J.C. Stranart: International Journal of Impact Engineering, Vol.27 (2002), pp.119-134.

[3] E. Rouhaud and D. Deslaef: Materials Science Forum, Vol.404-407 (2002), pp.153-158.

[4] P.A. Cundall and O.D.L. Strack: Geotechnique, vol.29 (1979), pp.47-65.

[5] K. Han, D. Peric, A.J.L. Crook and D.R.J. Owen: Engineering Computations, Vol.17 (2000), pp.593-619.

[6] K. Han, D. Peric, D.R.J. Owen and J. Yu: Engineering Computations, Vol.17 (2000), pp.680-702.

[7] T. Hong, J.Y. Ooi and B.A. Shaw: submitted to Advances in Engineering Software, (2006).

[8] T. Hong, J.Y. Ooi and B.A. Shaw: submitted to Computers and Structures, (2006).