Numerical modelling of shot peening process and corresponding products: Residual stress, surface roughness and cold work prediction

G.I. Mylonas, G. Labeas *

Laboratory of Technology and Strength of Materials (LTSM), Department of Mechanical Engineering and Aeronautics, University of Patras, Panepistimiopolis, Rion, 26500 Patras, Greece

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ABSTRACT

An investigation of the effects of controlled shot peening (CSP) process parameters on the treated material is presented. For this purpose, a three dimensional numerical model is developed, comprising the target plate and a number of shot impacts; their number is defined as the minimum required for a realistic simulation and minimum computational cost. The numerical model is verified by comparing the predicted residual stress (RS) fields to experimental. A parametric study of the shot velocity and impinging angle on the CSP products is performed for 4 shot types, i.e. S110, S230, S330 and S550. The main advantages of the present numerical model are: a) the relatively high number of shots introduced in the simulation compared to other publications that use only one shot, b) the number of shots dependency on the desired coverage, c) the thorough selection of numerical parameters, d) the high-strain rate material behaviour used for the target plate, e) the capability to calculate CSP effects on the target plate as function of coverage, f) the computed data which include RS field, surface roughness, cold work and geometrical stress concentration factor (Kt) and finally g) the computed results which are validated by experimental measurements.

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1. Introduction

Structural and surface integrity is the subject that investigates the effects of manufacturing and surface processes (e.g. machining, forming, shot peening, and laser-shock peening) with respect to RS, surface roughness and cold work of the surface and subsurface layers of the processed material, including the effect of these alterations on the surface-related physical and mechanical properties. Shot peening is one of the most important and widely used surface treatments that is used as a post manufacturing process in order to increase fatigue life and fatigue limit of components, to superimpose tensile RS (arising from machining, welding etc.) with beneficial compressive RS, to form locally the component in order to correct distortions and achieve tight tolerances and last but not least, to form thin sheets made of soft material.

There are several numerical models available in the literature, trying to describe shot peening process. Some of the existing finite element (FE) based models are discussed hereafter. An initial attempt on numerical simulation of shot peening on steel target was performed by Obaid in 1990 [1], who proposed a simple model based on three dimensional isoparametric elements. Along with the computational capabilities development, shot peening numerical models have been further extended.

Al-Hassani et al. [2], presented a three dimensional quarter-symmetric numerical model applicable to both single and multiple shot impacts on steel target plates. An oblique impact was also considered. A quarter-symmetric model, which introduces contact elements to represent the physical contact between the shot and the target steel plate was presented by Meguid et al. [3]. The authors examined several numerical parameters that can be critical to the convergence and the accuracy of the analysis, such as friction coefficient, normal and tangential stiffness. Meguid et al. [4], utilised the numerical model developed in [3] to calculate the equivalent stress, equivalent plastic strain and elastic strain as function of time due to a single spherical shot. The numerical model was used to study the effect of shot velocity, shot radius, shot aspect ratio and strain hardening rate of the target material, on the plastic zone depth developed from the impact.

The first publication in which computed results were validated by the analytical equations of Hertzian elastic contact and the RS profiles were compared to experimental results was by Schiffer et al. [5]. However, the two-dimensional model developed comprising an elastic sphere impacting to an elastic-plastic steel target, predicts maximum RS values, which were well above the respective experimental results. The first attempt to simulate an aluminium alloy target plate was presented by Han et al. [6]: RS and plastic strain results were calculated by an axi-symmetric numerical model and compared to the results from a complete three-dimensional numerical model. The computed results between the two numerical models were shown key differences. Guagliano [7] tried to relate the key process parameters, such as velocity and shot size to the resulting RS
and Almen intensity. Almen strips of specific geometry and material are positioned in Almen blocks, which in turn are positioned onto the component's critical areas. The component is shot peened and so is the Almen strip; when the Almen strip is removed from its holding fixture bends. The arc height is measured by a specific device called an Almen gauge and the reading in mm (or inches) is recorded. The process is repeated for different exposure times and the readings are drawn to a graph called “saturation curve”. Almen intensity (or peening intensity) can be established from this graph. Five subsequent shot impacts were simulated in Guagliano [7]. The numerical results were compared to experimental results measured by X-ray diffraction. The comparison has indicated a very good correlation between the results.

In 2002 Meguid et al. [8] examined the interaction of four uniformly spaced shots, which represent different “layers” of shots. In this study, emphasis was given to numerical convergence and to the validity of the RS results. The authors decided to use strain rate sensitive properties for the target, as there is a fairly significant difference compared to static properties. The shots were modelled as rigid bodies. A numerical simulation model was presented by Schwarzer et al. [9] comprising several rigid shots impacting on a three dimensional target steel plate. The target was surrounded by infinite elements in order to avoid strain wave reflections, which were generated due to the dynamic phenomenon. Time separation between the subsequent impacts and the effect of adjacent impacts on the RS profile were taken into account. A comparison between the numerical and the experimental residual stress profiles was presented. The two curves presented had significant differences. Wang et al. [10] presented a dynamic algorithm for simulating 1000 random impacts and a static algorithm for spring-back simulation: the combination of these two aspects by using Abaqus FE code predicted the final curved shape after shot peening on a small sized AA2024-T351 panel.

Majzoobi and Azizi [11] presented three numerical models simulating shot peening. The first is a quarter-symmetry numerical model comprising a single shot impacting on a strain rate sensitive steel target. The second numerical model includes multiple shot impacts of 4, 6, 8, 9, 13 and 25 impacts at specified locations, in order to reproduce high coverage percentage. The method followed by the authors can be characterised as controversial as shot peening is stochastic by nature. The RS computed for the 25 subsequent impacts was compared with available experimental results and the differences between the two curves have shown a small difference. The third model includes a single shot impacting to both flat and curved surfaces at different surface angles (30°, 45° and 60°) with the aim to examine the effect of impacting angle on the RS. A similar work was presented by Majzoobi [12] in 2005.

Klemenz et al. [2005] [13] presented a different approach to shot peening and its effects on the treated material. The method of similarity mechanics was applied to the shot peening process, a complete dimensional analysis was carried out and the functional dependencies of several output values were determined. In 2006, Klemenz et al. [14] presented a numerical model consisting of a rectangular body surrounded by the so called ‘half infinite’ elements, whilst the target base was constrained in a z-direction. The evolution of the RS field developed after several impacts (1, 2, 7 and 8 shots) were presented and the author concludes that a symmetrical shot peening model cannot represent the statistical shot peening process accurately. This was due to the inability of symmetric models to deal with the redistribution of the stresses into the available material volume after each shot impact, as well as to the fact that the maximum compressive stress always occurs below the region of the last impact.

A similar publication is presented by Klemenz et al. in 2007 [15].

Frija et al. [16] published in 2006 a numerical model capable to predict the compressive RS profile, the plastic deformations and the surface integrity. As the author states, the shot peening loading was realised by using the energy equivalence between the dynamic impact and a static indentation of a single shot on the treated material. This method was selected in order to solve problems of the dynamic analysis related to high computing time and result instability. The computed results were compared with experimentally measured RS curves by the X-ray method. The damage model does not seem to have a significant effect on the predicted RS curves, although some stress relaxation was found. In 2008, Hong et al. [17] presented a three dimensional FE dynamic analysis of a single shot impacting on a metallic component. The numerical model was validated by comparing the computed results to previously published numerical results presented by Meguid et al. [3]. Subsequently, a parametric analysis was conducted to investigate the effect of shot diameter, impact velocity, incident angle and component material properties on the resulting RS. The shot was modelled as a rigid body. In the same year (2008), Hong et al. [18] presented the same FE model as in Hong et al. [17] along with a discrete model. Discrete analysis was applied by Hong et al. to study the multiple particle dynamics and the interactions within the shot stream. Discrete analysis is commonly used to predict particle path, velocity profile etc. by solving Newton’s laws mainly in large scale industrial stochastic problems. Edem software was used to develop the discrete model and simulate 10,000 shot impacts onto a target surface. The velocity just before impact was recorded for each shot; this enabled the authors to produce a statistical distribution for the shot velocities recorded and calculate the deviation of the initial shot velocity. The first effort for performing a discrete analysis was introduced by Han et al. [6] in 2000.

Kim et al. [19] showed the importance of averaging the computed results over the representative area that the RS are experimentally measured. The model developed consists of a three-dimensional finite volume with symmetry boundary conditions. The target was impacted by 4 spherical shots in each corner; the impact sequence was repeated and 3 cycles were simulated. The RS was computed after each cycle: RS results for 4 and 16 impacts were compared with experimental RS data. The comparison between the results was very promising and validated the importance of averaging the computed RS over the representative area. The model was further validated by applying the computed results into analytical equations for the calculation of the Almen height after shot peening. Almen intensity was predicted with great accuracy. Klemenz et al. [20] simulated 121 rigid shots impacting with the same velocity onto a steel target material. Emphasis was given in the surface topography and surface RS after a single and two shot impacts. The through the thickness computed RS developed after 121 shot impacts was compared against experimental data; the presented results correlated well. Miao et al. [21] presented a model consisting of an aluminium target plate impacted by rigid shots (6, 12, 24, 48 and 96) that were generated randomly within an area of 1.5 by 1.5 mm. The computed RS was averaged over a reference area of 1 mm². Normal impact and impact at 60° angle were considered in the publication; the numerical RS results were compared against other computed RS results.

The current work includes the numerical simulation of appropriate shot patterns, which were calculated by a specific process. A preliminary attempt to perform a stochastic shot peening analysis was described in the work of Labeas et al. [22]. They presented an innovative solution to approach the shot peening stochastic nature. In contrast to other publications that use symmetric positioning of the shots or dents onto the target area, in [22] a full stochastic approach was followed.

Presently, further improvements of the concept in reference to Labeas et al. [22] are presented. The concept of the new approach includes the following steps:

a) The calculation of the total number of shots impacting to a reference area of 1 mm² dependent on process parameters (Table 1),
b) the development of a kinematic two dimensional (2D) model for the complete nozzle geometry, which is randomly filled with shots (Fig. 1),
c) the determination of shot velocity distribution (Fig. 2),
d) the calculation of the intensity $\lambda$, which represents the reduced number of shots impacting to a reference area of 1 mm$^2$ according to the velocity distribution (Table 1),
e) the development of a finite element model to investigate interactions of the effect of the distance between 2 shots and the subsequent shot impacts on the RS filed achieved (criterion development),
f) the creation of a germ–grain model, which represents randomly positioned dents (grains) and their corresponding centres (germs),
g) the criterion application for the thinning process in order to remove ‘ineffective’ germs.

The above mentioned steps will briefly explain in the case of an example referring to the shot pattern calculation of S230 shots.

Typical nozzle travelling velocities for shot peening process are within the range of 10 to 300 mm/s and typical mass flow rates are within the range of 0.2 kg/min and up to 20 kg/min. For nozzle travelling velocity extreme values the number of shots impacting onto a reference area of 1 mm$^2$ is calculated and presented in Table 1. The calculations are performed with an average mass flow rate value of 11 kg/min (0.183 kg/s) which are in accordance to the experimental parameters presented in Section 2. Consequently, a kinematic 2D model is developed and the velocity distribution calculation as presented in Figs. 1 and 2 respectively. The results presented in Fig. 2 are similar to Hong et al. [18]; Hong reports that for similar process parameters, the shot percentage which is impacting the surface with a velocity between 0 and 20 m/s is about 86%. Consequently the reduced number of shots impacting onto a reference area of 1 mm$^2$ with maximum impact velocity is calculated and shown in Table 1, which gives the intensity value $\lambda$. For an average nozzle travelling velocity of 175 mm/s (in accordance to experimental work described in Section 2) and for shot type S230, $\lambda$ is equal to 238 shot impacts. The next step of the process includes several numerical simulations performed with the FE model described in Section 2.1. Fig. 2 shows the developed numerical model with two subsequent impacts at the same location, whilst Fig. 4 shows two shots impacting at a distance R, which is parametrically defined. The RS profiles computed for the two situations described are plotted in Figs. 3 and 6, respectively. Fig. 3 shows the developed RS through the plate thickness, whilst Fig. 6 shows the in plane RS developed at a certain depth across a distance from the centre of impact at point 0 (path shown in Fig. 4). The outcome of this step is a minimum distance criterion. Subsequently, a germ–grain stochastic model is created according to the calculated intensity $\lambda$. The minimum distance for all germs is plotted in a graph. Thinning process starts in steps; after each step the minimum distance is plotted. Thinning process ends when the minimum distance criterion is fulfilled. The remaining germs correspond to the shot number and their coordinates.

Table 1
Approximated number of shots impacting on a reference area of 1 mm$^2$ for an average mass flow rate of 0.183 kg/s.

<table>
<thead>
<tr>
<th>Shot type</th>
<th>Total shots/s</th>
<th>Number of shots impacting a reference area of 1 mm$^2$</th>
<th>Reduced number of shots impacting a reference area of 1 mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nozzle velocity 50 mm/s</td>
<td>Nozzle velocity 300 mm/s</td>
<td>Nozzle velocity 50 mm/s</td>
</tr>
<tr>
<td>S110</td>
<td>16,218</td>
<td>32,437</td>
<td>5485</td>
</tr>
<tr>
<td>S230</td>
<td>2027</td>
<td>4055</td>
<td>686</td>
</tr>
<tr>
<td>S330</td>
<td>713</td>
<td>1426</td>
<td>241</td>
</tr>
<tr>
<td>S550</td>
<td>160</td>
<td>319</td>
<td>54</td>
</tr>
</tbody>
</table>

Fig. 1. a: Kinematic simulation model developed for stream analysis. b: Kinematic simulation result showing shot velocity distribution.

Fig. 2. a: FE model for two subsequent impacts at the same location. b: FE model for two shots impacting at a distance R defined parametrically.

correspond to the final pattern. The shot impacts pattern for S230 includes 10 (germs) shots.

At this point, the difference between “plastic coverage”, “optical coverage” and their relationship with experimental coverage, which is experimentally derived by examining the treated surface using a 10 times magnifying lens, should be mentioned. As stated by Labeas et al. [22], the main parameter that affects the minimum number of shots is the plastic zone developed from each shot impact. Shots coming from the nozzle and impacting the surface with maximum velocity are producing the maximum plastic deformation and thus plastic zone. The plastic zone developed after a single shot impact is approximately 3 times the dent diameter. This has as a result the development of higher “plastic coverage” in comparison to “optical coverage”. Oncoming shots with smaller velocities that are not able to change significantly the created plastic zone are excluded from the numerical analysis, even if they create some plastic deformation on the material surface and add up to the optical coverage development. This is in accordance to Wang et al. [10]; they found that 100% plastic coverage corresponds to only 50% optical coverage, when AA2024-T351 is considered. Their results have not been thoroughly validated up to now and further study is possibly required for several materials with different hardness. But also this statement is in accordance to Prevey and Cammet [23] as they present that RS is not significantly affected by coverage and that RS is established early enough with a coverage value of about 20%. Shot peening effects on the treated material after numerically simulating 100% plastic coverage can be directly compared with 100% experimental coverage measured on the treated material. By using these data, it is possible to compute the number of shots required in order to simulate experimental coverage values of 100% or less. This can be done by developing a stochastic model for a new SP application of the thinning criterion and reduction of the number of shots impacting on the reference plate, until the desirable plastic coverage is obtained. In this spirit, shot patterns as a function of coverage can be computed.

Shot peening process and the effects on the treated material cannot be fully described by a single shot impact. It is also true that the stochastic nature of shot impacts on the surface of the treated material cannot be represented by a deterministic shot arrangement. Most of the mentioned publications are aiming to achieve a certain coverage by positioning the shots at certain locations. Only a few publications are presenting experimental work and the available information is limited.

The main advantages of the present numerical approach are:
1. the reduction in computational time,
2. the ability to perform several parametric studies,
3. the study of the surface conditions after multiple impacts and
4. the comparison of the numerically predicted results to experimental results.

Briefly the contents of the current publication are categorised in three main sections. The first section includes the development of the multi shot peening simulation model that includes geometry, mesh,
discretisation, material properties, boundary conditions and introduction of the impact patterns; also a study for the calculation of the time interval between subsequent shots is presented. The second section refers to the computed RS calculation and the numerical model validation; this section concludes with a parametric study for the shot type (diameter), velocity and impinging angle. The final section of the present work refers to the calculation of surface roughness, geometrical stress concentration factor and cold work.

2. Development of the multi-shot shot peening simulation model

The present shot peening numerical model is based on a three-dimensional FE analysis using the explicit Visual-Crash for PAM 4.5 FE code, which is suitable for large-scale non-linear dynamic problems. In order to allow for the accurate calculation of the RS, surface roughness and cold work of the treated material, multi-shot impacts of specific shot patterns comprising a variable number of shots depending on the coverage value are considered. In this work only 100% plastic coverage is presented; however, FE simulations for 60% plastic coverage are presented by Mylonas et al. [24]. The parameters investigated with the developed numerical model are those used in the experimental tests performed by EADS Innovation works—Germany. The shot peening process parameters incorporated to the numerical model include: Shot type S230, nominal shot diameter 0.6 mm, shot impinging angle 90°, shot velocity 50 m/s and 100% experimentally measured coverage. The model details are presented in the following paragraphs of the present section.

2.1. Target geometry, mesh discretisation, material properties and boundary conditions

An overview of the developed numerical model is presented in Fig. 4. The plate geometry is parametrically introduced in the model, such that any plate dimensions may be easily represented; however, all simulation results presented in the present paper refer to a plate of 75 mm length, 71 mm width and 5 mm thickness, as the available experimental data refer to these dimensions.

The volume located at the centre of the plate is finely meshed, as shown in Fig. 8. Shot impact centres are located at this area. The dimensions of this fine meshed volume are 1 mm by 1 mm, by 0.68 mm height. The area of 1 mm² (in the xy plane) coincides to the average area of the most commonly applied experimental RS measurement techniques. The height of the finely meshed volume is parametrically introduced, taking into account the plate thickness. The lower part of this central volume is meshed with variable thickness elements, as shown in Fig. 8, with larger elements located towards the plate bottom. A moderately coarser mesh is used for the rest of the plate volume but a transition zone is created between the fine and coarse meshed volumes, as shown in Fig. 4. The transition zone developed in order to include dents that are formed at the boundary of the fine mesh area from shot centres located at its edges. The contact area defined to the numerical model includes both the fine and the transition zone areas to enable an accurate representation of shot impact.

The considered target plate material is the AA7449-T7651 high strength aluminium alloy. To introduce material’s behaviour to the numerical model, a multi-linear elastic–plastic material model with kinematic hardening is applied. The experimentally derived stress–strain behaviour of the specific aluminium alloy follows a kinematic hardening behaviour during the loading–unloading phases, as shown by Fribourg [25]. Fig. 5 shows absolute stress values from the tension–compression Bauschinger tests performed at a strain rate of 0.001 s⁻¹. The first stage (forward) comprises straining the specimen up to a certain forward plastic strain level. Once this level is reached, the specimen is completely unloaded and immediately reloaded (reverse stage) in compression, as much as possible before buckling occurs. This approach has been used by Moan and Embury [26] and more recently by Proudhon et al. [27] and Teixeira et al. [28]. The static material properties introduced in the material model are elastic modulus 70 GPa, yield stress (σ₀) 519 MPa and ultimate tensile strength 600 MPa, Poisson ratio 0.33 and mass density 2700 kg/m³.

When high strain-rate impact phenomena occur, the deformation rate has an important influence on the flow stress of the material. The general trend at room and low temperatures is an increase in flow stress for an increasing strain rate. In shot peening a rough estimation for strain rates developed can be realised by calculating the ratio of plastic strain to impact duration. For aluminium alloys strain rates can be from 1000 up to 20,000 s⁻¹, depending on shot velocity. Strain rates can vary for other metallic materials, such as steel for which they may reach up to 60,000 s⁻¹. As it was discussed by Meguid et al. [8], strain rates for steel AISI4340 that are developing locally (at a symmetry cell) can reach up to 600,000 s⁻¹.

Using the experimental Split Hopkinson Pressure Bar (SHPB) arrangement installed in the Laboratory of Technology and Strength of Materials (LTSM) in the University of Patras, several high strain rate experiments were conducted for the characterisation of AA7449-T7651 material and presented by Mylonas et al. [29]. It was found that for a maximum strain rate of 8000 s⁻¹, which is close to the upper limit of the specific SHPB arrangement, the flow stress is 830 MPa and the ultimate strength reaches 1000 MPa. A comparison between the reference tensile test and some high strain rate curves for AA7449-T7651 is shown in Fig. 10. With the available high strain rate data, ranging from 1000 to 8000 s⁻¹, as shown in Fig. 6, the coefficients (D and P) of Cowper–Symonds equation were calculated for room temperature equal to 15,007 and 0.95 respectively. This material model was introduced to the numerical model in order to describe the material behaviour of the target.

validity of the derived numerical results after Klemenz [15] and Alt-treated material and their re-
mation number. However, as shot peening is a high speed impact
the majority of the existing simulations in literature, only the volume in
unconstrained, whilst the bottom surface is placed on a stiff surface. In
shot peening applications (not for Almen strip) the plate edges are
important issue, as mentioned in almost all numerical shot peening
residual stresses is presented by Mylonas and Labeas [24]. In this spirit, a
chosen. In the present model, in order to overcome the edge boundary

careful selection of boundary conditions at the plate edges should be
Hassani [30]. The effect of the boundary conditions on the computed
in the SAE Manual on Shot
life errors that the shot arrangement (x

The shots are considered to have rigid behaviour, using the option of
spherical rigid wall in Pam-Crash FE code, which requires the input of
the mass centre coordinates, the mass, the radius and the initial velocity
of the shot; rotary inertia and rotary or spin velocity were not included in
the analysis. Elastic and the elastic–plastic options were rejected from
the present simulations, although initially they were tried in the initial
development, because they provided practically no difference in the
computed RS profiles with respect to the rigid shots, whilst the
computational cost was extremely increased; furthermore computing
the stress field inside the shot is out of interest, Meguid et al. presented a
similar study in [8]. A comparison of rigid and elastic shots revealed that
the difference in maximum RS is less than 4%; in the present analysis the
difference is negligible, as the aluminium material alloy applied in the
current numerical simulation is much softer as compared to the steel
material applied in Meguid et al. [8]. The fact that the complexity of the
numerical model is increasing when the shot is meshed with solid elements
is also mentioned by Mylonas et al. [32].

The four different patterns presented in Section 2.1 (Fig. 7) were
inputted to the numerical model, as shown in Fig. 8 for each shot type,
as clarified in Table 3. The x–y coordinates for each shot are extracted
after the removal of the germs. The thinning method applied is briefly
explained in Labeas et al. [22]. The z-coordinate for each shot is
defined after performing a study considering the time interval
between subsequent impacts. The parametric study is presented in
Section 2.3. The shot patterns shown in Fig. 8 are not physically
possible because of the shots interference, but the figure is an optical
representation of the random approach followed to simulate shot
impacts onto the surface. The impact sequence can change to produce
a better image, for example Miao et al. [21]; as impact locations will
not change, the computed results will also remain unchanged.

When shot type S110 is considered, the minimum number of shots
required to simulate 100% plastic coverage is 30. The respective
numerical model developed is shown in Fig. 8a. The arrangement for
shot type S230 is shown in Fig. 8b, showing the pattern of the 10 shots,
which are required in order to simulate 100% plastic coverage. The
arrangement for shot type S330, which is shown in Fig. 8c, requires 10
shots to be introduced in the numerical model; it is observed that for
shot types S230 and S330 for which the difference in diameter is only
0.25 mm, the same number of shots is required in order to simulate
100% plastic coverage; however it can be noticed from the relevant
figures that the shot arrangement (x–y location) is different. For the
case of the bigger shot type S330, the shots are more scattered, whilst
for the shot type S230 the shots are closely packed.

In Fig. 8d, the shot arrangement for the biggest shot type S550 is
presented, indicating that only 7 shots have to be included in the
numerical analysis in order to simulate 100% plastic coverage.

The optical coverage numerically simulated is presented in Fig. 9.
Contour plots of the equivalent plastic strain after impacts are shown;
more specifically, in Fig. 9a, b, c, and d the top view of the finely
meshed plate surface for S110, S230, S330 and S550 shots is presented
respectively. In all cases the optical coverage is about 50%.

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**Table 2**

<table>
<thead>
<tr>
<th>Shot type</th>
<th>Shot diameter (m)</th>
<th>Density (kg/m³)</th>
<th>Mass (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S110</td>
<td>0.30 × 10⁻³</td>
<td>7850</td>
<td>1.11 × 10⁻⁷</td>
</tr>
<tr>
<td>S230</td>
<td>0.60 × 10⁻⁴</td>
<td>7850</td>
<td>8.87 × 10⁻⁷</td>
</tr>
<tr>
<td>S330</td>
<td>0.85 × 10⁻³</td>
<td>7850</td>
<td>2.52 × 10⁻⁶</td>
</tr>
<tr>
<td>S550</td>
<td>1.40 × 10⁻³</td>
<td>7850</td>
<td>1.13 × 10⁻⁵</td>
</tr>
</tbody>
</table>

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In Eq. 1, \( \sigma_n \) is the yield stress that refers to a specific strain rate \( (\varepsilon) \) value
and \( \sigma_y \) is the yield stress of the material, which refers to a quasi-static
strain rate.

\[
\sigma_n = \sigma_y \left[ 1 + \left( \frac{\varepsilon}{\varepsilon_y} \right)^2 \right].
\]
2.3. Time interval between impacts

With the aim to examine the effect of time interval between subsequent impacts on the predicted RS, the contact duration of a single shot impact is initially examined, using S230 shot type. The contact duration of a single shot impact is computed by the numerical model; the contact duration is equal to 0.95 μs when the initial shot velocity is 20 m/s, whilst the contact duration is equal to 0.82 μs when the shot initial velocity is 140 m/s; the two relevant curves which refer to the top surface node located at the centre of the shot impact are presented in Fig. 10. The lower and upper shot velocity limits are used to determine an average value between the subsequent impacts that will applied to all shot patterns and shot velocities.

The values of the impact duration of a steel shot impacting onto an elastic aluminium plate can be analytically calculated by Eq. 2, Al-Hassani [30].

\[
t = 2.943 \times \left[ 2.5 \times \pi \times \frac{p_{\text{plate}}}{E_{\text{plate}}} \times \left( 1 - \frac{v^2}{E_{\text{plate}}} \right)^{\frac{1}{2}} \right] \times \frac{R_{\text{shot}}}{\nu} \quad (2)
\]

Using Eq. 2, the contact duration is calculated to 0.78 μs when the initial shot velocity is 140 m/s, whilst for initial velocity of 20 m/s the contact duration is equal to 1.15 μs. Eq. 2 refers to an impact onto an elastic medium; the respective numerical model is developed to describe an elastic–plastic impact thus the following comparison can only be used as a guideline. The differences between the numerical and the analytical results reach up to 17% for the lower velocity of 20 m/s. The relatively small differences revealed a good representation of the single shot impact by the full plate numerical modelling.

Four different conditions are considered with respect to shot impact time separation. The first case, presented in Fig. 11a, refers to the condition that all shots are impacting simultaneously on the finely meshed surface, whilst in Fig. 11b, time intervals (dt) of different values i.e. 0.20 μs, 0.85 μs and 1.75 μs are applied by adjusting the distance dS. The conditions in Fig. 11 refer to shot type S230, shot velocity 60 m/s and impinging angle 90°. For the four different cases examined, different RS profiles are computed and presented in Fig. 12. Differences are observed for the maximum RS, the through-the-thickness point where maximum stress occurs (Xd) and the point (W) where the RS changes sign (from negative to positive). All the computed data are presented in Table 5.

The outcome of this analysis underlines how sensitive the RS curve profile is to the time interval parameter. The time interval that can best describe reality and should be applied to the numerical model is the average time obtained from the highest and lowest velocities i.e. 0.85 μs. This method represents physical activity of the shot impacts; the shot impacted first should open the space for the next subsequent impact. The minimum time needed for the shot to open the space for the next shot can be defined as the impact duration (or contact time). The chosen time interval refers only to the specific material alloy. As it can be seen from the analytical Eq. 2, the impact duration is dependent on the elastic material properties of the target; therefore for a different material the contact duration should be appropriately adjusted.

3. Residual stress field numerical results

3.1. Numerical model validation

The numerical model is validated by comparing the computed results with available shot peening RS experimental results, derived
by applying the hole drilling method. The experimental RS results refer to shot peening treatment of specimens with dimensions of 75 mm by 71 mm and a thickness of 5 mm. Shot peening is performed in EADS Innovation Works, Germany by using spherical steel shots (S230) with an average diameter of 0.6 mm. Two peening strategies were followed as it can be seen in Fig. 13a and b; some specimens are shot peened to complete coverage, whilst other specimens were shot peened at the centre with a single pass.

The impinging angle is 90°, the working distance (defined as the distance from the nozzle to the surface of the treated material) is 150 mm and the tool diameter used for the hole drilling operation is 1 mm. Tool diameter is very important for the averaging process when comparing experimental with numerical results. The shot velocity \(V_{\text{shot}}\) is calculated from Eq. 3 equal to 48 m/s. In Eq. 3, the properties of the treated material (yield stress and specific density), as well as the shot and dent diameters are taken into account. The dent diameter is approximated to vary from 160 to 190 \(\mu\)m, as can be seen from Fig. 14, Heckenberger [33].

\[
V_{\text{shot}} = \left( \frac{1}{1.28} \right) \left( \frac{D_{\text{dent}}}{D_{\text{shot}}} \right)^{2} \left( \frac{\sigma_{0.2}}{\rho} \right)^{0.5}
\]  

(3)

In order to compare the computed FE results with the respective experimental results, it is necessary to consider the area over which the measured stresses are averaged by the chosen experimental process as proposed by Kim et al. [19]. Herein, the computed results are averaged across the elements of the finely meshed volume. The computed results are averaged over the square area of 1 mm\(^2\) whilst the experimental hole drilling method uses a measurement area of approximately 1 mm\(^2\). The numerical results are computed by applying the impact pattern presented in Fig. 7b for the shot type S230, initial velocity of 50 m/s and impinging angle of 90° for all the shots. In Fig. 15, a comparison between the numerical averaged results against the experimental results is presented. As can be observed in Fig. 15, the numerical results are in very good agreement with the experimentally measured results. In order to further confirm the FE model, the sequence of the 10 shots impacted to the finely meshed surface is changed and the RS curve computed for sequence no. 2 is also presented in Fig. 15.

At this point it should be reminded that the applied impact pattern arises from a stochastic procedure, which is based on the assumption

<table>
<thead>
<tr>
<th>Shot type</th>
<th>Shot impacts simulated</th>
<th>Figure no.</th>
<th>Optical coverage</th>
<th>Plastic coverage</th>
<th>Figure no.</th>
</tr>
</thead>
<tbody>
<tr>
<td>S110</td>
<td>30</td>
<td>7a</td>
<td>50%</td>
<td>100%</td>
<td>9a</td>
</tr>
<tr>
<td>S230</td>
<td>10</td>
<td>7b</td>
<td>50%</td>
<td>100%</td>
<td>9b</td>
</tr>
<tr>
<td>S330</td>
<td>10</td>
<td>7c</td>
<td>50%</td>
<td>100%</td>
<td>9c</td>
</tr>
<tr>
<td>S500</td>
<td>7</td>
<td>7d</td>
<td>50%</td>
<td>100%</td>
<td>9d</td>
</tr>
</tbody>
</table>

Table 3
Shot patterns and coverage clarification.

Fig. 8. Shot arrangements considered for the simulation of different shot types: (a) S110, (b) S230, (c) S330, and (d) S550.
that the patterns should take into account only the shots which are capable to develop a plastic deformation to the subsurface of the treated material, therefore the shots that are unable to modify the developed plastic zone are excluded. In order to verify this critical assumption, and validate the outcome of the shot pattern approach, the shots excluded during the stochastic approach are gradually (10 shots in each model) introduced into the numerical analysis. A study for the effect of the additional shots that were excluded from the analysis, on the S230 shot pattern, which is used as basic model to compute the RS filed is examined. The first 10 shots correspond to the S230 shot pattern presented in Fig. 8b. The velocities of the additional impacts are within the range of 0 m/s to 50 m/s according to the diagram presented in Fig. 2. The additional shots correspond to 10 shots with 40 m/s (8%), 12 shots with 30 m/s (11%), 13 shots with 20 m/s (12%) and 5 shots with 10 m/s (16%).

The differences observed for the maximum RS, Xd and the W are shown in Fig. 16 and summarised in Table 6; in brackets the percentage difference with the experimental results is shown. The percentage difference obtained for the peak RS for 50 shots is 15%; this value is considered to be within the acceptable accuracy limits of the hole drilling method applied to measure the RS field.

This study confirms the methodology (presented in detail in the Introduction and in Labeas [22]) of excluding numerous shots from the simulation, thus making it practically possible to simulate shot peening through an FE model by reducing the total number of shots. At the same time, the coverage achieved in the simulation is controllable for simulations to approach to any value of optical coverage.

The numerical model is further validated by comparing predicted RS data against experimental data that are available in the literature. In Fig. 17a, predicted RS for AISI 4140 is compared versus the experimental RS profile from Kim et al. [19]. The shot pattern applied to the numerical model is shown in Fig. 7c and the material model applied to the target plate is according to Kim et al. [19]. Fig. 17b and c, is showing numerically predicted RS profiles compared against experimental data from internal work for a common type of stainless steel and a 2000 series aluminium alloy.

Table 4
Comparison between the numerical and the analytical results.

<table>
<thead>
<tr>
<th>Velocity m/s</th>
<th>Numerical (μs)</th>
<th>Analytical (μs)</th>
<th>Difference %</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.95</td>
<td>1.15</td>
<td>17</td>
</tr>
<tr>
<td>140</td>
<td>0.82</td>
<td>0.78</td>
<td>5</td>
</tr>
</tbody>
</table>

Fig. 9. Top view of plate’s fine mesh area showing the plastic coverage for (a) S110, (b) S230, (c) S330 and (d) S550.

Fig. 10. Velocity time history of the top surface node at the centre of impact location for initial shot velocities 20 m/s and 140 m/s.
3.2. Parametric study

After the validation of the numerical model, a parametric study is conducted in order to create a RS database for different shot peening parameters for the AA7449-T7615 material. Such a database can be a very useful tool for the engineer in the process of shot peening parameter selection. Furthermore, such database provides the basics for the development of a numerical model that could simulate the distortion of thin sheets.

The parametric analysis was performed by applying the shot patterns previously presented, including 4 shot types (S110, S230, S330 and S550), different shot velocities in the range of 20 to 100 m/s and two impinging angles (75° and 90°).

The maximum compressive stress computed for the 4 shot types and for the 2 impinging angles is plotted versus shot velocity in Fig. 18. As can be observed from Fig. 18, the maximum RS is increasing with increasing shot velocity for all cases.

Considering the shot size (for the same impinging angle), it can be observed in Fig. 18, that the maximum RS is increasing when a larger shot is used. When the shot type S110 is compared to S230, it can be seen that for all the velocities examined, there is an almost constant RS difference of about 35 MPa. When the shot size S330 is used the difference for all velocities considered is about 50 to 70 MPa compared to shot type S230. The maximum RS magnitude is slightly increased between shot type S330 and S550 for low velocities; for higher velocities, above 60 m/s, the difference can reach up to 35 MPa.

It is also clear that for the same shot size, the effect of impinging angle on the RS magnitude is insignificant. A small variation to the RS results is observed for velocities above 60 m/s. The same is found by Hong [17], who showed that the maximum RS is significantly affected at impinging angles less than 45°; above this value the differences in subsurface RS are negligible.

At this point it should be mentioned, that the maximum RS computed (Fig. 18) for each shot type should be examined together with the depth Xd presented in Fig. 19, in order to better understand the effect of shot velocity, shot size and impinging angle to the treated material.

The through-the-thickness depth is increasing with increasing velocity for all cases examined. Xd is increasing with increasing shot diameter, i.e. for the same velocity of 60 m/s and 90° impinging angle, Xd is equal to 43 μm for shot type S110, 85 μm for S230, 158 μm for S330 and 296 μm for S550.

The effect of the angle on the through-the-thickness depth appears to be insignificant, in particular when the shots diameter is small. For shot types S330 and S550, the effect of the impinging angle seems to have greater effect. As it can be observed, for impinging angles close to 90° the RS occurs at higher depth (Xd); when smaller impinging angles (75°) are used, the maximum RS occurs closer to the surface (smaller Xd). This practically means that the shot size, velocity and impinging angle are the parameters that govern the available shot stream energy. It is also a clear indication that there are multiple combinations between these parameters, which could produce the desirable process result; this can be an advantage for the engineer, if an accurate and comprehensive prediction pre-exists.

In Fig. 20 the through-the-thickness depth W (μm) where the RS changes sign from negative to positive is presented. It is found that W is increasing with increasing velocity and with increasing shot diameter in all cases. The effect of the angle seems to be insignificant.
for all shot types examined. Results from angle 75° and 90° are very similar.

4. Calculation of surface roughness and cold work

4.1. Surface roughness calculation

Surface roughness is a critical parameter when fatigue strength resistance is concerned, because it is related to the geometrical stress concentration factor Kt, which is critical for the damage tolerance of the treated component. The developed FE model is applied to compute the critical surface roughness parameters, such as $R_{tm}$ and $S_m$. $R_{tm}$ is defined as the average of the highest and lowest points between dents and $S_m$ is defined as the peak-to-peak distance between dents, as it can be seen from Fig. 21.

In Fig. 21, a detailed contour plot of a section in the finely meshed area for the case of shot type S230, velocity 80 m/s and 90° impinging angle is shown. The numerical model represents the surface roughness for the worst peening conditions. As stated by Dai et al. [34] in his work about surface nanocrystallisation and hardening (SNH), there are 3 stages in surface roughness evolution. In stage I some areas are not covered. In stage II more areas are covered and the sharp lips formed in stage I are becoming smoother. Finally in stage III, the surface roughness comes to a steady state. This means that the surface roughness numerically modelled with the shot patterns in this work represents stage I. An approximation of surface roughness by assessing computed results is also presented by Miao et al. [21] in 2009.

It should be mentioned that when a prediction for the fatigue performance of a component is required, the worst peening conditions should be taken into account. The fatigue performance of a component after shot peening process will be reduced in conditions such as over-peening or incomplete peening; the outcome of which is a damaged surface and high surface roughness, respectively.

The $R_{tm}$ value which was numerically calculated from the developed FE model was compared to the experimental results of Heckenberger [33] in Fig. 22, indicating a good agreement. The numerically calculated values are higher compared to the experimental as expected, because the numerical model with the applied shot pattern is simulating 50% optical coverage which corresponds to 100% plastic coverage and the experimental coverage refers to 100%. The data in Fig. 22 also support the statement of Dai et al. [34] that the same mechanism for roughness evolution might be true for shot peening.

By using the computed surface roughness parameters, the geometrical stress concentration factor Kt can be calculated by using Eqs. 4 or 5, dependent on the ratio of $R_{tm}/S_m$ after Li et al. [35], Clausen and Stangenberg [36] and Rodopoulos et al. [37].

\[
K_t = 1 + 4 \times \left( \frac{R_{tm}}{S_m} \right)^{1.3} \quad (R_{tm} / S_m < 0.15) \quad (4)
\]

\[
K_t = 1 + 2.1 \times \left( \frac{R_{tm}}{S_m} \right) \quad \begin{cases} 
R_{tm} / S_m & \leq 0.30 \\
0.30 & \end{cases} 
\]

(5)

The calculated stress concentration factor (Kt) refers to the worst peening conditions simulated by the present numerical model and indicates a critical area of the peened surface from which a crack is possible to initiate. This is due to the limited number of spherical shots included to the FE model. Apparently, by simulating more spherical shots a finer surface finish can be achieved; as the surface roughness will pass to stage II (Dai et al. [34]). In fact the surface roughness from

<table>
<thead>
<tr>
<th>Data series</th>
<th>Max. RS (MPa)</th>
<th>Xd (m)</th>
<th>W (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>365</td>
<td>−0.0000800</td>
<td>−0.00030</td>
</tr>
<tr>
<td>10 shots</td>
<td>373 (5%)</td>
<td>−0.0000813 (1.6%)</td>
<td>−0.000287 (4.5%)</td>
</tr>
<tr>
<td>20 shots</td>
<td>364 (2%)</td>
<td>−0.0000848 (5.7%)</td>
<td>−0.000291 (3.1%)</td>
</tr>
<tr>
<td>30 shots</td>
<td>393 (9%)</td>
<td>−0.0000851 (6.2%)</td>
<td>−0.000291 (3.1%)</td>
</tr>
<tr>
<td>40 shots</td>
<td>405 (12%)</td>
<td>−0.0000847 (5.5%)</td>
<td>−0.000291 (3.1%)</td>
</tr>
<tr>
<td>50 shots</td>
<td>418 (15%)</td>
<td>−0.0000847 (5.5%)</td>
<td>−0.000291 (3.1%)</td>
</tr>
</tbody>
</table>

Fig. 14. Surface at middle (hot spot) of single line one pass.

Fig. 15. Comparison of computed and experimentally measured residual stress profiles for shot type S230, velocity 50 m/s and an impinging angle of 90°.

Fig. 16. Computed versus experimentally measured residual stress profiles when additional shots are considered.

Table 6 Differences found on max. RS, depth Xd and W of residual stress curves computed.
the case study of 50 shot impacts is examined and the result included in Fig. 22.

In Fig. 23, the geometrical stress concentration factor $K_t$ is presented for three shot types, namely $S_{110}$, $S_{230}$ and $S_{330}$ and four velocities (40, 60, 80 and 100 m/s). As it is observed from Fig. 23, $K_t$ is increasing for increasing velocities for all shot types.

4.2. Calculation of cold work

Cold work percentage (CW%) expresses the hardening of the material due to plastic deformation. A material is considered to be cold worked, if its grains are in a distorted condition after plastic deformation. The mechanical properties that are dependent on the lattice structure are affected by plastic deformation or cold working.

Cold work is experimentally determined by Prevéy and Cammett in 2002 [38] after X-ray diffraction experiments by relating diffraction peak breadths to the equivalent true plastic strains.

During shot peening, severe plastic deformation occurs as a result of shot impacts. It is critical to know cold work because the material hardness and tensile strength are locally increased, whilst ductility is lowered. As a result of the material transformation close to the surface, the new material properties should be considered before this material will enter to its operational environment.

Mesoscopic influences of the shot peening treatments have been investigated on transverse micro-sections. The through-the-thickness hardness measurements, shown in Fig. 24 and the change in the measured hardness were applied to estimate the percentage of cold work (Fig. 25). Hardening measurements performed before shot peening revealed a value equal to 189HV for the specific aluminium alloy.

In Fig. 24, the plastic region below the surface of the treated material after shot peening is presented both numerically and experimentally, as presented by Kang et al. [39]. The equivalent plastic strain values refer to the SP conditions used for the case studied in Section 3.1 for model validation, i.e. shot type $S_{230}$, initial velocity 50 m/s and impinging angle 90° to all the shots.

In order to calculate cold work analytically, it is assumed that the material’s plastic behaviour follows a power hardening rule and can be described by:

$$\sigma = K \times \varepsilon^n.$$ (6)
Therefore, cold work can be calculated by:

\[
CW\% = \frac{\sigma_{ref}}{\sigma_{0.2}} \times 100 = \left(\frac{\varepsilon_{ref}}{\varepsilon_{0.2}}\right)^n \times 100. \tag{7}
\]

In Eq. 7, \(\varepsilon_{ref}\) is the computed plastic strain through-the-plate thickness, \(\varepsilon_{0.2}\) is the strain at yield point and \(n\) is the hardening exponent of the material, which is given by Eq. 8, Zhang et al. [40].

\[
\log n = \log \left(\frac{\sigma_f}{\sigma_{0.2}}\right) - \frac{\log(500\varepsilon_f)}{2 \log(100)} \tag{8}
\]

In Eq. 8, \(\sigma_f, \sigma_{0.2}\) and \(\varepsilon_f\) are the fracture strength, ultimate strength and yield stress respectively, whilst fracture ductility is stated by \(\varepsilon_f\). The hardening exponent of the specific aluminium alloy was found to be 0.02. In order to calculate the cold work percentage, Eq. 7 is applied. The analytical results for shot type S230, impinging angle 90° and for four different velocities are presented in Fig. 25.

An approximation of the cold work percentage is performed by using the hardness experimental measurements as Kudryavtsev [41].

\[
CW\% = 100 \times \frac{H V_z}{H V_{ref}} \times 100 \tag{9}
\]

In Eq. 9, \(H V_{ref}\) is the hardness value for the unreformed specimen and \(H V_z\) is the through-the-thickness experimental measurement. The approximated cold work from the experimental measurements is plotted in Fig. 25 for a direct comparison with the numerical results.

As it can be seen, the experimental and the numerical data are not correlating very well; although the similar curve profile can be promising.

5. Conclusions

A three-dimensional FE model that consists of an elastic plastic aluminium alloy target plate and rigid spherical steel shots is developed in order to simulate shot peening process. The elastic plastic material model used for the AA7449-T7651 plate is based on high strain rate experimental tests described via the Cowper–Symonds material model. By modelling the entire plate geometry any influence from the plate boundary conditions to the finely meshed area is avoided. The finely meshed area of 1 mm² which is located in the middle of the plate is utilised to compute the RS profiles. Experimental results of RS profiles for AA7449-T7651 and for two other metallic materials from the literature are used to validate the numerical model and the simulated shot patterns.

The developed numerical model is mainly used to predict the effect of shot velocity, impinging angle and shot size on the induced RS profile for the specific aluminium alloy through a parametric study. The parametric study illustrated that the peak RS value is affected by both the shot velocity and size. Shot velocity and size have also a significant influence on \(X_d\) and \(W\). On the other hand, the effect of the impinging angle of 75° at the peak RS, \(X_d\) and \(W\) is negligible.

The developed numerical model is also used to predict the surface roughness, geometric stress concentration factor (\(K_t\)) and cold work percentage by applying the computed results as inputs to analytical
equations. The prediction of geometric stress concentration factor (Kt) via surface roughness and cold work percentage via computed results described by the authors is a useful tool for the optimisation of the shot peening process. This can also trigger researchers for further activity on the topic as it is presented for the first time.

The prediction of these magnitudes via the numerical model is something novel and can be applied to several materials as shown. The predicted RS profiles for different coverage ratios are valuable for the development of a numerical model that accurately predicts the induced distortion of the treated material. The current model can be extended to a global distortion prediction finite element model.

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Fig. 24. Numerically computed plastic strain and experimentally measured hardness plotted against the trough-the-thickness plate depth (µm).

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