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FINITE ELEMENT SHOT PEENING SIMULATION FOR RESIDUAL STRESS. ANALYSIS AND COMPARISON WITH EXPERIMENTAL RESULTS

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Abstract *This study was performed using the Finite Element Method with the main objective of simulating the shot peening process to evaluate the residual stresses. Shot peening was simulated considering the one single shot impact against a plate throughout an axisymmetric model. An integration explicit dynamic algorithm was employed, taking into consideration the elastic plastic behavior of the two bodies in contact. Slidelines were utilized to simulate the impact zone. The obtained results were compared with values of experimental expressions found in specialized literature. The finite element professional software denominated LUSAS® was used in the simulation.*

INTRODUCTION

Parts and mechanical structures can fail during lifetime service, even sustaining values of loading, inferior to the projects' criteria. This situation may be accelerated, or not, with the presence of residual stresses. These residual stresses, in some cases, could bring about a premature fracture. Several methods, like heat treatment, shot peening, surface polishing, among others, are utilized aimed at retarding the start and propagation of defects.

Shot peening is one of the surface treatments for metals largely used to increase their fatigue and fracture strength. It may be defined as the process of cold working the surface of structural or machine parts by means of a stream of high velocity shots. Relatively hard particles, usually steel shots, are entrained in an air jet and blown towards the part to be peened at a high velocity.

The intensity of peening depends on such variables as shot size, shot velocity, angle of impingement and duration of peening, etc.

This process leads to three important mechanical effects:

- Plastic deformation causes the surface to become slightly dimpled, so that the surface roughness is increased, which may or may not facilitate crack initiation on the surface.
- Plastic working on the surface means that strain hardening occurs, resulting in a change in surface hardness and an increase in the yield stress of the material.
- Elastic plastic relaxation of near surface layers as the shot rebounds induces residual compressive stresses parallel to the free surface of the component. The effects of these stresses act to delay crack initiation, and hence hinders crack propagation by alleviating the resultant applied stress.

There are compressive residual stresses at the surface of the work-piece with a maximum value just under the surface and small equilibrating tensile stresses inside the work-piece.

SHOT PEENING PROCESS SIMULATION

Simulation of the shot peening process was modelled on the one perpendicular single shot impact against a centre of a plate, using a dynamic two-dimensional axisymmetric finite element model. The general characteristics of the model are presented in Figure 1.

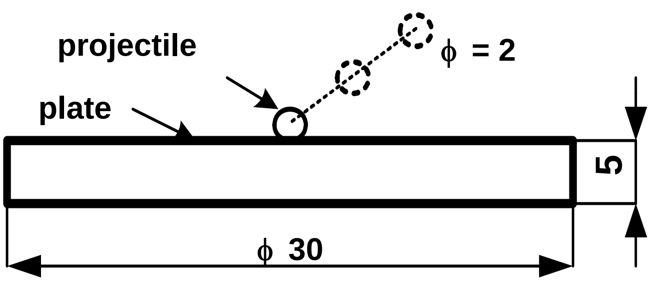

Figure 1 Dimensions of the model [mm]

Material specifications

For instance, the material used in the simulation was steel called "10 steel" for the plate and steel called "40 steel" for the spherical shot, Pisarenko[1]. Non-linear behaviour for both materials was considered, using a non-linear strain hardening law in the case of a plate. Their mechanical properties are presented in Tables 1 and 2.

Table 1 Mechanical property for a shot

E [MPa]	ν	ρ *[kg/m³]*	σ_e *[MPa]*	σ_u *[MPa]*
2e+05	0,3	7840	340	580

Table 2 Mechanical properties for a plate

E [MPa]	ν	ρ *[kg/m³]*	σ_e *[MPa]*	σ_u *[MPa]*
2e+05	0,3	7840	240	340

Impact zone definition

Contact due to impact is defined between the shot and the plate. In LUSAS version 12.1 a contact surface pair consists of two slidelines surfaces (slidelines for 2D), called master and slave, who are initially in contact or which are expected to come into contact during the response solution process.

Their applications range from projectile impact, vehicle crashworthiness, the containment of failed components such a turbines blades, interference fits, rock joints and bolt/plate connections, LUSAS[2].

In this case the slidelines options are based numerically on the penalty function slideline method. After several convergence tests, the zonal contact detection parameter was set as 0,55, and the stiffness scale factor for the shot and the plate was introduced as 0,1 and 0,01 respectively.

Both parameters are very important to control and avoid an excessive penetration of a shot into a plate.

Integration method

As the finite element method is used to map a continuous mechanical system into a discrete system, time integration schemes are used to change a continuous dynamic phenomenon into a step-by-step phenomenon.

The main time integration schemes are deduced from Taylor expansions or temporal finite element methods. The widely used Newmark time integration scheme consists in approximating the displacement and velocity vectors. The Newmark scheme is second order accurate and depends on two real parameters β and γ. The parameter values are directly linked to accuracy and stability of Newmark integration scheme.

The classical Newmark parameter values are: ($\beta = 1/6$; $\gamma = 1/2$), which lead to a linear acceleration approximation (conditionally stable scheme); ($\beta = 1/4$; $\gamma = 1/2$), which lead to a constant average acceleration. This choice of parameters corresponds to a trapezoidal rule (unconditionally stable scheme in linear analysis); (β = 1/12; γ = 1/2), the Fox-Goodwin method which is fourth order accurate (conditionally stable scheme).

In order to keep a second order accurate scheme and to introduce numerical dissipation, a modification of the initial Newmark scheme was proposed by Hilber et al (LUSAS[2]), introducing a new parameter α which is a numerical dissipation parameter. The original Newmark scheme becomes the α-method or Newmark HHT modification. The α-method leads to an unconditionally stable integration time scheme and the new Newmark parameters are expressed as a function of the parameter α: $\beta = (1+\alpha)^2/4$ and $\gamma = 1/2 + \alpha$, where the value of α belongs to the interval [0, 1/3].

If $\alpha = 0$, the scheme is reduced to the classical trapezoidal rule, without any dissipation. Increasing α leads to increased amount of numerical damping (LUSAS[2]).

The central difference explicit method was used to solve the model. The central difference method corresponds to a Newmark HHT time scheme with parameter values α = 0, β = 0 and γ = 1/2.

Explicit algorithms are generally used for problems which require small time steps irrespective of the stability requirements.

These problems are classed as wave propagation problems because the behaviour of the wave front, dominated by high frequency components, is of engineering importance.

This category includes the shock response from explosive or impact loading. The central difference method is particularly effective with a uniform discretisation of low order elements.

When a conditionally stable integration scheme is used, the user has no choice but to use a time step $\Delta t \leq \Delta t_{cr}$, where

$$\Delta t_{cr} = \frac{2}{\omega_{\max}} \tag{1}$$

and ω_{max} is the maximum circular frequency of the system; however, LUSAS will automatically compute an appropriate Δt, if this is not specified.

Type of elements

The surfaces forming the projectile and the plate were meshed using 2D axisymmetric explicit dynamic elements. The elements are 4-node quadrilaterals (QAX4E) and 3-node triangles (TAX3E), which were optimized specifically for explicit dynamics analysis.

A number of preliminary runs were conducted to establish the appropriate mesh design for the model.

In the spherical shot case were tested four different meshes and two for the plate, one uniform, and the other with transition zones between the impact zone and the regions of less influence. The meshes tested for the shot and the plate are shown in Figure 2.

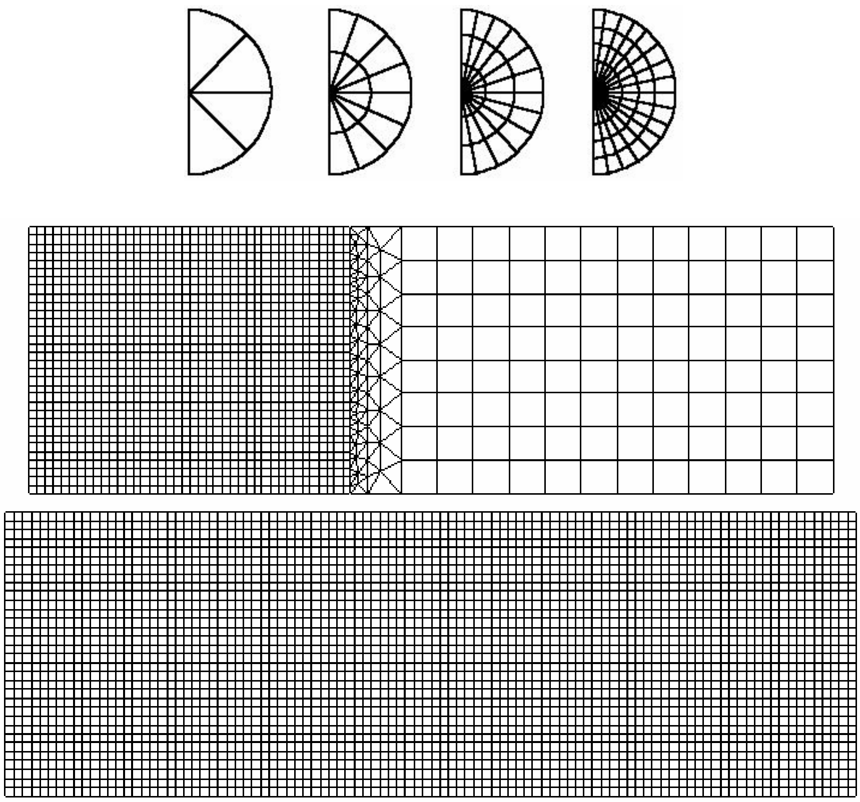

Figure 2 Different mesh discretization for a shot and the plate

Finally the mesh presented in Figure 3 was chosen because of good agreement found when compared with the results obtained with other papers' experimental data.

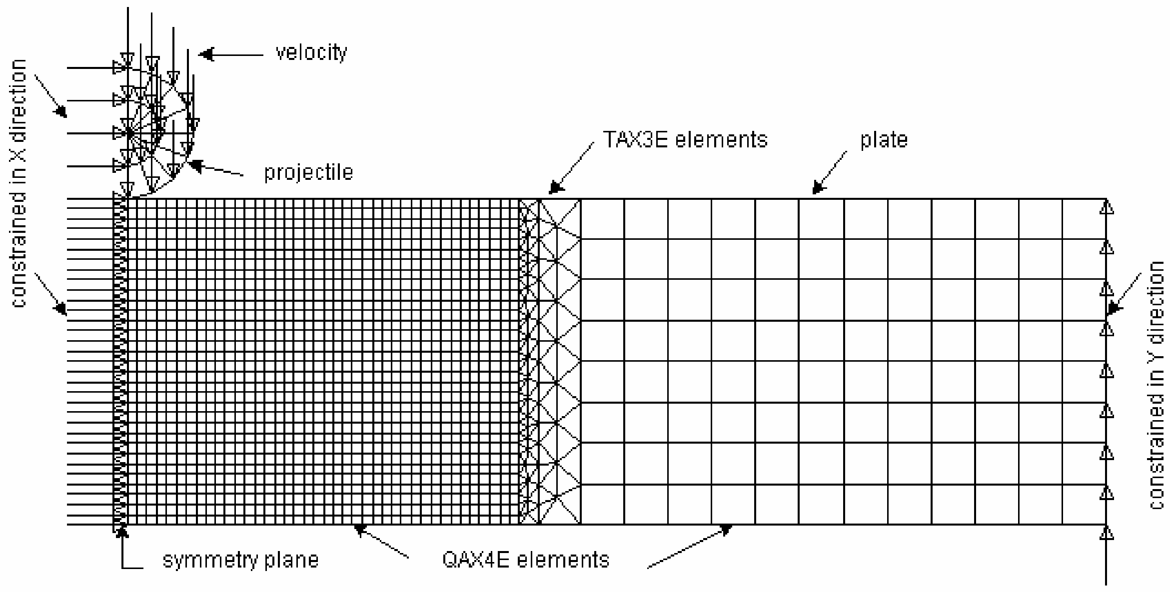

Figure 3 Mesh discretization and boundary conditions for the model shotsym2

It can be observed that in the impact zone up to an equivalent distance equal to three times the projectile diameter were employed QAX4E elements, while in the transition zones were used TAX3E elements. At the furthest regions the mesh density doesn't need to be very fine, due to the poor influence on the results. The calculations become faster and more economical.

The residual stress field for the model shotsym2 can be observed in Figure 4. Figure 4 shows a transition between tensile and compression residual stress. This fact occurs at a certain distance beneath the plate surface. This distance is called by many authors as a depth of a plastic zone, and could be calculated using the following equation, Al-Obaid[3]:

$$\frac{h_p}{R} = 3\left(\frac{2}{3}\right)^{\frac{1}{4}}\left(\frac{\rho V_0^{\ 2}}{\overline{p}}\right)^{\frac{1}{4}} \tag{2}$$

where:
h_p - depth of the plastic zone;
R - radius of the shot;
ρ - material density of the shot;
V_o - shot's initial velocity;
$\overline{p}$ - Average pressure.

In conditions of full plasticity, the average pressure can be assumed as three times the yield strength σ_y, Al-Obaid[3]. Figure 4 also presents that at the impact zone, identified with the straight (1), tensile residual stresses appear. This behaviour is in agreement with the experimental work presented by Kobayashi[4], where it was demonstrated that for a dynamic impact case either the strain and stress values are positive at the centre of the indentation, while in the neighbourhood of the impact region, the originated residual strain and stresses due to impact are in compression. The uniform layer of compression residual stress formed by the shot peening process is considered to be the result of the superposition of residual stress produced by surrounding shots.

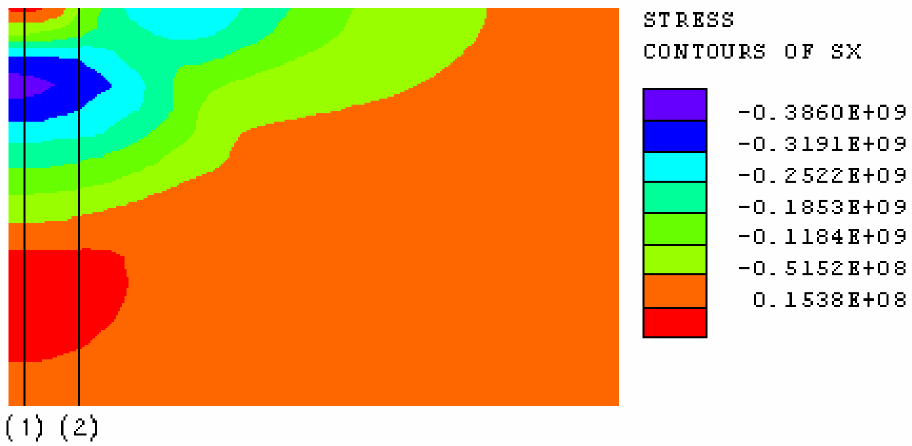

Figure 4 Residual stress fields for the model shotsym2 [Pa]

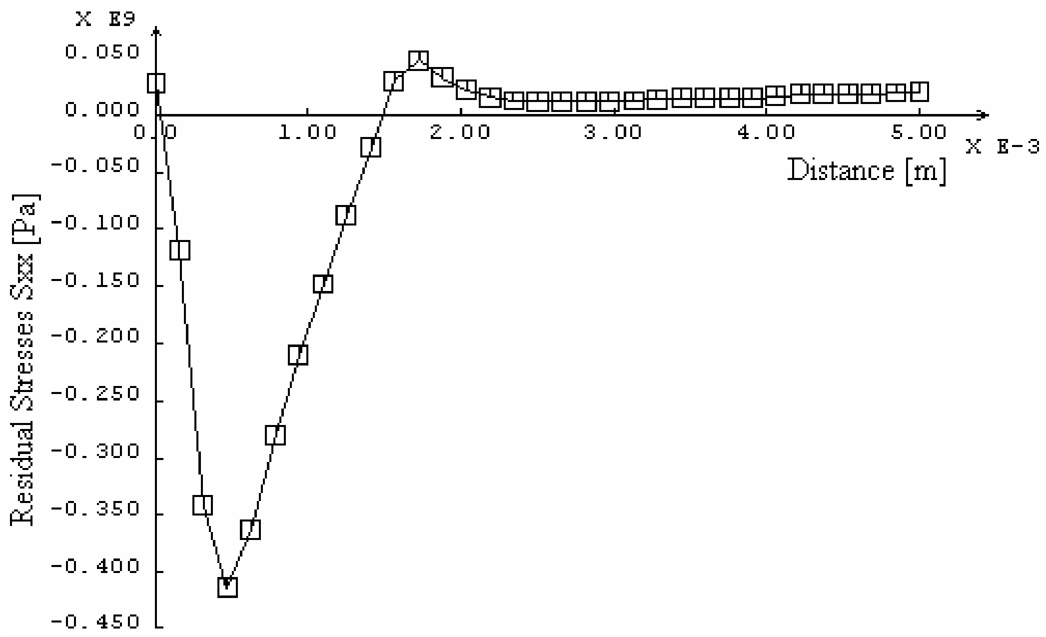

Figure 5 Residual stress graph corresponding to straight 1

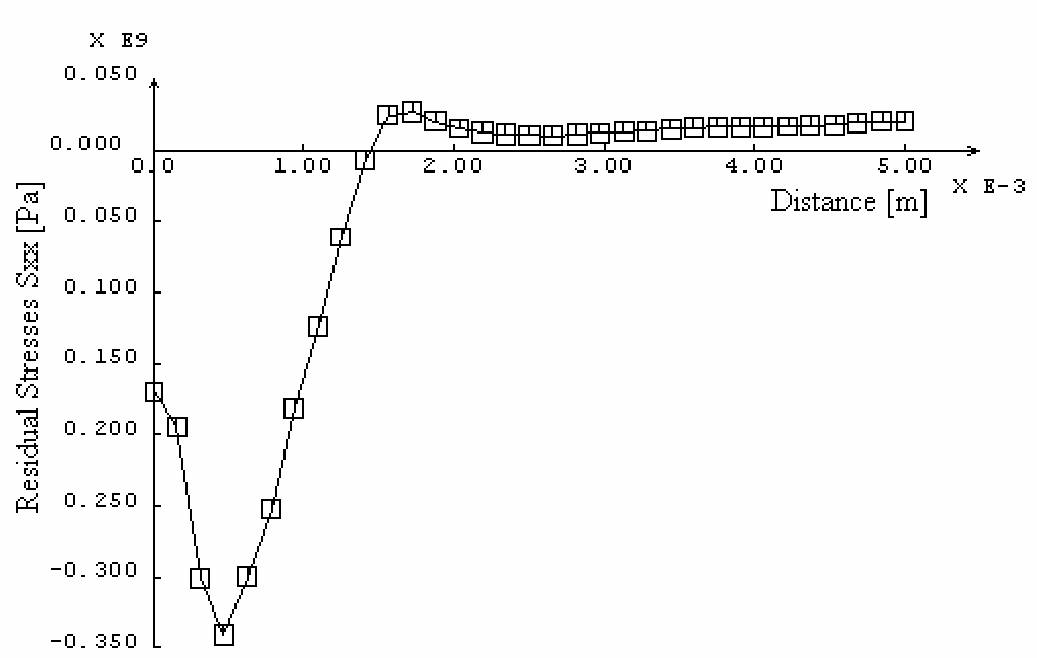

Figure 6 Residual stresses graph corresponding to straight 2

Table 3 show the comparison between the depths of the plastic zone values obtained by the model and by the equation proposed by Al-Obaid[3].

Table 3 – Plastic zone depth values obtained by MEF and employing the equation proposed by Al-Obaid

Equation and Model	***Depth of the plastic zone h_p [mm]***
Al-Obaid	1,549
Model shotsym2	1,562

Comparison between the numerical result and the equation 2 proposed by Al-Obaid reveals satisfactory agreement. This is an important result, because the correct determination of the plastic zone depth value leads to know the transition region between tensile and compression residual stress values and the depth reached by the compression residual stresses layer.

The residual stress calculated value at the surface of a plate (σ_S^R), as well as the residual stress maximum value (σ_{max}^R) obtained by MEF, were compared with the experimental equations (3 and 4) of WANG et al[5].

$$\sigma_S^R = 120 + 0{,}5\sigma_y(\pm 30) \tag{3}$$

$$\begin{aligned} \sigma_{\max}^R &= 70 + 0{,}667\sigma_u \quad (\sigma_u < 1000\,MPa) \\ \sigma_{\max}^R &= 430 + 0{,}323\sigma_u \quad (\sigma_u \geq 1000\,MPa) \end{aligned} \tag{4}$$

where:

σ_S^R - residual stress at the surface of a plate;

σ_y - yield stress;

$\sigma_{\max}^R$ - maximum residual stress;

σ_u - ultimate stress.

These empirical equations were proposed as a result of an experimental statistic analysis for different materials (aluminium alloys and steels). Those materials were submitted to a shot peening process.

Table 4 present a comparison between the residual stress at the surface (σ_S^R) and the maximum residual stress value ($\sigma_{\max}^R$) obtained through the model shotsym2 with the Wang et al equations calculated values. Table 4 also shows another residual stress values due to shot peening process calculated using MEF (MEGUID et al[6]; SCHIFFNER et al[7]), residual stress results obtained by the ShotPen software (a computational program to simulate the shot peening process (FATHALLAH et al[8]) and experimental research values (MEGUID et al and WAISMAN). In all cases, the residual stress values were compared with those calculated by Wang et al. experimental equations. From Table 4 a remarkable difference between the residual stress values obtained by several researchers and the values determined through the Wang et al equations can be observed. It must be said that these differences may be caused because the models results presented in Table 4, came from the single impact analysis. The Wang et al equations consider the real situation, the impact of hundreds of balls against the piece surface.

Table 4 – Comparison between experimental and modelling results

Models and Wang et al equations values	σ_s^R[MPa]	σ_{max}^R[MPa]
Shotsym2(LUSAS)	**146,6**	**384**
Wang et al.(1998)	**240**	**296,78**
Meguid et al. (1999) (ANSYS 5.3)	**300**	**1020**
Wang et al.(1998)	**420**	**636,95**
Schiffner et al. (1999) (ADINA)	**nd**	**1800**
Fathallah et al. (Shotpeen softw.)	**550**	**1100**
Wang et al.(1998)	**505**	**681,63**
Meguid et al. (1990) (experim.; steel 808M40)	**333**	**443**
Wang et al. (1998)	**320**	**436,85**
Meguid et al. (1990) (experim.; Al 7075)	**129**	**208**
Wang et al.(1998)	**351**	**420,84**
Waisman (1952) (experim.; Al 7075-T6)	**nd**	**400**
Wang et al.(1998)	**nd**	**436,85**

CONCLUSIONS

- The shot peening process modelling presented a compression stress field distribution at the plate surface due to shot impact, with a peak of stress beneath a surface.
- Comparison between the numerical results and classic formulation plastic zone depth values reveals satisfactory agreement.
- Only with the application of multiple impacts it is possible to obtain a compressive residual stress uniform layer.
- The depth of the plastic zone defines the transition region between the compressive and traction residual stress values.
- Shot peening process can successfully be simulated by LUSAS finite element code. Numerical simulation allows a parametric study of shot peening process. This could mean a better understanding of shot peening mechanism.

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