Multiple impact modelling for shot peening and peen forming

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Abstract: Impact modelling for shot peening or peen forming has progressed from simulating a single impact (or local multiple impacts) to simulating a large number of multiple impacts. It is the aim of this paper to provide quantitative results with a detailed finite element study, and to compare the effects of a single impact and global multiple impacts. Using a two-dimensional (2D) axisymmetric single impact model with a very fine mesh as reference, an appropriate three-dimensional (3D) mesh density for the target material is chosen by evaluating the 3D results against the axisymmetric results. A 3D explicit dynamic finite element analysis combined with a static springback analysis is then used to simulate a large number of steel shot impacts on an aluminium 2024-T351 target. The multiple impact modelling results indicate a clear difference of residual stress profiles between those obtained from single and multiple impact modelling. This difference is due to the global uniformity effects of shot peening, which involves numerous impacts. In addition, equivalent plastic strain obtained from the analysis is compared with microhardness test data on an experimental sample. Finally, the shot peen forming effect of multiple impacts is also evaluated by showing the macroscopic surface deformation. The comparison between single and multiple impact modelling results indicates that it is appropriate and important to model an appropriate coverage of multiple impacts for shot peening and peen forming at its various coverage.

Keywords: impact model, shot peening, shot peen forming, finite element method

1 INTRODUCTION

Shot peening is a cold working process which involves a large number of impacts on the surface of metal components. It is well known as a method to increase resistance to fatigue and to reduce stress corrosion cracking of metal parts by creating a hardened layer with compressive residual stresses. When shot peening a metal sheet or plate, it is also known that the sheet metal will curve with a macroscopic forming effect, besides the individual local indentations.

A single impact determines the fundamental features of a shot peening process, for example the indentation size and the plastic depth. The final effects are accumulated by these individual indentations. Therefore, an understanding of the single impact has been a logical starting point to investigate the whole process. Some analytical theories [1–4] have been proposed to understand a single impact. However, the complexity of material models and contact conditions has led to the adoption of the finite element method [5–8]. Particularly for the multiple impacts that are realistically involved in shot peening, finite element impact modelling has become popular in recent years to understand the mechanics underlying shot peening or peen forming processes [3, 9–14].

A brief review of the residual stress profiles simulated from single or local multiple impact modelling in the available literature shows that there is still a certain gap between the obtained profiles and those expected from shot peening, as suggested by Al-Hassani [2] and by Al-Obaid [4]. In general
applications of shot peening, it is normally conducted to a certain coverage over the target surface. For single-sided peening with high uniform coverage on a metal block with limited thickness and without boundary load, an individual residual stress profile through the thickness should be sufficient to satisfy both the force and moment equilibrium conditions [2, 4]. However, this equilibrium condition for an individual residual stress profile cannot be met under single or local multiple impact modelling because the local effect does not reach uniformity. An attempt has been made to address this gap [3, 10] by simulating a large number of shot impacts, where the formation of a layered structure of plastic deformation and residual stresses was presented. However, the requirement of high computation resources limited the analysis, especially the residual stress profiles, to qualitative results.

It is the aim of the current paper to provide detailed quantitative results from finite element multiple impact modelling. A two-dimensional (2D) axisymmetric single impact model with a very fine mesh is first presented as a reference for the subsequent three-dimensional (3D) model. Using an appropriate 3D mesh density for the target material, a 3D explicit dynamic finite element analysis combined with a static springback analysis is then used to simulate a large number of steel shot impacts on an aluminium 2024-T351 target. The development of residual stress profiles from local non-uniformity to global uniformity is demonstrated using an artificially specified impact pattern. This impact pattern starts from a single impact, and progresses to a number of impacts covering more of the target surface. Besides the residual stress profiles, the average equivalent plastic strain obtained from the analysis is compared with microhardness test data on an experimental sample. Finally, the shot peen forming effect of multiple impacts is also evaluated by showing the macroscopic surface deformation.

2 TWO-DIMENSIONAL AXISYMMETRIC SINGLE IMPACT MODEL WITH A VERY FINE MESH

For a single impact involved in shot peening an aluminium alloy target material, it can be assumed that a spherical rigid shot impacts at moderate speeds (e.g. up to 50 m/s) frictionlessly and vertically on the target surface of a relatively large solid with isotropic strain-rate-insensitive elastic–plasticity. These assumptions are generally applicable to the practical operations of shot peening on aluminium alloy materials, which are discussed in detail in reference [3]. To study such a dynamic process of a single impact, an explicit dynamic finite element method is well suited. A 2D axisymmetric model with a very fine mesh can result in accurate analysis results with acceptable computation time. It is believed that the results obtained through such a refined finite element mesh can be used as a reference to verify the model for multiple impact analysis, which has to be a compromise between accuracy and computational cost.

A common aluminium alloy, 2024-T351, is used for the target material. Its stress–strain relationship with isotropic hardening is defined by a power function when plastic deformation occurs, whereas in the elastic region a linear relationship is automatically used by the finite element code. Based on its uniaxial tensile test, the strain-hardening exponent is found to be 0.1675, Young’s modulus 69 GPa, the proportional limit 305 MPa, Poisson’s ratio 0.33, and density 2700 kg/m³. To use the axisymmetric model, the target material is assumed to be cylindrical, with a radius at least ten times greater than the shot radius. The thickness of such a cylinder is chosen to be 4 mm.

As shown in Fig. 1, an analytical rigid surface with a mass element is used to model the steel spherical shot with 0.968 mm radius \( R \). This is an average measured from a number of randomly selected cast steel S660 shots. Its mass is calculated using density \( ρ \), given as 7500 kg/m³. The indenter is assumed to impact the material vertically along the symmetric axis with a specific velocity defined by an initial
condition, from 21 to 35 m/s corresponding to the condition used in the experimental work. During the frictionless impact between the indenter and the target material, no other velocity or rotation is allowed.

On the top surface of the target, a frictionless contact condition is defined with the spherical surface of the shot. As the region around the contact between shot and target is the most important concern, the finite element length along the possible contact region is refined to 5 μm, which is about 0.5 per cent of the shot radius. At this meshing level, the calculated residual stress along the impact axis is within 5 per cent of the maximum absolute value calculated using a coarser meshing level of 10 μm, as shown in Fig. 2 for an indentation radius \( a \approx 0.34 \text{ mm} \) created by a 31 m/s impact. Apart from this contact condition on the top surface, another frictionless contact is also defined between the bottom surface and a rigid flat surface. This rigid surface, as shown in Fig. 1, serves as a fixed ground for the impact process, which is similar to the experimental condition being used.

The explicit dynamic analysis, such as ABAQUS/Explicit, is suited to simulate dynamic problems with a short duration. For example, a time of 5 μs is sufficient to finish the process of a single impact. It is also well suited to analyse dynamic events with complex contact conditions. However, explicit dynamic analysis needs a very long computation time to reach a steady-state solution. Since a steady state of residual stresses and deformation of the target material after being impacted is the main concern, a static analysis following the dynamic analysis provides an efficient means. This is called ‘springback’ analysis in metal forming, and can be realized by transferring the results from a dynamic analysis in ABAQUS/Explicit to a standard static analysis in ABAQUS/Standard. Figure 3 shows the comparison between the residual stress profiles obtained from the dynamic and springback analyses. Although the difference is small, it is clearly shown in Fig. 3(b) that the springback analysis can provide a very smooth residual stress profile.

### 3 THREE-DIMENSIONAL MULTIPLE IMPACT MODEL

In practice, shot peening involves a large number of randomly distributed impacts over the target surface. This impact process was studied by Wang [3] and
Wang et al. [10]. The results were mainly qualitative, which showed a clearly layered structure of plastic deformation and residual stresses. With the improvement of computation powers over the past few years, a refined model is required and can be described as follows.

3.1 The target material

A 4 mm thick 20x20 mm square aluminium 2024-T351 sheet is employed with the same material property as in the single impact model. This target sheet is modelled by only a quarter to save computation cost, as shown in Fig. 4, so that faces ABPO and AORD are symmetrical to the XOZ and YOZ planes respectively. Although it is not strictly symmetric in reality, it is expected that this symmetric configuration may cause a small error because a large number of shot impacts are being modelled. Unlike that used by Wang and co-workers [3, 10], a structured mesh is used with 3D continuum elements C3D8R. Although this eight-node hexahedral element requires a greater computational cost, it is more accurate than the four-node tetrahedral element. At least 15 elements are arranged through the thickness. The element dimensions on the top surface OPQR are uniform 0.1 x 0.1 mm, whereas the through-thickness element dimensions are gradually increased from 0.1 mm on the top surface OPQR to 0.5 mm on the bottom surface ABCD. A close-up view of the meshing near the top surface is also shown in Fig. 4.

3.2 Shot stream

Each individual shot is defined as a rigid spherical surface with a discrete mass element similar to the single impact model. Unlike the single impact model, a rotary inertial element is also defined to account for the 3D condition. The rotary inertia is calculated according to the density of the shot and its spherical volume by

\[ I_{xx} = I_{yy} = I_{zz} = \frac{2}{5} m R^2 \]

where \( m \) is its mass.

To create the shot stream for multiple impacts, a special series of impacts are used as shown in Fig. 5, which artificially creates a coverage of \( 4^{(n-1)} \) uniformly distributed impacts at a specific step \( n \). Although this does not really happen in normal shot peening, it is believed that this artificial coverage can reveal the progress of shot peening from a single impact to a large number of multiple impacts. It is also worth noting that this is actually the advantage of numerical simulation, which enables the study of shot peening in such a ‘designed’ experiment. Under the experimental condition, the shot flowrate over a quarter of the sample area 20x20 mm is about 20–40/s. Therefore, each shot has an average time of
about 0.03 s. From the single impact analysis, each impact has about $3 \times 10^{-6}$ s duration, which is only 0.01 per cent of the whole interval for an individual shot. This means that the real time is too long for an explicit dynamic analysis. Hence, the analysis has to be accelerated by arranging impacts to occur one by one, but no more than two impacts occur at the same time. A MATLAB program is written to create such a special series of shot impacts uniformly distributed in both space and time. At each step, the impact point starts from the smallest coordinates $x$ and $y$. Then, $y$ of the impact point is increased while its $x$ is kept constant. When the impact point reaches the edge of the target sheet, $x$ is increased for an increment and $y$ starts from its smallest value. This process repeats until all $4^{(n-1)}$ impacts are completed.

A frictionless contact condition between each rigid spherical surface representing the impacting shot and the deformable target surface (surface OPQR as shown in Fig. 4) is defined. Corresponding to the unconstrained peening in experiments, a fixed rigid surface is arranged under the target sheet to provide support as shown in Fig. 4. A frictionless contact condition is also defined between them.

### 3.3 The finite element analysis

At a specific step $n$, $4^{(n-1)}$ impacts are simulated using the explicit dynamic analysis. At the end of this dynamic analysis, the result for the target sheet is transferred to a static springback analysis as a restarting condition. In the static analysis, apart from one of the corners (for example point C, as shown in Fig. 4) being fixed to prevent rigid movement, there is no additional constraint. When the static analysis is completed, the residual stresses and deformation in the steady state can be obtained. This steady-state result also serves as a restarting condition for the next step $n + 1$.

A compromise between the computational cost and accuracy is one of the most important concerns for simulating multiple impacts because of the larger number of finite elements and contact conditions involved. The comparison between the simulation results from the first step of the 3D multiple impact model, which involves only one impact as shown in Fig. 5, and the 2D axisymmetric single impact model can be used to validate this compromise. As shown in Fig. 6, the residual stress profiles along the impact axis from both models are compared. It is clear that the residual stress profile calculated from the 3D model is able to follow the one from the 2D model with a very fine mesh, which indicates that the compromise of using a coarser mesh for the 3D model is acceptable.

### 4 SHOT PEENING EXPERIMENTS

The experimental peening machine is a manually operated direct-pressure air-blast system. It consists of an HPC Plusair SK26 screw compressor supplying compressed air at a nominal pressure of around 0.69 MPa to a Vacu-Blast PB100 peening cabinet via an accumulator vessel of about 0.5 m$^3$ volume. When
the main switch and air supply valves are turned on, the compressed air passes through a regulator valve for the air pressure control, which is the main variable of the experimental procedure and is normally controlled from 0.14 to 0.35 MPa. Cast steel S660 peens are used in this machine with the mass flow-rate kept at 13.67 g/s and pressure at 0.28 MPa. The calibration of shot velocity with the air pressure was done on a sister machine by Airbus UK, which gives about 31 m/s impact velocity under this pressure. The nozzle is kept vertical to the worktable at a distance of 300 mm. Unlike Almen tests, specimens are not constrained by a holder during peening. Instead, only adhesive materials (e.g. tapes) around the test pieces are used to prevent the specimen from moving laterally as a result of air blast. Therefore, the specimen is unconstrained and is free to bend and elongate.

Square 20×20 mm samples of aluminium 2024-T351 sheets with 4 mm nominal thickness are used for this study. Within the target surface area, the distribution of peens can be approximated as a uniform distribution for the peening machine being used. After peening, the specimen is cold mounted in an acrylic material to preserve the deformed configuration. It is then cut through the thickness near the initial diagonal of the square surface in a precision cutting machine. This cross-section is finally ground down to a grit size of 1200 for the measurement of deflection and microhardness in a micro-indentation machine. The curvature can then be determined by approximating the measured points with a second-order polynomial function. Another convenient method to measure the curvature is to measure a number of points on the unpeened bottom surface by a coordinate measurement machine and to approximate these points by a sphere. These two methods give similar results. In the present paper, the results are provided by measuring along the diagonal section using the first method.

5 RESULTS AND DISCUSSION

The multiple impact analyses as described in section 3 were conducted with an Intel Pentium-4 3 GHz-based PC with 1.5 GB DDR-400 SDRAM. There are a total of 150,000 elements for the target material. Corresponding to the experimental condition of 0.28 MPa peening, 31 m/s impacts are simulated. For the explicit dynamic analysis, each impact took about 6 min of CPU time. After each dynamic analysis step, a static springback analysis took about 37 min of CPU time. Up to five impact steps (341 impacts in total, see Fig. 5) were simulated in this study, which took a total of 36 h to obtain all of the modelling results.

To study the progress of residual stress and plastic deformation, a diagonal section through the target material, OACQ as shown in Fig. 4, is selected to present the results. On this planar section, the normal stress and plastic strain are calculated at each nodal point by interpolating the surrounding elemental results. Three parallel straight-line paths through the thickness, NM, N1M1, and N2M2 as shown in Fig. 4, are chosen to provide the profile of residual stress and plastic strain. For the first impact step, NM is the central axis of the first impact, while N1M1 is near the border of the elastic–plastic region and N2M2 is in the elastic region.

Figure 7 gives the profiles of residual stress and plastic strain calculated from three steps of the multiple impact model, which shows the progress from a single impact to multiple impacts. In the first row, step 1 is the result of a single impact. The residual stress near the impacted surface along the impact axis NM is compressive. However, the near-surface residual stresses around the elastic–plastic border (path N1M1) and at the elastic region (path N2M2) are tensile. This is due to the equilibrium in the entire
diagonal section OACQ: because the integral over thickness of the residual stress profile along the impact axis is less than zero (i.e. compressive), there must be other residual stress profiles to provide tensile components. As the calculated results for step 2 are very similar to those for step 1, they are not shown in Fig. 7. This also indicates that low coverage shot peening with individual plastic regions being far apart does not alter the residual stress profile.

In step 3 of the multiple impact modelling, as shown in the second row of diagrams in Fig. 7, plastic deformation extends to path N\textsubscript{2}M\textsubscript{2}. This alters the near-surface residual stress along N\textsubscript{2}M\textsubscript{2}, and creates a small portion of compressive stresses. However, with further impacts up to step 4, the magnitudes of plastic deformation along all three paths approach uniformity, which is like creating a plastically deformed layer \([16]\). As a result, the residual stress profiles are also approximately uniform. In addition, the integral over thickness of each residual stress profile is approaching zero, which indicates an equilibrium condition in terms of force. The development of such a uniform residual stress profile brings to mind the comments from Al-Hassani \([17]\): ‘It may well be worth remembering that in shot peening we are dealing with more than one axisymmetric indentation and therefore the equivalent two-dimensional problem could offer a better value!’

Clearly this also demonstrates that it would be more important and appropriate to study the plastic deformation and residual stress profiles with a multiple impact model for shot peening.

The thickness of such a plastic layer is estimated by measuring the change of microhardness through the thickness. As shown in Fig. 8, this layer is about 1 mm for shot peening the target surface for 10–20 s, which is similar to the calculated results from this multiple impact model.

To demonstrate the macroscopic forming effect due to a large number of impacts, the deflection of the bottom line AC in the diagonal section (see Fig. 4) is extracted from the finite element analysis and compared with the experimental data. In the shot peening experiment, a number of points along the unpeened surface on the cross-section were measured under a microscope in the microhardness machine. These 2D positions are then rotated and translated to a curve, as shown in Fig. 9, so that the slope at the origin is horizontal, i.e. comparable with the computational result. The shot flowrate is about

![Equivalnt plastic strain vs. Microhardness](attachment:equivalent-plastic-strain.png)

**Fig. 8** Comparison of experimental microhardness through the thickness with plastic strain calculated in step 5 of the multiple impact model.
40/s, which gives 400 impacts over 10 s. After step 5 of the multiple impact model, there is a total of 341 impacts. From Fig. 9, it can be seen that the peen forming effect is in agreement between experiment and modelling.

It is also interesting to compare the deformation on both the peened and unpeened surface. Because there are a lot of indentations in the peened surface, local fluctuations of deflection occur, as shown in Fig. 10 for line OQ. However, if this deflection curve is compared with the one along line AC in the unpeened surface, a global or macroscopic trend of deflection can be observed. This deflection can be regarded as bending or in-plane deformation for a shell structure, which is a basic assumption for the process model of shot peen forming [16].

6 CONCLUSION

The general agreement between the experiments and modelling results confirms that the multiple impact model is appropriate for shot peening and peen forming. The development of residual stress and plastic deformation from a single impact to a large number of multiple impacts shows a clear trend of approaching uniformity. This also meets the authors’ initial aim of bridging the gap between the results obtained from single impact modelling and from multiple impact theoretical analysis based on force and moment equilibrium [2, 4]. The results indicate that it is more appropriate and important to model multiple impacts for shot peening and peen forming at the various levels of coverage. It can also be seen from the results that the macroscopic forming effect is created from a layer with rather uniform plastic strain. Such a layered structure means that this macroscopic effect could be analysed using shell or plate theory in future studies. The analysis based on shell or plate theory is particularly useful for practical peen forming processes of large aircraft panels, because the analysis of 3D impact modelling is not realistic in terms of computational cost.

This study is particularly aimed at understanding the progress from a single impact to multiple impacts, where an artificially designed series of impacts was modelled. It should be noted that in normal shot peening applications, impacts are randomly distributed. The random distribution of impacts may be non-uniform, which can create different effects from the artificially designed distribution, but the multiple impact model can still be used for further studies.

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REFERENCES


