Numerical simulation of the shot peening process under previous loading conditions

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Abstract.
This research presents a numerical simulation of the shot peening process and determines the residual stress field induced into a component with a previous loading history. The importance of this analysis is based on the fact that mechanical elements under shot peening are also subjected to manufacturing processes, which convert raw material into finished product. However, material is not provided in a *virgin* state, it has a previous loading history caused by the manner it is fabricated. This condition could alter some beneficial aspects of the residual stress induced by shot peening and could accelerate the crack nucleation and propagation progression. Studies were performed in beams subjected to strain hardening in tension ($5\varepsilon_y$) before shot peening was applied. Latter results were then compared in a numerical assessment of an induced residual stress field by shot peening carried out in a component (beam) without any previous loading history. In this paper, it is clearly shown the detrimental or beneficial effect that previous loading history can bring to the mechanical component and how it can be controlled to improve the mechanical behavior of the material.

1. Introduction

Residual stresses are defined as stress acting into a material that is free of the action of external agents. The effects of this stresses can be beneficial or detrimental depending on their magnitude and distribution. Residual stresses are auto-equilibrate, but in particular residual stresses are beneficial when they are compressive (they can increase service life, arrest crack growth and increase fatigue strength). It is important to mention that the residual stresses aren't the only kind of prior history found in the mechanical components, which are produce by non-homogeneous loading. In this sense, loading a material in a homogeneous manner beyond the yield stress, induce an increment in the elastic zone (yield stress) in the direction of load implicated, known as strain hardening. Consequently a decrease in the elastic zone (yield stress) at the opposite direction of the first load, the phenomenon is known as *Bauschinger* effect. This phenomenon not only affects the yield strength of the material, but also affects the residual stress field distribution when prior loading is present.

On the other hand, shot peening is one of the most used techniques to improve the performance of the components and has proven to be a very effective method that increase fatigue strength. During the shot peening process, each blast that strikes the material acts as a tiny peening hammer, introducing into the surface a small indentation or dimple. To dimple developed in the surface of the material must yield in tension. Below the surface, the material tries to restore its original shape. Nearly all fatigue and stress corrosion failures are originated at the surface of the component, but cracks will not initiate or propagate in a compressively stressed zone. Because the overlapping dimples from shot peening are developed, a uniform layer of compressive stress at metal surfaces is induce, the shot peening provides considerable increases in service life.

In this work it is shown a numerical evaluation on the effect of strain hardening and residual stress induces by shot peening. The shot peening effect is analyzed by considering a metallic beam with previous homogenous loading (tension or compressive loading respectively). Additionally, a numerical simulation of the shot peening process in a specimen free of previous loading history is performed. Results are compared, observing changes in the residual stress field distribution and magnitude, which depend on the magnitude and direction of the previous loading history.

2. Numerical analysis development.

The numerical simulation was performed by the application of commercial computational software that uses a Finite Element Method algorithm (ANSYS). The analysis was carried out under structural considerations, on a 2D configuration, applying plane stress theory and using a solid element (*Plane183*) with higher order (8 nodes). The geometry proposed was a rectangular metallic beam, with 100 mm long and 10 mm high. The mechanical properties simulated were related of SAE/AISI 1045 steel and considering the behavior as bilinear; Elastic Modulus (E) = 200 GPa, Poisson's Ratio (υ) = 0.28, Yield Strength (σ_y) = 622 MPa, Yield Strain (ε_y) = 0.00311, Ultimate Strength (σ_u) = 944.7 MPa, Ultimate Strain (ε_y) = 0.0964 (Figure 1). Additionally, kinematic hardening ruling option was considered to simulate the mechanical properties with the elastic and plastic modulus varying as the load is increased. A general material model consisting of a non-linear kinematic and isotropic hardening component was given by Equations 1 and 2 [11] and no contact consideration were taking into account.

$$d \propto = C \frac{1}{\sigma}(\sigma - \alpha) d\varepsilon^{-pl} - \gamma \alpha d\varepsilon^{-pl} \qquad (1)$$

$$\sigma_0 = \sigma|_0 + Q_\infty \left(1 - e^{-\varepsilon^{-pl_b}}\right) \qquad (2)$$

Where ε^{-pl} is the equivalent plastic strain, α is the back-stress, C is the initial kinematic hardening modulus, γ determines the rate at which kinematic modulus decreases with plastic deformation, σ_o is the current yield stress, $\sigma|_o$ is the initial yield stress, Q_∞ is the maximum change in the size of the yield surface and b defines the rate at which the size of the yield surface changes as well as plastic straining develops. Equation 1 describes the translation of the yield surface in the stress space due to the back-stress, α, while Equation 2 describes the change of the equivalent stress defining the size of the yield surface, σ_o, as a function of plastic deformation [10 to 12]. For the numerical simulation of the shot peening process it was necessary to add into the numerical analysis a penetrate object, to simulate the shot peening process [13]. The shot effect cause by the ball in this manufacturing technique was simulated by rigid component which is harder than the beam (Figure 2)

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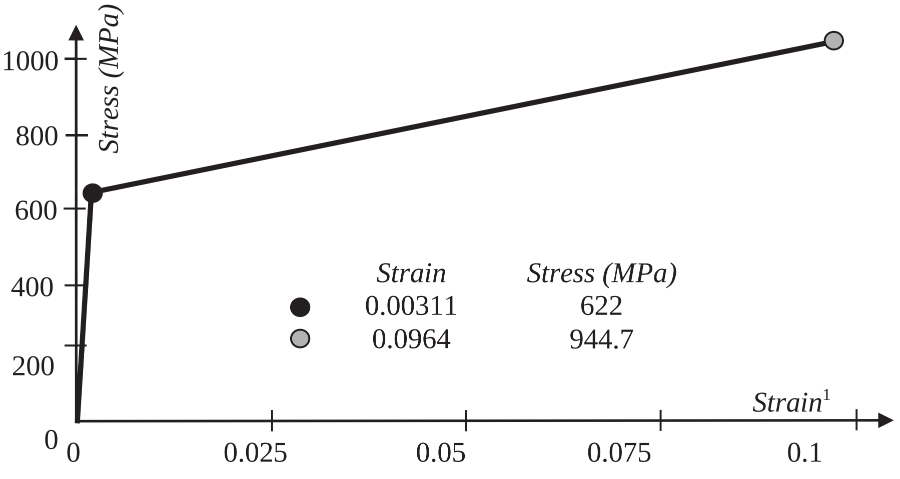

Figure 1. Mechanical properties applied to the numerical simulation.

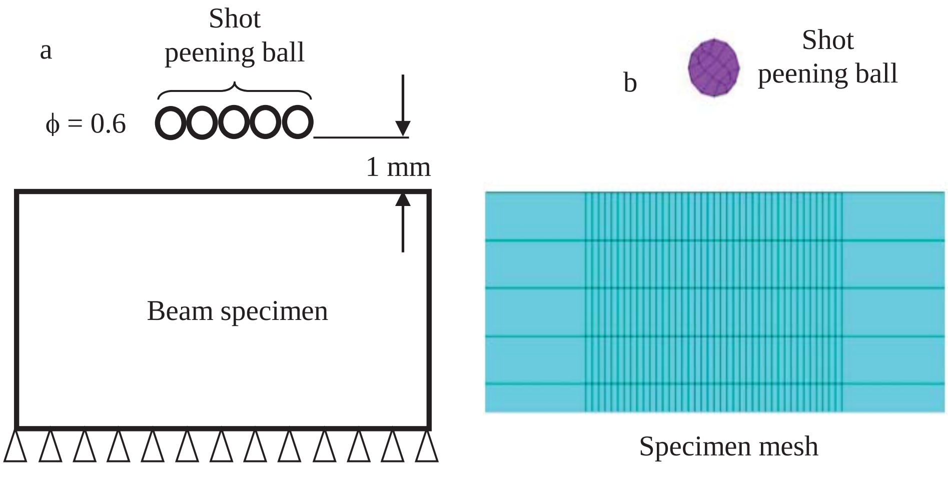

Figure 2. Shot peening process simulation. a) Geometries. b) FEM simulation.

SAE J-441 standardizes the ball applied to the shot peening processes [14]. For this research it was designated *S-230* that has a radius of 0.3 mm. In previous studies *Urriolagoitia-Sosa* and coauthors have found good numerical relation against experimental shot peening data [6]. The discretization of the beam was developed in a controlled manner, making it finer at the center of the element and harsh at both ends of the specimen [13]. The solution of the system is a multi-step one, where the shot is consecutively loaded and unloaded to generate the residual stress field. A shot is produced followed by a second shot in a distance of 0.4 mm; this procedure was carried out until 7 shots were performed. The separation between the specimen and the ball was decided to be 1 mm and the penetration of each ball into the specimen was selected to be 0.2 mm (to simulate the experimental effect in the shot peening process). The specimen is restricted to move in the *y* direction at the bottom surface.

2.1 Numerical simulation of the shot peening process with a tensile previous loading in a beam.
For the case of study with previous loading history, the beam was subjected to an axial tensile homogeneous plastic deformation before the shot peening effect was induced. The beam was axially tensile pulled (by pressure to avoid stress concentrations) until a strain equal to $5\varepsilon_Y$ was reached (Figure 3). By this manner it was possible to assess the change in the isotropic condition of the material and transformed it to anisotropic behavior, which could be corroborated by a bending procedure [15].

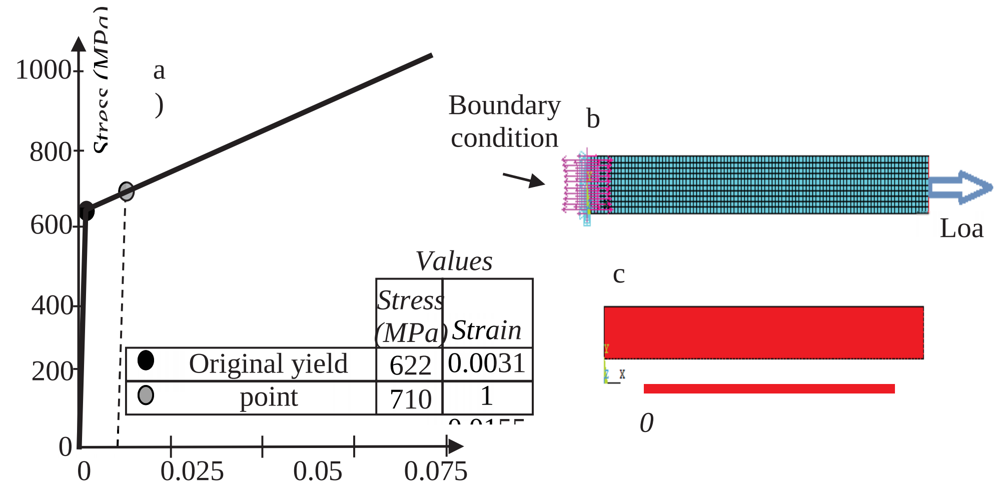

Figure 3. Strain hardening process (simulation of previous loading history). a) Material stress-strain curve. b) Numerical axial tensile homogeneous loading. c) Stress results by axial tensile procedure.

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After the axial tensile load was applied and the system was unloaded, the specimen was modified in its boundary conditions to apply the shot peening process. The boundary conditions were applied at the rear base of the beam by constraining displacements at *y* direction (UY) that will prevent movement of the element and will permit both elements to compress between them (Figure 4). The rigid element is move into the beam until a penetration of 0.2 mm is reach (Figure 4a), which is sufficient to generate a non-homogeneous plastic deformation into the material surface. The system is unloaded by retiring the rigid component until the original position and the residual stress field has been applied (Figure 4b) [16].

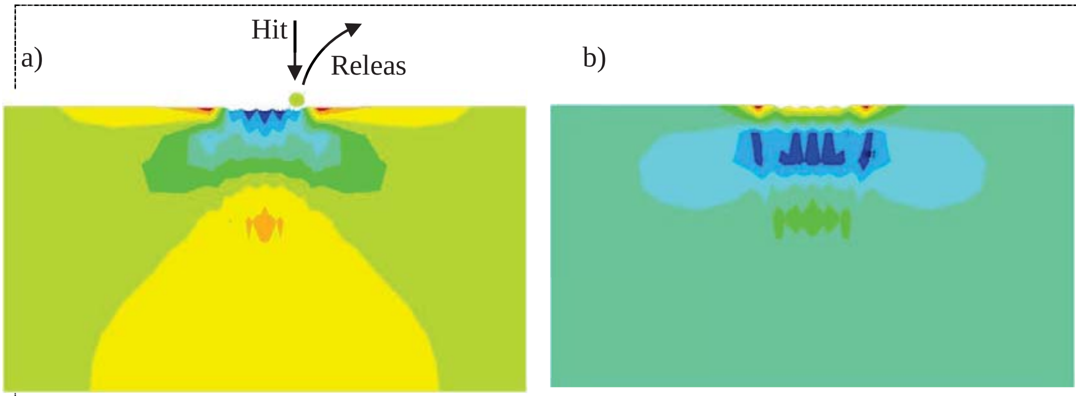

Figure 4. Shot peening simulation. a) Load step. b) Unload step.

2.2 Numerical simulation of the shot peening process without a tensile previous loading in a beam. This case of study was performed to evaluate the effect of prior loading history. The beam was subjected to the same shot peening process numerically simulated as in the section before. All the same conditions were applied.

3. Numerical results

The numerical results obtained by this research are presented in Figure 5.

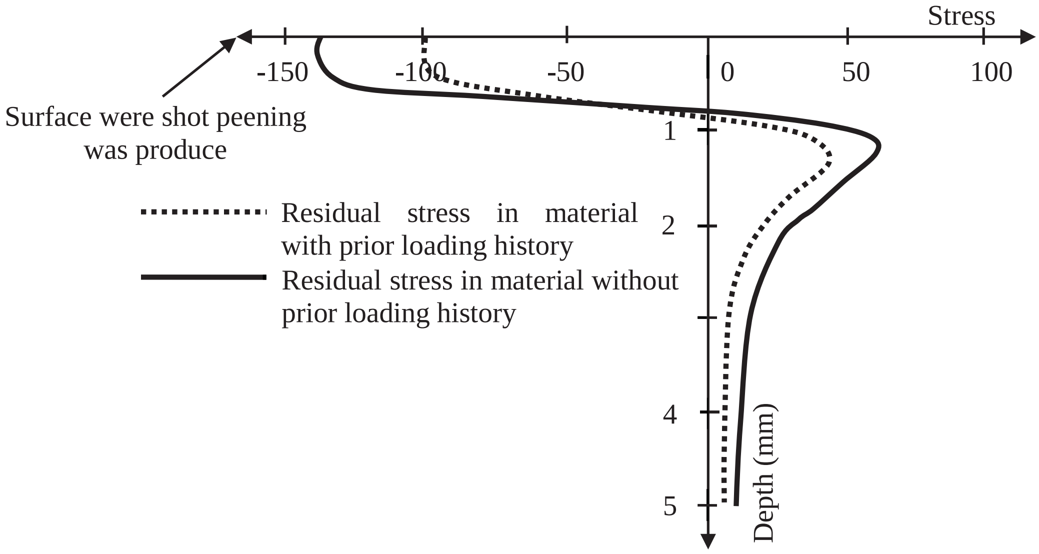

Figure 5. Comparison of residual stress field induced by shot peening.

In this figure it can be observed the comparison between the result on the shot peening numerical simulation process; with and without a prior loading history. Prior loading history has an effect on the resulting induced residual stress field, it could be seen a reduction on the magnitude of the compressive residual stress at the surface of the component. This residual stress field reduction could decrease the resistance to fatigue that the residual stress field introduces into the material without a prior loading history. In both cases were the residual stress field was generated by shot peening process in a beam, the stress distribution began in compression and end with small tensile magnitude.

4. Conclusions

In this paper it is presented a numerical study on the effect that a prior loading history has on the introduction of residuals stresses by shot peening procedure. Two different configurations are used; the first one is a metallic beam without a previous loading history which is subjected to shot peening and the induced residual stress field is determined. The second case is related to a metallic beam with a previous axial homogenous tensile loading on which it is then applied a shot peening process. Results in both cases show a compressive residual stress at the peened surface of the component. The depth of penetration in both cases is almost the same (0.9 mm approximately). Approximately at 1 mm depth (in both cases), appear tensile residual stress fields, which will promote crack nucleation and propagation.

In the Figure 4a, it can be observed that the strain hardening effect modifies the elastic range of the material by modifying the yield strength of the component. The homogeneous tensile loading has to be applied further than the original yield stress and by a pressure manner; otherwise (punctual load) stress concentrations can appear. If stress concentrations are present in the system, no homogenous loading will be produce causing the induction of residual stress and not a strain hardening effect (Figure 4b and 4c).

Compressive residual stress field could be enhanced by increasing the depth of penetration of the shot peening process, not by increasing axial tensile pulling. In fact, if homogeneous tensile pulling is increase, the beneficial effect of the compressive residual stress field can disappear. It is recommended, to increase the beneficial compressive residual stress field to strain hardening the material in opposite direction (the material axially compressed by homogeneous loading).

It is very complex to determine the best shot peening condition to increase the fatigue strength, because it depends on many variables. Nevertheless, in this paper it was demonstrated that shot peening effects depends on the prior condition of the material. In fact, higher compressive residual stress field at the surface of the material will produce the best results against fatigue and will increase service life.

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