Numerical and experimental investigation on shot-peening induced deformation. Application to sheet metal forming.

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ABSTRACT

The peen forming process is commonly used in the aeronautical industry to form large wing skin panels. This process presents many advantages in terms of cost, production time, and beneficial induced residual stresses. Setting the accurate process parameters to form a given pattern requires however a certain experience and sometimes many trials and errors. The authors propose to model the shot peening induced deformations by elastically equilibrating the real plastic strain gradient present in the whole structure. A complete numerical and experimental protocol is proposed to determine the plastic strain gradient assuming the knowledge of some experimental data. The proposed approach consists in determining the plastic strain field by inverse calculation based on experimentally measured residual stresses fields. A second approach is based on the inverse calculation of shot peening induced plastic strains knowing the global deformation of the treated sheet. A comparison between the proposed approaches applied to partially treated sheets is presented along with experimental data. The numerical results are in good agreement with experimental data and show the strong influence of the peening path on the resulting global deformations of the treated samples.

INTRODUCTION

Shot-peening processes have been used for more than fifty years to improve the mechanical behaviour of mechanical components. It consists in impacting the surface of the treated part with many steel shots, which induces a plastic strain flow and a corresponding compressive residual stress state under the surface of the component (Lu et al., 1991). The induced residual stresses are not supposed to modify the geometry of the part, because it is confined to the surface but it can nevertheless imply a distortion of the structure depending on its geometry, due to the global equilibrium of stresses. The peen forming process itself is applied to metal sheets to form complex metallic panels with local repeated impacts of shots on the surface (O'Hara, 2002). It is mainly used to form large wing skin panels in the aeronautic industry. This forming process offers many advantages: the manufacturing requires no dies or presses, complex sheets metal can be treated and beneficial mechanical performance can be obtained (Baughman, 1984). While its application to form aeronautical components dates from over fifty years, the choice of peening parameters still depends on the manufacturing operator knowledge and trial and

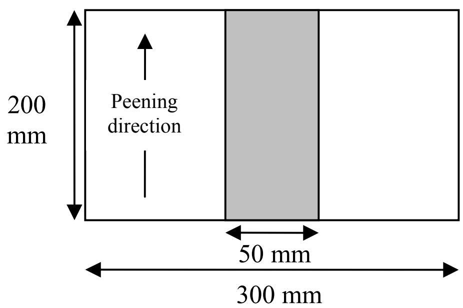
error tests (Yamada et al., 2002). Numerical models have also been proposed to predict the effects of shot-peening on the geometry of the treated parts (Levers and Prior, 1998). These models are generally based on an experimental calibration of a user-defined equivalent load that is able to model the final distortion of the shot-peened part.

The scope of the presented work is to investigate the plastic strain field in shot-peened metallic plates in different treatment cases. A numerical procedure based on the introduction of initial plastic strain gradients is proposed to model the deformations of shot-peened plates. Aluminum alloy plates have been shot-peened and the measurement of the resulting residual stresses and distortions has been carried out for comparison with numerical modeling.

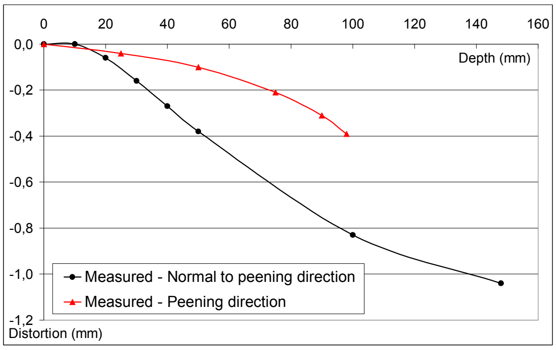
After the definition of experimental cases, this paper deals with numerical identification of plastic strain fields along the treated samples. Finally, the numerical results are compared for validation to experimental measurements.

EXPERIMENTAL DATA

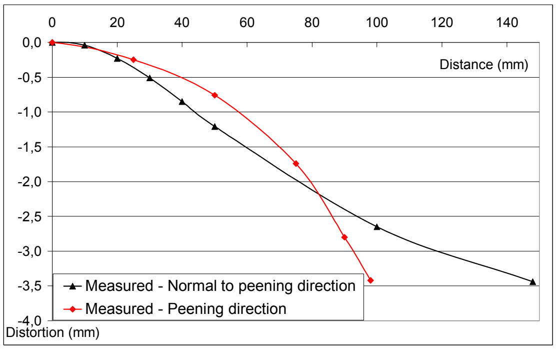
2024T3 aluminum alloy laminated plates of different thicknesses have been shot-peened without constrain under the same peening conditions. All the peened plates have been cut out from the same material batch. The peening treatment was performed with air compressed peening machine. The plates have been totally or partially shot peened. The plates deflections have been measured using a three dimensional measurement machine. The geometry of the treated plates and the defined peening paths are given in Figures 1.a and 2.a for partially and totally shot-peened cases. The resulting distortions are plotted in Figures 1 and 2. These distortions present an important variation in the topology itself depending on whether the plates are thick or thin. The distortions show that for thick totally shot-peened plates, the peening path has no influence on the topology of the shape while for thin plates the shape depends strongly on the peening path direction.



a. Illustration of the geometries of the partially shot-peened plates.

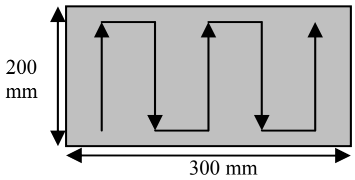


b. 5 mm thick shot-peened plate.

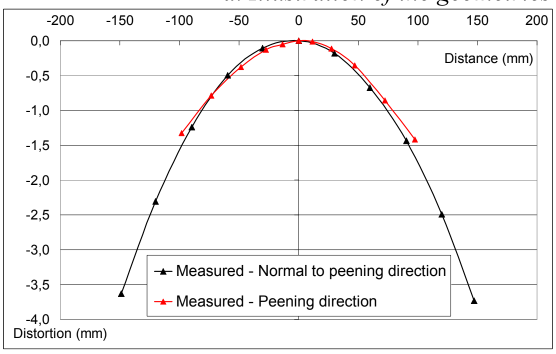


c. 2 mm thick shot-peened plate.

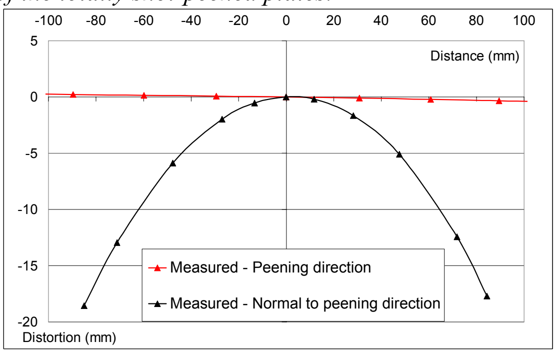
Figure 1. *Illustration of the partially shot-peened cases and resulting distortions.*



a. Illustration of the geometries of the totally shot-peened plates.



b. 5 mm thick shot-peened plate.



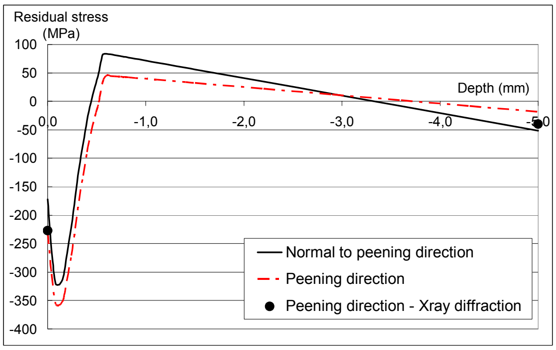
c. 2 mm thick shot-peened plate.

Figure 2. *Illustration of the totally shot-peened cases and resulting distortions.*

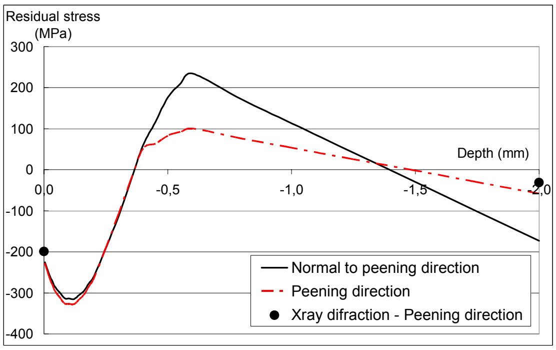
The in-depth residual stress profiles were measured using the incremental hole-drilling method and have been completed by surface measurements of the stresses by X-ray diffraction in the peening path direction.

The microstrains induced by the drilled hole have been measured with strain gages and a finite element procedure has been specifically developed to compute the residual stresses. This finite element treatment relies on the numerical introduction of an initial plastic strain field in order to simulate the real complete residual stress state of the structure. Then, the drilling is simulated on the modeled structure submitted to an unknown plastic strain field and the microstrains induced by the drilling are calculated. Then, an inverse calculation is made to compute the plastic strain field that induced the measured microstrains profiles. This protocol insures that the computed residual stresses respect the equilibrium conditions of the whole structure. This is especially important for calculating the correct residual stresses field in the partially shot-peened plates.

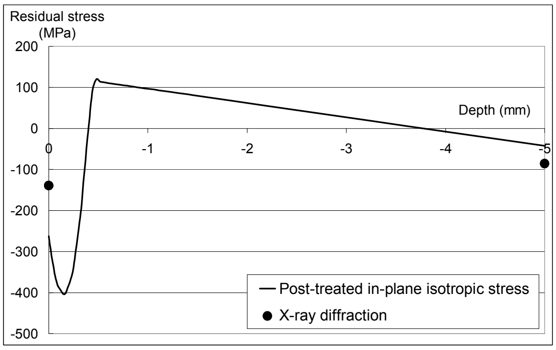
The X-ray diffraction analysis has been done using the classical *sin²(ψ)* method, the diffracted lattice plane being the *{3 1 1}* plane.
The in-depth residual stresses profiles are given in Figure 3 for the peening cases defined above. The residual stresses measured in the partially shot-peened relatively thick specimen (see Figure 3.a) show a similar form between peening and normal to peening directions while those measured in relatively thin specimen (see Figure 3.b) show a strong difference between these two directions, which confirms the observations made on the distortions of these plates. The microstrains evaluated with the drilling of the 5 mm thick totally shot-peened specimen presented an independence are the same in all the direction on the surface. The computation of the residual stresses has thus been done under an axisymmetric assumption (see Figure 3.b).



a. 5 mm thick partially shot-peened plate.



b. 2 mm thick partially shot-peened plate.



c. 5 mm thick totally shot-peened plate.

Figure 3. *Residual stresses measured for the different peening cases.*

NUMERICAL IDENTIFICATION OF PLASTIC STRAIN GRADIENTS

The scope of the numerical study is to compute the deflections associated to the material accommodation of the incompatible plastic strain field induced by the process. The plastic strain field is supposed to be unchanged after shot-peening, i.e. no plastic flow occurs after releasing the samples. The problem can then be treated in elasticity and the knowledge of the geometric domain, the residual stresses and the elastic characteristics of the sample provides the existence and uniqueness of the solution (Bérest et al., 2003).

Let us consider a structure with a free surface of normal z that presents a superficial plastic zone induced by shot-peening. The plastic strain tensor is assumed to take the form:

$$\tilde{\varepsilon}^{p} = \begin{pmatrix} \varepsilon^{p}_{xx} & 0 & 0 \\ 0 & \varepsilon^{p}_{yy} & 0 \\ 0 & 0 & -(\varepsilon^{p}_{xx} + \varepsilon^{p}_{yy}) \end{pmatrix} \qquad (1)$$

The total strain tensor $\tilde{\varepsilon}^{T}$ can be decomposed additively in its elastic and plastic parts:

$$\tilde{\varepsilon}^{T} = \tilde{\varepsilon}^{e} + \tilde{\varepsilon}^{p} \qquad (2)$$

The plastic flow induced by the repeated impacts, represented by the strain tensor field $\tilde{\varepsilon}^{p}$, and the total strain field $\tilde{\varepsilon}^{T}$ are taken as the unknown of the problem. The generalized Hooke's law lets us express the elastic tensor field in function of the residual stresses under the following form:

$$\tilde{\sigma}^{R} = \lambda\, tr(\tilde{\varepsilon}^{T})\, \tilde{I} + 2\mu\tilde{\varepsilon}^{T} - 2\mu\tilde{\varepsilon}^{p} \qquad (3)$$

The total strain tensor must respect the compatibility equations which are, in the case of a numerical resolution using a finite element method, implicitly verified by the condition of connectivity of the nodes describing the structure. The compatibility conditions, accompanied by the knowledge of residual stresses in the structure, are then sufficient to determine the plastic strain tensor and the resulting total strain tensor.
The equivalent problem is treated as an initial strain problem. The plastic strain field $\tilde{\varepsilon}^{p}$ induced by the repeated impacts is numerically introduced in a z-polynomial form:

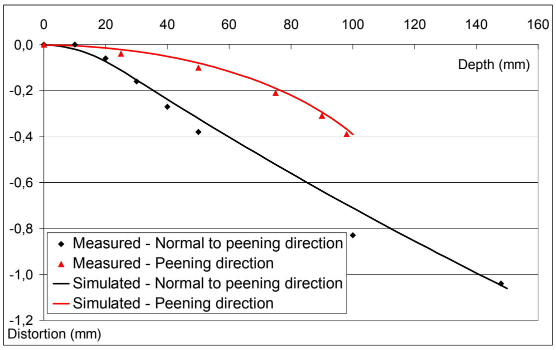
$$\begin{aligned} \varepsilon^{p}_{xx} &= (z-\Delta).(A_2 z^2 + A_1 z + A_0) \\ \varepsilon^{p}_{yy} &= (z-\Delta).(B_2 z^2 + B_1 z + B_0) \\ \varepsilon^{p}_{zz} &= -\varepsilon^{p}_{xx} - \varepsilon^{p}_{yy} \end{aligned} \qquad (4)$$

Where Δ is the plastic depth and $A_0, A_1, A_2, B_0, B_1, B_2$ are real coefficients. The specified boundary conditions are only symmetry conditions. The gravity is neglected in all cases. While little strains assumption is made, the problem is treated by using corotational reference frames in order to take large displacements into account. A unique relation exists between the incompatible part of the plastic strains and the residual stresses, so the coefficients $\Delta, A_0, A_1, A_2, B_0, B_1, B_2$ can be identified by inverse calculation while comparing the simulated and measured residual stresses.

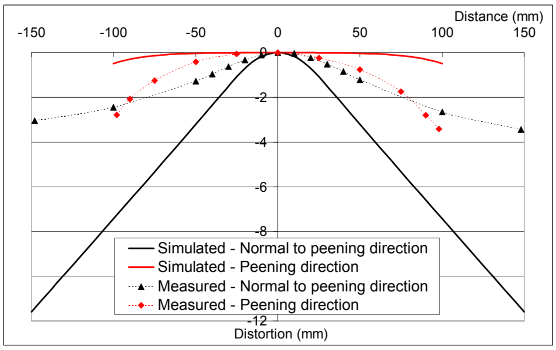
Another way to compute the in-plane repartition of plastic strains is to iteratively compare the simulated and measured deflections under some assumptions. The relationship between the distortion of the plate and residual stresses being not unique, it is necessary to fix some of the coefficients of the z-polynomial form. The choice has been made to fix pseudo-arbitrarily the real coefficients $\Delta, A_1, A_2, B_1, B_2$ of equation (4). The inverse calculation of the A_0 and B_0 coefficient can then be made by comparing the simulated and measured distortions. The identified plastic strains are, in such a case, qualitatively interesting for the investigation of the in-plane direction dependency of the plastic strains induced by shot-peening.

RESULTS

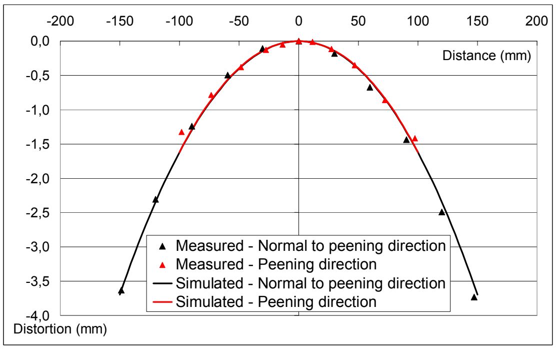
The plastic strain gradients have been identified with the measured residual stresses profiles. The identified plastic strains profiles are not depending of the in-plane directions for the 5 mm thick partially shot-peened cases while strong differences are observed for the 2 mm thick specimen. The resulting simulated deflections are plotted in Figure 4 and compared with the measured deflections. The plastic strains gradients identified from the distortion measurement of the plates are plotted in Figure 5 for the 5 mm and 2 mm thick partially shot-peened cases.



a. 5 mm thick partially shot-peened plate.



b. 2 mm thick partially shot-peened plate.



c. 5 mm thick totally shot-peened plate.

Figure 4. *Comparison of the measured and simulated distortions for the different peening cases. Inverse calculation based on measured residual stresses.*

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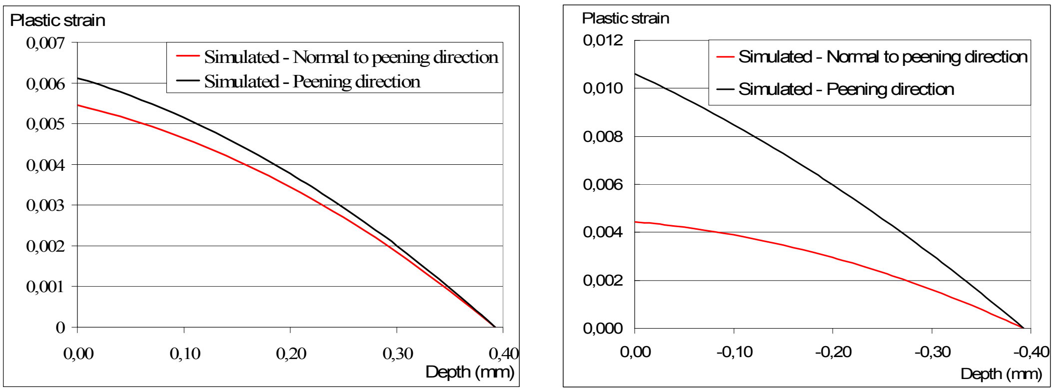

a. 5 mm thick partially shot-peened plate. *b. 2 mm thick partially shot-peened plate.*

Figure 5. *Identified plastic strains gradients. Inverse calculation based on measured distortions.*

DISCUSSION

The presented numerical model gives good results for thick shot-peened plates. In this case the same plastic strains gradients exists in all directions of the plane, the curvatures and residual stresses being dependent of the geometrical characteristics of the samples and of the peening treatment. The results obtained for thin shot-peened plates differ from the experimental observations. The identified plastic strains profiles plotted in Figure 5.b show indeed a strong difference between peening direction and normal to peening direction. Such a trend is observed while identifying plastic strains by comparing measured distortions or measured residual stresses. The deflections shown in Figure 4.b are calculated with plastic strains that are directly identified to the measured residual stresses. This leads to large errors committed on the simulated distortions. In Figure 5.b, the plastic strains are directly identified to the measured distortions under the assumption of the form of its gradients along the depth of the plate. This leads to large errors on the estimation of the in-plane stress repartition along the surface of the plate. The experimental observations that can be made on thin totally shot-peened plates show that the plastic flow is largely oriented in the normal to peening direction (see Figure 2.c). Then, it can be assumed that the plastic strains identified from the measurement of the residual stresses in the depth of the plate are satisfying. The hypothesis of homogeneity of the plastic strains along the peening strip has then to be revised by further experimental and numerical investigations.

CONCLUSION

A pertinent numerical model has been established for the simulation of the distortions induced by shot-peening. The numerical results are in good agreement with experimental measurements for relatively thick specimens. It shows that such plates present an in-plane isotropic behavior in terms of plastic strains, residual stresses and curvatures. The results obtained for relatively thin plates are in poor agreement with experimental measurements. It shows nevertheless a strong biaxiality of the mechanical fields induced by the repeated impacts. Cylindrical shapes have indeed been obtained while peening such thin plates without constraining devices. Further numerical and experimental investigations will be run in order to evaluate the gradient of plastic strain that can exist along the peening strips, which could lead to a bad prediction of the final distortion of the treated plates. The numerical model will be applied to more complex sheet geometries to show its applicability to real peen forming industrial problems.

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