# Residual Stress Field Prediction in Shot Peened Mechanical Parts with Complex Geometries

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**Abstract.** In order to introduce automatically the residual stresses field into a Finite Element model with complex geometry, a PYTHON code has been developed and linked to the software ABAQUS. A comparison between modelling and experiment is carried out by using X-ray diffraction analysis to determine the in-depth residual stress state of Ni-based alloy samples after shot peening.

## Introduction

Most manufacturing industries perform mechanical surface treatments at the end of the manufacturing chain to reinforce relevant working parts. Shot peening is probably the most common of those processes. This treatment modifies the near surface of treated parts by introducing compressive residual stresses due to the repeated impacts of shots leading to an enhanced life.

The objective of this work is to simulate the residual stress state after shot peening, for mechanical parts with complex geometries (thin sheets, curved surfaces). It is part of an industrial collaborative project which one of the work packages consists in developing a complete simulation model of a structure made of a Ni-based alloy and submitted to cyclic loadings in service including the manufacturing process history.

## Numerical Model

**Introducing residual stresses in a Finite Element model**. Several methods have been developed to introduce the stress-free strains into a Finite Element model [1]. Indeed, depending on the capabilities of the finite-element codes, it is possible to introduce the plastic deformation field and/or the stress field as initial conditions. Nevertheless these methods are not directly applicable if the geometry of the part is complex. They require some assumptions:

- The analytical technique used is available only if the geometry of the treated part can be reduced to a semi-infinite body. It means that the treatment is homogeneous, the treated surface is regular and the depth affected by the treatment ($\Delta$ in Fig. 1) is small (few hundred micrometers) compared to the other dimensions of the part ($\Delta$□e, e.g. for sheet of thickness e).
- The computational technique implies that the geometry has to be plane in order to introduce in a convenient way the mechanical fields into the model.

**A predictive model for complex geometries**. Because the geometry of the mechanical part induces a rebalancing of the stresses, a model to predict residual stresses for complex geometries build with the analytical relationships for massive and plane geometries is proposed.

Considering that residual stresses arise from the incompatibility of plastic strains between each depth, it is possible to establish analytical relationships between residual stresses $\overline{\overline{\sigma}}$ and incompatible plastic strains $\overline{\overline{\varepsilon^p}}$ in the case of an isotropic semi-infinite plane geometry [2,3] such as:

$$\overline{\overline{\varepsilon^p}}(z) = \begin{pmatrix} \varepsilon^p(z) & 0 & 0 \\ 0 & \varepsilon^p(z) & 0 \\ 0 & 0 & -2\varepsilon^p(z) \end{pmatrix} \text{ and } \overline{\overline{\sigma}} = \begin{pmatrix} \sigma(z) & 0 & 0 \\ 0 & \sigma(z) & 0 \\ 0 & 0 & 0 \end{pmatrix} \; with \; \varepsilon^p(z) = \frac{\nu-1}{E}\sigma(z). \quad (1)$$

Typical residual stresses (RS) and plastic strains (PS) profiles in shot peened massive and plane geometry are presented in Fig. 1.

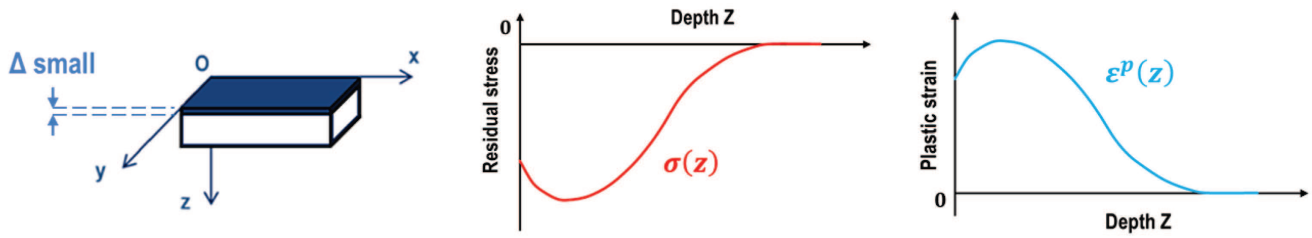


*Figure 1. Typical residual stress and plastic strain profiles induced by shot peening in a semi-infinite body*

Because the hypothesis of a semi-infinite body can be made for most shot peened parts on a local basis, and since it is easy to get analytically [1,2,4] or experimentally [5,6,7] the RS profile for massive and plane geometry, a simplified approach is proposed for complex geometries by using the stress-free strains computed for the semi-infinite body (with the same peening conditions).

The approach consists in introducing into the Finite Element model an unbalanced stress field as initial stresses field: this field is computed thanks to the stress-free strains due to shot peening for a semi-infinite body; then it is transferred into the geometry of the part and will lead to the residual stress field after static equilibrium.

The computation is driven by analytical relationships proposed in the literature [3]. In a local coordinate system, the initial stress tensor is given by Eq. 2:

$$\overline{\overline{\sigma^0}} = -2\mu\overline{\overline{\varepsilon^p}} \quad (2)$$

where μ is the shear modulus.

**Implementation of the method**. In order to generate residual stress field automatically into a mechanical part, a PYTHON code has been developed and linked to the Finite Element software ABAQUS. This code proposes an efficient way to calculate the residual stress field induced by estimating the initial stress state for each integration point of the model.

The method is divided into three main stages:

- The depth of each integration point is computed by using nodes and elements data of the surface layer through the connectivity tables of the Finite Element model.
- Using SIGINI subroutine, initial stresses corresponding to the plastic strains that would exist in a semi-infinite body are introduced locally in a local coordinate system defined with the normal vector of the surface.

- Then a static equilibrium computation is performed. After this purely elastic computation, the result is the stress field due to shot peening in the mechanical part.

## Numerical Test Cases

**Massive and plane geometry.** The first study focuses on a cube of size 10 mm as illustrated in Fig. 2. Only the top of the part is considered as a shot peened area. A random RS profile for the semi-infinite body (SIB) is used. The shot peened part is a Ni-based alloy (Inconel 718 DA) with an elastic isotropic behavior (elastic constants: E = 210 GPa, μ = 81 GPa; mesh size: $1 \times 1 \times 10^{-2}$ $mm^3$ minimum).

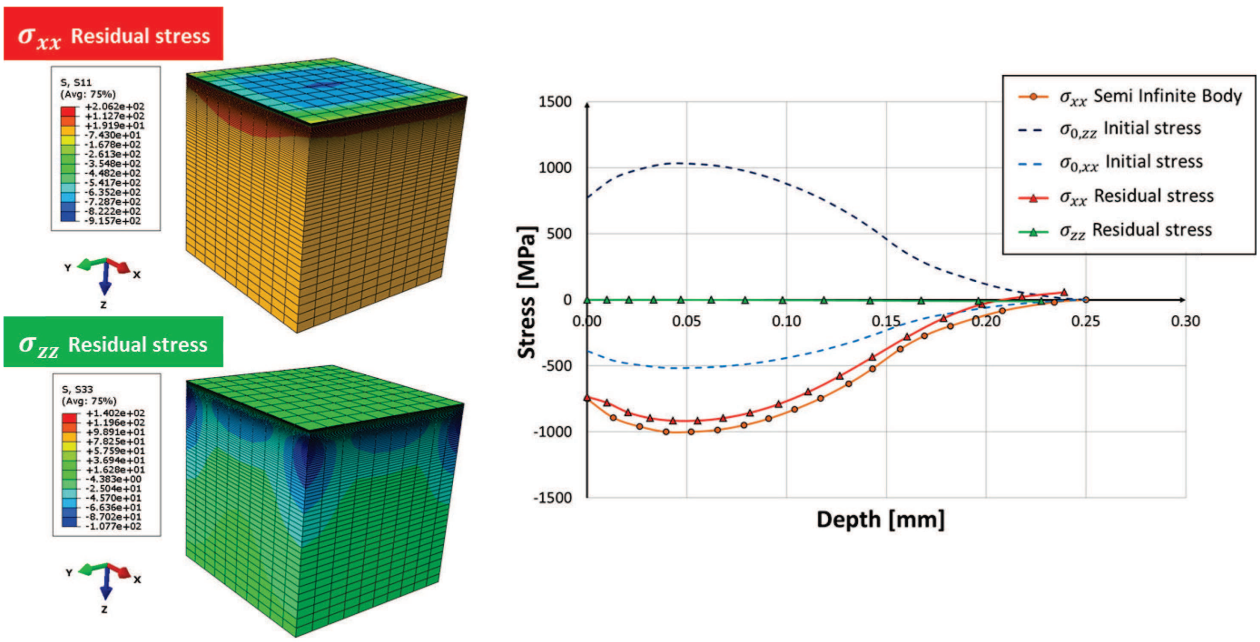


*Figure 2. Comparison between the residual stresses within a semi-infinite body (orange line), the initial stresses introduced into the Finite Element model (dashed lines) and the residual stresses computed in the middle of the cube (red and green lines)*

It can be observed that the RS profile computed for the Finite Element model (so-called $\sigma_{xx}$ Residual stress in Fig. 2) is very close to the one of the SIB. It means the geometry is thick enough to be considered as a semi-infinite body. Hence the result from this preliminary study shows a good agreement with the theoretical expected results.

**Complex test cases.** The method has been also applied to several cases to ensure the numerical tool works when the geometry and/or the peening conditions become complex. Consequently the objective is to look at the initial stresses field within the part. We have to check if the initial stress gradient through the thickness is correctly described.

For instance, as illustrated in Fig. 3, we used three random peening conditions (it means three different RS profiles within a SIB). One area is considered as non-peened. We can notice that the initial stresses field introduced into the mechanical part is accurately described, especially in the sharp corner where the border through the thickness is equidistant to both surfaces of areas 3 and 4.

Besides, we performed successfully the same kind of computation for several other Finite Element models, with a more complex geometry: curved shapes (convex and concave), smooth and notched fatigue test specimen, etc.

For example, the numerical method has been proven successful in the case of a spring of 10 mm diameter. A random RS profile for the SIB is used. The entire surface of the part is considered as shot-peened, except the ends. Fig. 4 shows the results computed after the equilibrium computation.

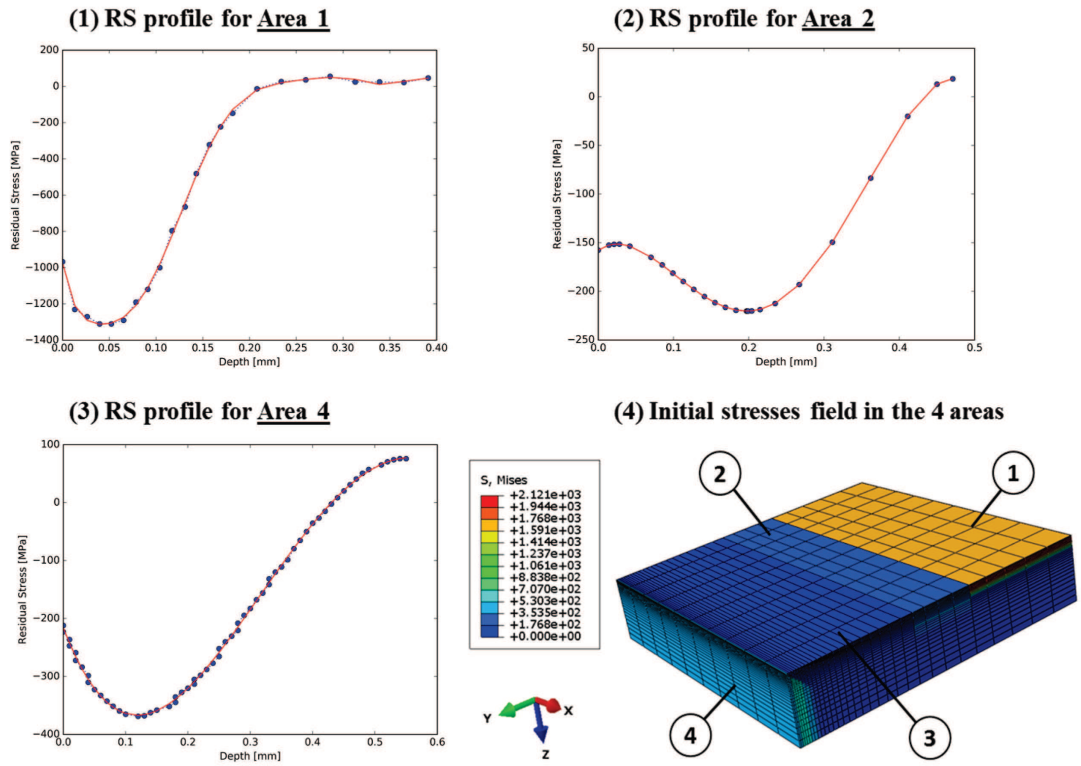


*Figure 3. Residual stress profiles within a semi-infinite body for three peening conditions (1,2,3) and preview of the associated initial stresses field introduced into the FE model (4)*

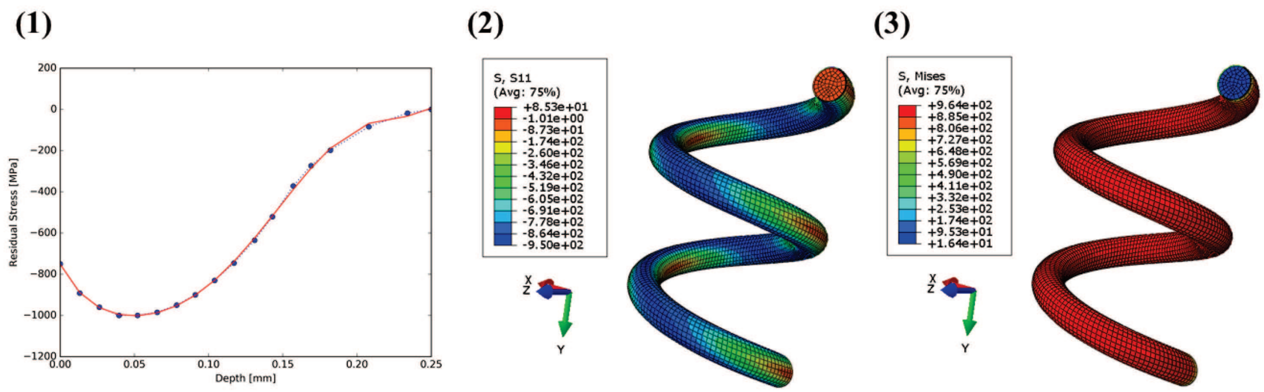


*Figure 4. Residual stress profile within a semi-infinite body (1), preview of the associated residual stresses field $\sigma_{xx}$ (2) and the Von Mises stress distribution (3)*

However, the RS field become sometimes complex: it differs from the one that would be found in a semi-infinite body due to the geometry. Thus, even if the treatment is considered homogeneous and the surface regular, the global equilibrium of the structure may change the RS field. Hence we need experimental data to understand what occurs after the rebalancing of the stresses.

## Modelling vs experiment

**Experimental procedure.** A Ni-based alloy (Inconel 718 DA) thin plate ($75 \times 25 \times 5$ mm$^3$) is homogeneously peened with cast steel shot S130 on one surface, with the following settings: F22-23A Almen intensity, 200% coverage. Then the study of residual stress state is performed.

Besides, the modelling approach is based on the knowledge of the RS profile through the thickness of a SIB. As we mentioned before, the hypothesis of SIB for a 10 mm thickness sample seems reasonable. Thus the previous surface treatment is carried out on a thicker Inconel 718 DA plate (25×19×10 mm$^3$).

**Comparison of residual stress states.** A characteristic residual stress profile after shot peening is achieved by using X-ray diffraction analysis. Material removal correction is evaluated using relationships derived from Moore and Evans method [8]. The main test parameters were as follows:

- χ goniometer (SEIFERT XRD 3000 PTS),
- Mn Kα radiation (30 kV and 20 mA),
- Rear Cr filter in front of P.S.D.,
- 2 Φ angles,
- 11 χ angles,
- Collimator giving a spot of 1.5 mm diameter,
- Family of diffraction planes: {311} at 2Θ = 150°.

Fig. 5 shows the experimental and modelling results of the residual stress state after shot peening. The 2 Φ angles equal to 0° and 90° represent respectively the transverse (TD) and longitudinal direction (LD) of the plate. The SIB profile (green line) is a polynomial interpolation between experimental data for the 10 mm sample. This curve is used to compute the initial stresses field. Then this field is applied to the Finite Element model of the 5 mm plate.

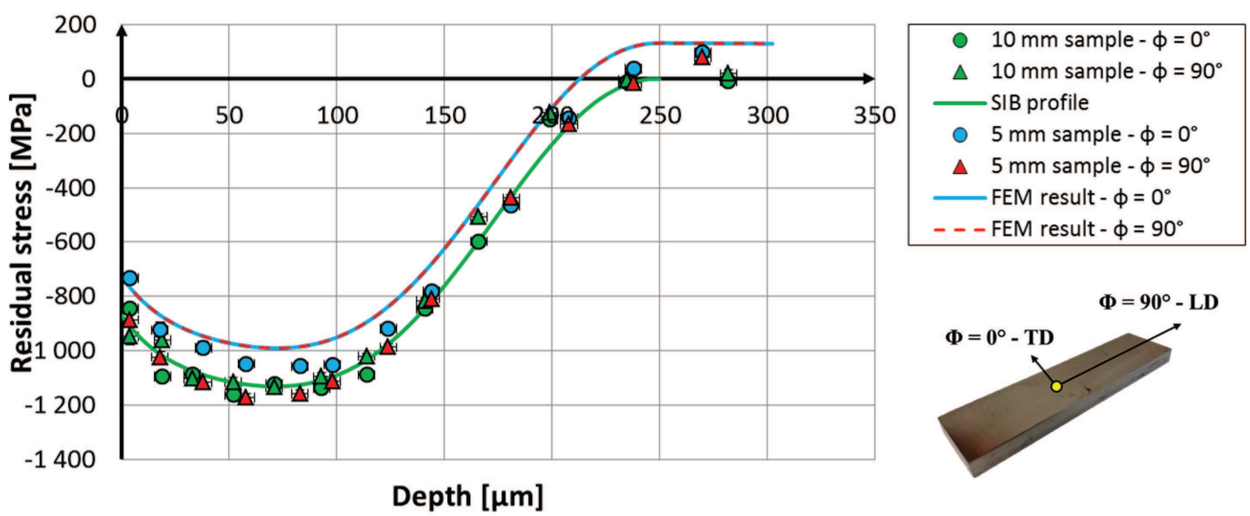


*Figure 5. Distribution of the residual stress below the surface of Inconel 718 DA alloy*

Residual stress profiles after equilibrium (FEM results) in both directions TD and LD are respectively presented with red dashed line and blue line, whereas experimental values are given by blue circles and red triangles. As a matter of fact, the Finite Element approach underestimates the compressive residual stresses. However the gap with the SIB profile is reasonable: it remains below 200 MPa.

It means the 5 mm plate could be considered as a SIB too, and the present approach is suitable to simulate the residual stress state after shot peening.

## Conclusion

A method that enables to predict the residual stress field due to shot peening knowing the stress-free strains into a semi-infinite body has been presented. An experimental validation has been performed on a thin plate by using X-ray diffraction analysis. According to these preliminary results, the proposed method is efficient.

Nevertheless, this work needs to be completed with other experimental measurements in order to test the semi-infinite body hypothesis. What makes this hypothesis valid in terms of geometries is not clearly defined yet. Thus the perspective is:

- To evaluate the deformation field of thin shot peened plates by using three-dimensional coordinate measuring machine (MMC). It will provide the profile height which is also a characteristic parameter to link with the rebalancing of the stresses.
- To lead the experimental validation with curved surfaces.
- To define the scope of validity of the method.

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