THEORETICAL PRINCIPLES OF PEEN FORMING: AN EXPERIMENTAL AND NUMERICAL ANALYSIS

Daniel Benítez Barrios, danielbb@mackenzie.com.br
Grupo de Simulação Numérica (GSN) do Dpto de Engenharia Mecânica, Universidade Presbiteriana Mackenzie.
Rua da Consolação, 930 - Cep 01302-907 Consolação - São Paulo - SP – Brasil. Pós-doutorando no Instituto de Pesquisas Energéticas e Nucleares (Ipen).

Miguel Angel Calle Gonzales, mcallegonzales@gmail.com
Centro de Estruturas Navais e Oceânicas (CENO) da Universidade de São Paulo.
Av. Prof. Mello Morais, 2231, Butantâ, São Paulo, SP, Brasil, CEP 05508-900.

Arnaldo H. Paes de Andrade, aandrade@ipen.br
Centro de Ciência e Tecnologia de Materiais (CCTM), Instituto de Pesquisas Energéticas e Nucleares (Ipen).
Av. Prof. Lineu Prestes 2242 – Cid. Universitária – CEP 05508-900

Nelson Batista de Lima, nblima@ipen.br
Centro de Ciência e Tecnologia de Materiais (CCTM), Instituto de Pesquisas Energéticas e Nucleares (Ipen).
Av. Prof. Lineu Prestes 2242 – Cid. Universitária – CEP 05508-900

Edison Gonçalves, edison@usp.br
Centro de Estruturas Navais e Oceânicas (CENO) da Universidade de São Paulo.
Av. Prof. Mello Morais, 2231, Butantâ, São Paulo, SP, Brasil, CEP 05508-900.

Abstract. *Shot peen forming is a non-destructive process performed at room temperature when small steel balls impact a work piece surface. Each small ball acts as a tiny peening hammer, producing elastic stretching of the upper surface and local plastic deformation that manifests itself as a residual compressive stress. This combination causes the material to develop a compound, convex curvature on the peened side. The main objective of this work is to show the residual stress distributions originated by shot peen forming using a finite element model. First, a computational model of a plate under several shot impacts is developed. The results are compared with X-rays diffraction experimental data. This paper shows that it is possible to simulate the peen forming residual stress distribution with numerical methods. This data can be superimposed on Finite Element Model predictions to improve the accuracy of life prediction, even when fracture mechanics models are required. As a conclusion, although shot peen formed pieces usually require shot peening on one side only, the result causes both sides to have compressive stress. These compressive stresses inhibit stress corrosion cracking and improve fatigue resistance.*

Keywords*: peen forming, finite element, residual stress, experimental analysis.*

1. INTRODUCTION

What is shot peening? What happens when a machine element or a structural component is shot peened? When a mechanical piece is pelted/bombarded with a stream of round metallic media (referred to as shot). Each shot dents at the impact, when causes plastic deformation on the surface. This extends the superficial layer creating compressive stresses underneath and providing a balance to the applied working (tensile) stresses. This residual compressive stress delays the formation of fatigue cracks thereby increasing the useful life of a component (Balan, 2007). The layer of compressive stress commonly extends to depths varying from 0.12 to 0.78 mm. Greater depths, if desired, are achieved by altering process parameters such as shot size, velocity and angle of impingement, exposure time, etc.

It is important to know the values of the residual stresses in order to predict the mechanical strength of peened parts, and to know how these stresses vary by changing the shot peening parameters.

Shot peen forming is a non-destructive process performed at room temperature, when small steel balls impact the surface of the work piece. Each small ball acts as a tiny peening hammer, producing elastic stretching of the upper surface and local plastic deformation that manifests itself as a residual compressive stress. The combination of elastic stretching and compressive stress generation causes the material to develop a compound, convex curvature on the peened side.

Although no dies are required for shot peen forming, for severe forming applications, stress peen fixtures are sometimes used. Shot peen forming is effective on all metals, even honeycomb skins and ISO grid panels. Shot peen forming reduces material allowance from trimming and eliminates costly development and manufacturing time to fabricate hard dies. The shot peen forming process also is flexible to design changes, which may occur after initial design. Metal Improvement Company can make curvature changes by adjusting the shot peen forming process (Figure 1, 2004).

Figure 1. Example of a part made it by shot peen forming

Parts formed by shot peen forming exhibit increased resistance to flexural bending fatigue. Unlike most other forming methods, all surface stresses generated by shot peen forming are of a compressive nature. Although shot peen formed pieces usually require shot peening on one side only, the result causes both sides to have compressive stress.

These compressive stresses serve to inhibit stress corrosion cracking and to improve fatigue resistance. Some work pieces should be shot peened all over prior to or after shot peen forming to further improve fatigue and stress corrosion cracking resistance.

Shot peening of cold formed other processes parts, overcomes the harmful surface tensile stresses, set up by these other forming processes.

The main objective of this work is to show the residual stress distributions originated by shot peen forming as a consequence of the shot peening process application using a finite element model. First, a computational model of several shot impacts against the plate is developed. The results were compared with X-rays diffraction experimental data. This paper shows that it is possible to evaluate residual stress distribution due the peen forming , by using numerical methods.

2. THEORETHICAL CONSIDERATIONS

When a part, like e plate for example, is submitted to a shot peening process, in several occasions bolts or other mechanical devices fix it. After the treatment, being the piece free of constraints, the residual stress distribution change. In fact, once the constraints are removed a plate, originally straight, becomes curved and modified the residual stresses field. Thus, the residual stresses due to impact are not equilibrated; consequently, the plate will bend and elongate. These effects are prevented by the boundary conditions. A compressive force F and a bending moment M are applied in order to keep the plate straight (see Fig. 2).

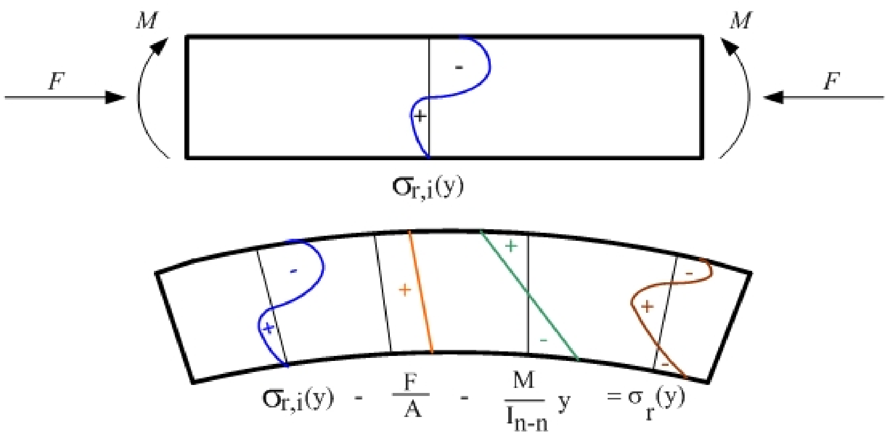


Figure 2. Calculation of the residual stresses in the plate after constraints removal

If is assumed that the impact residual stresses are elastic, the force and the moment can be calculated as (Guagliano, 2001):

$$F = \int_A \sigma_{r,i}(y) dA \tag{1}$$

$$M = \int_A \sigma_{r,i}(y) y dA \tag{2}$$

where $\sigma_{r,i}$ are the residual stresses due to the shot impacts, A is the plate section and y is the distance from the neutral axis. The removal of the constraints can be interpreted as the application of a moment and a force of equal value but with an opposite sign with respect to M and F. The stresses, strain and deflections of M and F are determined, once the residual stresses due to the impacts are known, by using the Theory of Elasticity; with reference to Fig. 1, it is possible to affirm that the residual stress field in the plate after the constraints are removed is equal to:

$$\sigma_r(y) = \sigma_{r,i}(y) - \frac{F}{A} - \frac{M}{I_{n-n}} y \tag{3}$$

where I_{n-n} is the moment of inertia and A the sectional area of the plate (Guagliano, 2001).

3. MODELLING CONSIDERATIONS

Shot peening involves dynamic deformations, and the formulas relating to static contact lead to approximate results in terms of residual stresses. An experimental study (Kobayashi et at, 1998) showed that the residual stress field due to static contact between the shot and a metal part is quite different from that obtained by dynamic impact between the same bodies. Thus, a finite element procedure was developed with the aim of simulating the dynamic impact of one or more shots against a deformable plate.

3.1. Finite element procedure assumptions

The ANSYS LS-DYNA code was used in the finite element analysis. The principal assumptions employed in the implementation of the finite elements model are: The explicit integration scheme was used in this research. The major advantage of the explicit solution scheme is its computation efficiency because iterative calculation is not used and the tangent stiffness matrix is not formed. Furthermore, if a correct increment time is chosen, there are no convergence problems.

The main problem with the use of explicit techniques is that analysis is purely dynamic: if some approximate damping is not included in the model, once the shot on rebound separated from the plate and the plastic deformation phenomena have ended, the model will never reach a state of static equilibrium. In other words, the stresses in the plate will oscillate around average values which, in the present work, is taken to be the stable residual stress (Guagliano 2001).

The shot particles are considered rigid spheres of uniform radius. It is worth noticing, that the stream kinetic energy is qualified experimentally by the Almen arc height (Guagliano, 2001).

The area density of impacts is considered uniform (Calle et al, 2007). The residual stress profile is obtained by taking the residual stresses values from the in-depth nodes located on the central axis of the damped zone. We suppose that it is representative of a shot peening with 100% coverage. The shot is supposed impinging the target surface at normal incidence $\alpha = 90°$.

The velocity of the shot is assumed to be constant during the impact. Its value has been determined by using available curves giving the Almen arc height with shot velocity for a specific shot. In this work the used shot is made it of cast iron. Those curves were obtained by numerical simulations predicting the Almen arc height obtained by the shot peening (Guagliano, 2001).

The material properties of the steel shot were: ρ (density) = 7440 kg/m^3, E (elastic modulus) = 21 GPa and ν (Poisson's ratio) = 0.3. The target plate was made of annealed SAE 1070 steel and its mechanical properties were: ρ = 7800 kg/m3, E = 210 GPa, ν = 0.3, σ_y (yield stress) = 480 MPa and the H (plasticity modulus) = 928 MPa.

The numerical method used to create contact elements between the impacting surfaces was the penalty function. The parameters of the penalty function were automatically calculated by the LS-DYNA to be rigid enough to avoid penetration. The friction coefficient was 0.25.

3.2. Finite element model

The model consists in a plate being impacted by several shots. One symmetric plane (X-Y) and boundary conditions were considered with a considerable saving in calculation time. There are 16362 three-dimensional elements, tetragonal and hexagonal, supported by 19199 nodes. In Fig. 3, the mesh model is illustrated. The kinematics work hardening rule was assumed to describe the material's mechanical behaviour. The strain rate sensitivity of the material was taken into account according to the Cowper-Symonds model (Calle, 2007).

The finite element mesh was refinement in those regions corresponding to the impact of the shot on the plate.

The size of the shot is defined by the S330 size according to the SAE J444 specification, 1993. The diameter of the shot taken into account corresponds to the diameter of the sieve having a rate of 85 % cumulated shots. For the case of shot size S330, the most representative diameter is 0.875 mm, used in this research (Calle, 2007).

The shot velocity was set as an initial condition a value of 83.7 m/s. This velocity was adopted because it corresponds to the intensity of 0.83 mm Almen (Almen scale A).

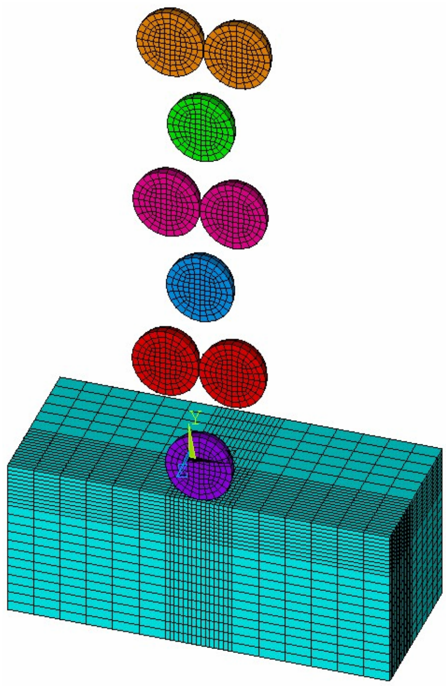


Figure 3. 3D finite-element model used for the determination of the residual stresses due to the multiple impacts of shot

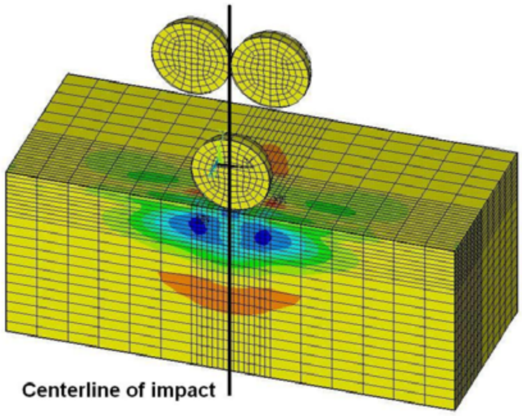
3.3. Results and discussion of numerical simulation

The residual stresses were obtained along the centerline of impact of the finite-element model. These residual stresses were considerate the more representative than others obtained because it involves a direct and lateral media impacts. Stresses were considered in direction X because they are parallel to the surface of the part and responsible for the compressive residual stress distribution in shot peening process. They have approximately the same values that the stresses in z direction for the considered model (Figure 3).

The Figure 4 shows the residual stress profile in depth for the centerline of impact, showed too in the same Figure.

The residual stress profile illustrated in Figure 5 shows that exists a minimum value of compressive residual stress at the surface.

This value decreases first and after that increase until reach a peak of maximum compressive residual stress. This behavior may be a consequence of multiple impact effects.



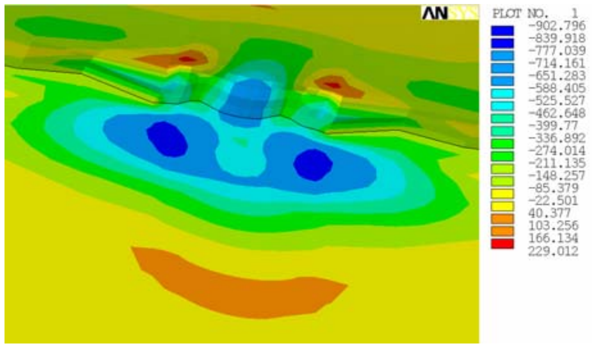


Figure 4. Resultant residual stresses in the numerical model and detail of the impacted zone

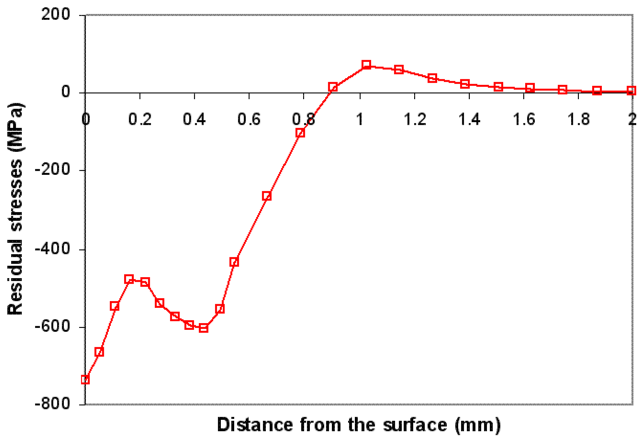


Figure 5. Residual stress profile in depth in the centerline of impact due to shot peening

Figure 6 shows the residual stress profile when a plate is fixed by the constraints (curve 1) and the resultant residual stress distribution that remains once the plate is free (curve 3).

It is important to notice that the resultant residual stress distribution was obtained by treating the original residual stress distribution with the 1, 2 and 3 equations.

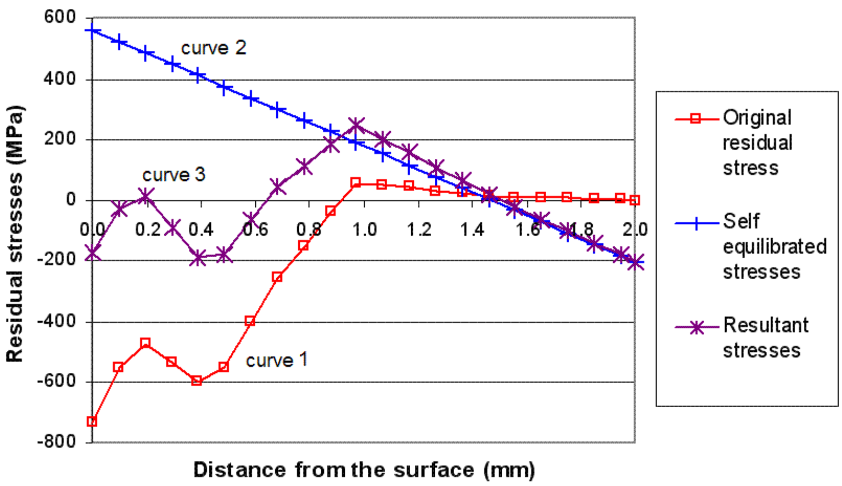


Figure 6. Residual stress profile in depth: a) when the plate is restricted and straight (curve in red), and b) when the plate is unrestricted, elongated and bended (curve in purple)

4. EXPERIMENTAL MEASUREMENTS

4.1. Material

The results obtained by means of the finite element simulations were compared with the data obtained from experimental measurements of the residual stresses carried out on some test specimens. The material used is the SAE 1070 steel supplied by Brasmetal Waelzholz Co. The specimens were obtained from an original plate, which had dimensions of 250 mm by 200 mm and 2 mm of thickness. The mechanical properties were obtained through mechanical tests showing a yield stress of 480 MPa and the ultimate stress of 568 MPa.

The specimens required for these tests were machined under the ABNT NBR 6152 specifications.

4.2. Experimental procedure

The shot peening treatment of the SAE 1070 plate was made in the Cindumel Company under the SAE J442 specification. As mentioned previously, the Almen intensity applied was 0.83 mm A. The hardness of the media shot is between 530 – 650 HV and the size is defined by the S330 size according to the SAE J444 specification, 1993.

From the original plate were cut three specimens of dimensions 50 mm × 50 mm for having a size capable to be entered to the X-ray diffraction machine for the residual stresses measurement.

The measurements were carried out by means of a X-ray diffractometer using the $\sin^2\psi$ method, Figure 7. There were made 13 angular measures, from -60° to 60° with intervals of 10°. The elastic properties of the analyzed material used to the results processing were the standard properties of the steel, Young modulus of 210 GPa and Poisson coefficient of 0.3.

The areas subjected to the X-ray measurement were 2 mm × 1 mm and, in this work, only the surface residual stress values were taking into consideration in the analysis.

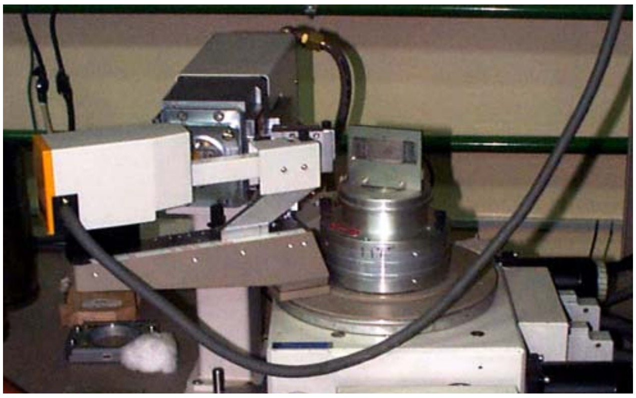


Figure 7. Surface residual stress measurement using an X-rays diffraction technique

The surface residual stress for three test specimens was measured. The Table 1 shows the obtained results.

Table 1. Surface residual stress of the specimens submitted to the shot peening treatment

Specimens	Superficial residual stress [MPa]
A1	-264 ± 40
A2	-198 ± 40
A3	-212 ± 40
Average	-225 ± 40

The residual stress analyzed by rays-x diffraction resulted in -225 MPa, while the value obtained for the numerical analysis and the stresses relaxation caused by the deformation of the plate was of - 188 MPa, presenting an error of 16.4%.

This difference appear because the residual stress distribution in each point of the target surface, obtained by the numerical simulation or by the experimental work, varies in function of the distance to the axle of the central impact.

On the other hand, the stresses provoked by the shot peening process are many variables for its proper chaotic and fortuitous nature. It must be noticed that the numerical simulation presented a difference of 37 MPa, value that is inside of the margin of error of the proper system of rays-x diffraction (40 MPa).

5. CONCLUSIONS

Due to many different parameters involved it is not easy to simulate the shot peening process. However, a Finite Element Method can be considered an interesting tool to modeling it. The numerical simulation results (Figure 5), when compared to the experimental X-rays diffraction technique values (Table 1), show a good agreement. In this work only the residual stress at the surface of the plate were studied. Future research pretends to study the complete residual stress profile. This paper may serve as a basis for many applications of peen forming originated by the shot peening process.

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