# From process parameters to residual stress field: complete ultrasonic shot peening simulation

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**Abstract:**
Shot peening is a pre-stressing surface treatment used in high-technological industries (aeronautics, nuclear) to enhance the mechanical characteristics and lifespan of mechanical parts. The component to be treated and spherical shot are placed within a treatment chamber; then the shot is projected onto the surface of the component. The multiple impacts induce compressive residual stresses in the material and enhance the surface characteristics and fracture resistance of the mechanical components. Modelling shot peening process is very complex as it involves several parameters such as shot velocity, mechanical properties of material, etc.The aim of this work is know the residual stress field after treatment using a simple model obtained with dimensional analysis exploiting experimental data. A comparison between experimental residual stress profile and computing residual stress profile is proposed. Using a model, which enables to track the motion of shot for ultrasonic shot peening (USP) and obtain the complete velocity distribution of the shot impacts, we can use à residual stress model for USP.

**Keywords:** Ultrasonic Shot Peening, Dimensional Analysis, Almen Intensity, Numerical Simulation.

## Introduction

This work proposes a complete simulation of conventional or ultrasonic shot peening technology. The objective of the work is to create a model able to provide a accurate residual stress state after shot peening treatments in a time that is compatible with an industrial context. Using a numerical model for shot dynamics, we can know the impact velocity field. To establish the residual stress state a dimensional analysis model is used that depends on shot peening parameters (velocity and size of shot, mechanical properties of shot and work piece). This profile is then introduced in a finite element code as an initial stress state. A calculation of static equilibrium is carried out in order to have the deformation field due to the treatment.

## Dimensional analysis and model description

This model is based on approximations of stress due to shot peening [2]. It is supposed that the stress tensor has the general simple form

$$[\sigma] = \begin{pmatrix} \sigma & 0 & 0 \\ 0 & \sigma & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (1)$$

The radial stress en function of depth obtained by shot peening (Figure 1) has been approximated to fourth degree polynomial equation (equation 2):

$$\sigma = \sum_{k=0}^{4} a_k Z^k = a_0 + a_1 Z + a_2 Z^2 + a_3 Z^3 + a_4 Z^4 \quad (2)$$

This equation was resolved taking into account the key values of the profile ($\sigma_{surf}$; $\sigma_{max}$; $\sigma_p$; $Z_{max}$; $Z_p$), known with dimensional analysis.

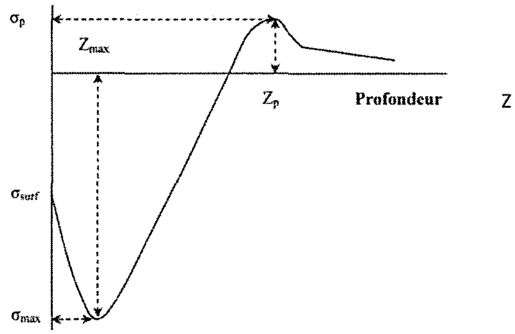


Figure 1 Typical residual stress profile after shot peening ($\sigma_{surf}$ = stress on the surface; $\sigma_{max}$ = Maximal compressive stress ; $\sigma_p$ = maximal traction stress ; $Z_{max}$ = Depth of maximal compressive stress ; $Z_p$ = = Depth of maximal traction stress ;)

Dimensional analysis is a problem-solving method able to reduce the complexity of a physics phenomenon by identifying the dimensions of the variable and find a relationship between them. It is based on theorem II of Vaschy-Buckingam. This theorem says that if we have a relationship between n dimensioned variables and independent each other like $a_0 = f(a_1, a_2, \ldots, a_{n-1})$ with K independents dimensions, it is possible write it as a relation between n-K adimensional number like $C_0 = F(C_1, C_2, \ldots, C_{n-k-1})$. If the function F is not calculable analytically, it will be found experimentally. In this case, the key values of profile have been linked by dimensional analysis with shot peening parameters (velocity and size of shot) and mechanical properties of treated materials and shot [2]. Finally we have analytical model (example equation 2) able to calculate the key values of the profile and plot a residual stress profile resolving P(z).

$$\sigma_{surf} = \left[ 1{,}3243 \cdot 10^{7} \left( \frac{V^2 \rho_{mat}}{E} \right)^2 - 6{,}1824 \cdot 10^{3} \left( \frac{V^2 \rho_{mat}}{E} \right) - 1{,}2383 \cdot 10^{-1} \right] \sigma_y \qquad (2)$$

The model is able to reproduce the residual stress profile after shot peening, in figure 2 the calculated profile is compared with experimental data.

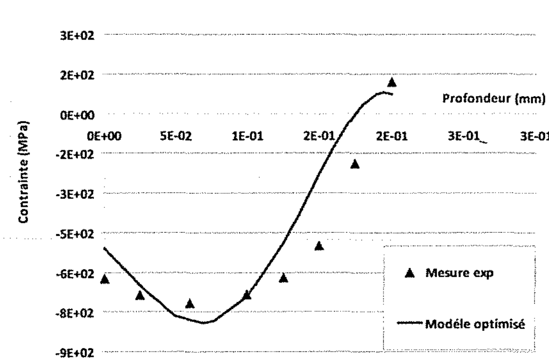


Figure 2 Comparation between experimental data (on steel AISI4140 shot peened ref. KLEMENZ M .Numerical prediction of the residual stress state after shot peening. Karlsruhe University) and the profile plotted with the model.

## Model testing and introduction of residual stress state into finite element code ABAQUS

Using finite elements (Abaqus 6.10) the residual stress profile obtained with the above model is introduced in the tested geometry. After an equilibrium computation it is possible to observe the deformation field on the specimen due to the residual stress. We tested the method on aluminum 2024T3 sheet metal (dimensions are 200x300x5mm). The sheet metal has been treated with conventional shot peening with shot S230 and Almen intensity of 45A. The whole surface has been treated for the case a, and only partially ( shoot peening on a stripe 50 mm wide on the middle) for case b [3]. The residual stress profile has been calculated using known parameters and introduced in a finite element code to calculate the corresponded deformation. With the same profile an analytical calculation was carried out using a relationship with residual stress [5].

The figure 3a and 3b show that numerical simulation give a very good results, therefore a viable solution the for analysis of complexes geometries, a possibility that is not offered by the analytical computation.

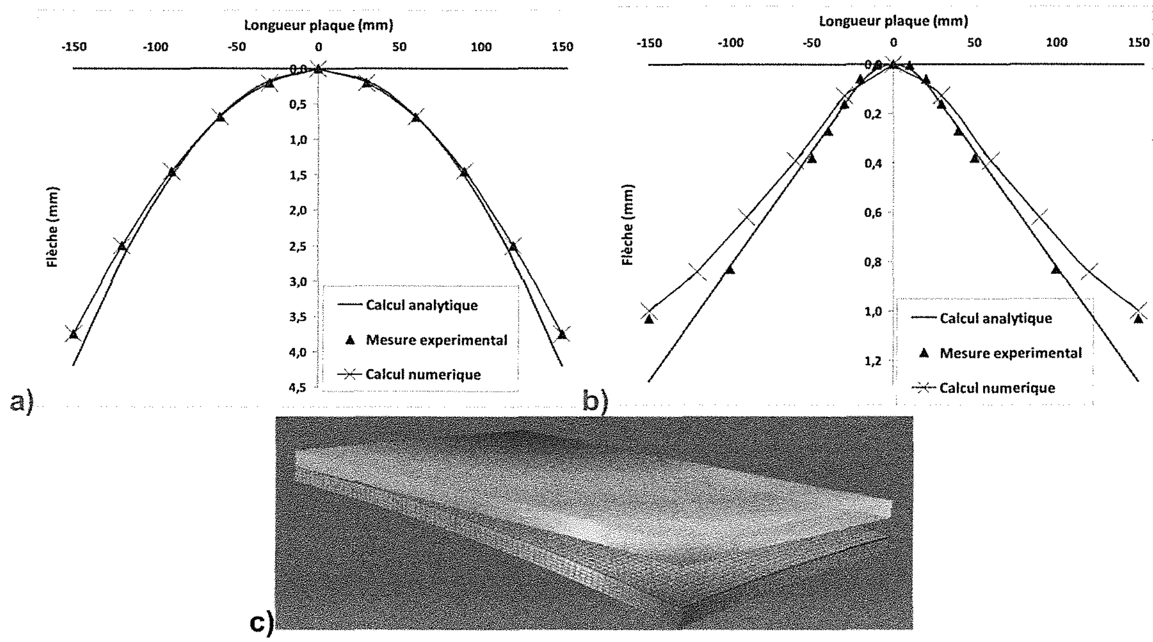


Figure 3 Comparation of deformation calculated analytically and simulated (model introduced on Abaqus) with experimental data : a) Aluminium 2024T3 sheet metal 5 mm thinkness treated on whole surface ;b) Aluminium 2024T3 sheet metal 5 mm thinkness treated partially (ref. F. Cochennec et al.) ; c) Aluminium 2024T3 sheet metal 5 mm thinkness designed by before and after FEM calculation.

**Complete simulation of ultrasonic shot peening process and comparison with experimental data on Almen strip**

A model for the dynamics of the shot has been developed [15]. With that model it is possible to have an impact velocity field on treated part (figure 4). Once the velocity is known, it is possible to plot the residual stress profile with the analytical model using the process parameters. This residuals stress is then introduced into FE Abaqus for numerical calculation to obtain the deformation field. The difference with the method presented in the above section resides in the fact that with dynamic shot model it is possible to carry out the same step for ultrasonic shot peening. Figure 5 shows the complete simulation process of ultrasonic shot peening from shot dynamic to the deformation field.

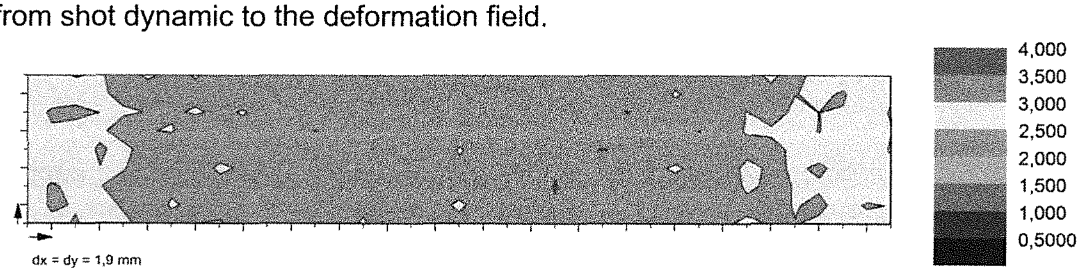


Figure 4 Impacts velocity field (m/s)

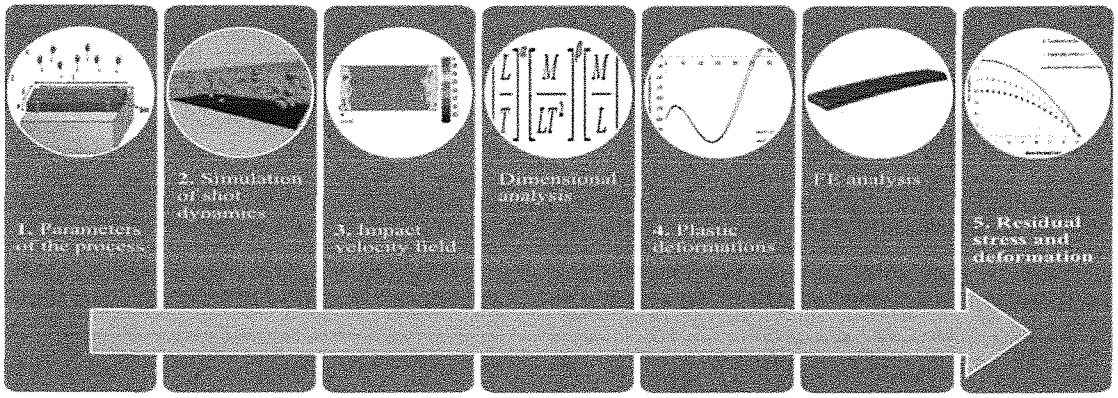


Figure 5 Schema complete simulation of ultrasonic shot peening process (ref. D. Gallitelli, J. Badreddine, E. Rouhaud: From process parameters to residual stress field: complete ultrasonic shot peening simulation).

The complete simulation was carried out on Almen strip at the same time with experimental ultrasonic shot peening in order to be able to compare the results in term of Almen intensity*. An Almen strip type A was peened for 15 minutes with known conditions, and the Almen intensity was measured with Almen comparator. After that the simulation process has been realized with Abaqus. Finally the Almen strip deformation is available, the numerical Almen Intensity is measured and compared with experimental data. How shown in table 1, the difference of Almen intensity between experimental data and simulation is very small, this is a first confirmation about reliability if the model and the method adopted.

**Table 1** Comparison between experimental data and complete simulation of process

| Almen Intensity | | |
|---|---|---|
| Experimental (mm) | Complete simulation (mm) | Error % |
| 0.34 | 0.36 | 6.1% |

**Conclusion and perspectives**

In this work we have described the model of residual stress state after shot peening and how it is coupled with a finite element calculation. It has been applied to ultrasonic shot peening. Two results were presented, the first for conventional shot peening on sheet metal, and the second for ultrasonic shot peening on Almen strip. The analysis of results was in term of warp or Almen intensity. The calculus on the Almen strip and the metallic sheet are good tests to make a comparison between experimental measures and numerical calculus and for model validation. The main objective of the present method is the possibility to study the stress and deformation field of a treated part. Then is possible to take this information into account in the design step of mechanical parts. Thanks to the whole simulation process and a relative simple model, it is possible have an accurate idea of the residual stress state and deformation field after shot peening treatment. The main idea for future work is the possibility to apply the same process to complex geometries.

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* Standard indication about Shot peening intensity

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