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Maxime GELINEAU, Laurent BARRALLIER, Emmanuelle ROUHAUD, Régis KUBLER, Quentin PUYDT, Jawad BADREDDINE, Clément MAUDUIT, Bastien WEBER - Residual stress field prediction and fatigue post processing for shot peened mechanical parts with complex geometry - In: International Conference on Shot Peening, Canada, 2017-09 - ICSP13 - 2017

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Residual stress field prediction and fatigue post processing for shot peened mechanical parts with complex geometry

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Keywords: residual stresses modelling, complex geometries, finite element simulation, fatigue

Introduction

Even when properly controlled, shot peening treatment may induce a complex residual stresses (RS) field depending on the geometry of the treated part. Hence, among the variables which affect the fatigue behaviour of shot peened components, the geometry could play a major role.
The more widespread method for predicting RS after shot peening consists in modelling the process by simulating the impacts between the shot and the treated part. When the geometry become complex, this method is not consistent with industrial constraints in terms of computing time. Thus the need is to develop a methodology in order to generate the RS field into a shot peened mechanical part with complex non flat geometries, and consequently predict the lifetime in a high cycle fatigue (HCF) regime.

Objectives

This study aims to understand and predict the effect of the geometry on the redistribution of residual stresses (RS) into a shot peened mechanical part. Because the RS field depends on the process parameters coupled with the geometry of the treated part, a methodology is proposed to predict RS for a complex geometry build with the analytical relationships [1] for massive and plane geometries homogeneously treated. A comparison between modelling and experiment is carried out on Ni-based alloy thin sheets.

Methodology

Residual stresses modelling

In order to get the RS mapping after shot peening, a simplified approach based on a PYTHON code and linked to the finite-element (FE) software ABAQUS has been developed [2]. This approach proposes an efficient way to:

- Calculate the initial stress field corresponding to the free stress strains that would exist in a semi-infinite body.
- Introduce this unbalanced field locally at each integration point of the model in a local coordinate system defined with the normal vector of the surface.
- Perform a purely elastic computation so that the rebalancing of the stresses due to the geometry is considered.
- Display the RS field into the shot peened part.

Validation of the approach

A comparison between the developed approach for RS modelling and experimental data is carried out on plates of 5 mm thickness made of Inconel 718 DA, with two peening conditions. For each condition, two samples are measured in order to improve the statistic.

Here are the experimental methods:

- The shot peening treatment is performed on one side of the plate, with spherical cast steel S310 (58 HRC) shots projected through one nozzle by compressed air, according to two sets of parameters denoted SP1 and SP2: the Almen intensity achieved and the coverage are respectively F12-13A and 125% for the condition SP1, F22-23A and 200% for SP2. The specimens are totally or partially shot-peened. When a sample is partially shot-peened, half of the treated surface is covered with a mask.
- In-depth RS distributions are determined by X-ray diffraction analysis and layer removal technique. Electropolishing is applied for removing the material locally as a thin layer. The {311} lattice planes of the fcc γ-matrix are used with Mn K_α radiation to record the diffraction patterns. RS are identified through a least square fitting with the elliptical $sin^2\psi$ method, in longitudinal and transverse directions. The material removal correction of the RS profiles is established with analytical relationships [3].
- Curvatures of thin sheets are characterized with a three-dimensional measuring machine. The device is equipped with a sensor of 1 mm diameter. Measurements are carried out before and after shot peening so that the deflection of the sample due to the treatment can be calculated.

Results and analysis

Inputs for the modelling approach

The developed approach for RS modelling is applied to a flat sample of 5 mm thickness. For both shot peening conditions SP1 and SP2:

- A 2D model using bilinear generalized plane strain quadrilateral elements CPEG4R with reduced integration is considered.
- Material properties are: Young modulus 222 GPa and Poisson ratio 0.3.
- The global mesh size is constant and equal to 0.2 mm. A refined mesh is adopted near the shot-peened and the non-peened surfaces with a minimum size equal to 4 µm.

Because it remains RS due to the machining near the non-peened surface, two different SIB profiles are considered:

- For the treated surface: the SIB profile is determined by an inverse analytical method [3] applied to experimental data for a shot-peened massive plate of 10 mm thickness.
- For the milled (and non-peened) surface: the SIB profile is assumed to be equal to -400 MPa from 0 to 75 µm of depth, then it decreases to zero linearly from 75 to 150 µm of depth.

Comparison of in-depth RS profiles

For totally shot-peened samples, the simulated RS profiles ($\sigma_\Phi - \sigma_{33}$) through the sample thickness are determined by extracting at the nodes of the FE model the main components of the RS tensor. The comparison with experimental data is plotted in (Fig. 1): in the Longitudinal Direction (LD) $\sigma_\Phi = \sigma_{11}$, in the Transverse Direction (TD) $\sigma_\Phi = \sigma_{22}$. Because the simulation provides the same results in both longitudinal and transverse directions, one curve is plotted.

The results show a good agreement: for the peening conditions SP1 and SP2, the modelling approach provides a balanced RS profile which is less compressed than the SIB due to the thickness of the sample, and it fits correctly the cloud of data points.

For partially shot-peened samples, the comparison between simulation and experiment for residual stresses distribution along the longitudinal direction is carried out near the surface. Because the mean penetration depth for X-rays is 4 µm, the simulated RS components are determined at the nodes located for the same depth.

The results are plotted in (Fig. 2) and it shows the effect of non-homogeneous shot-peening. For both peening conditions, the border between the peened (on the left side) and the non-peened (on the right side) areas is well described by the modelling approach, as well as the stress level for the peened area. The stress level determined with the simulation for the non-peened area is not in good agreement with data points, but it can be explained by the dispersion induced by the milling process which is observed experimentally with repeated RS analysis with XRD for non-peened samples.

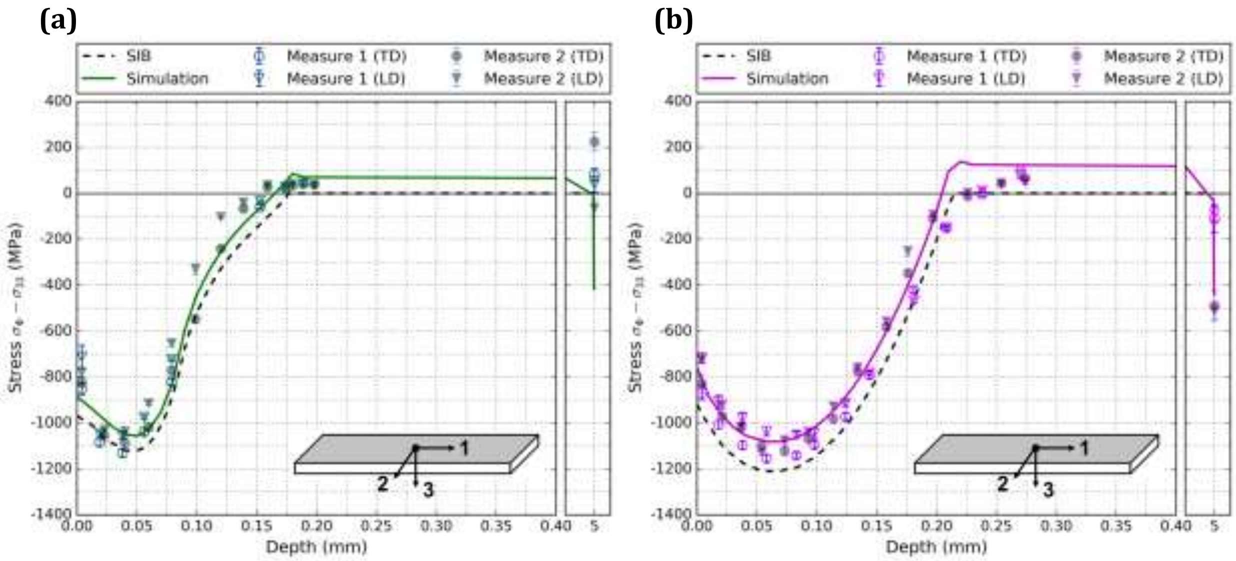

Fig. 1: In-depth residual stresses distributions for samples of 5 mm thickness: a) totally shot-peened SP1, b) and totally shot-peened SP2

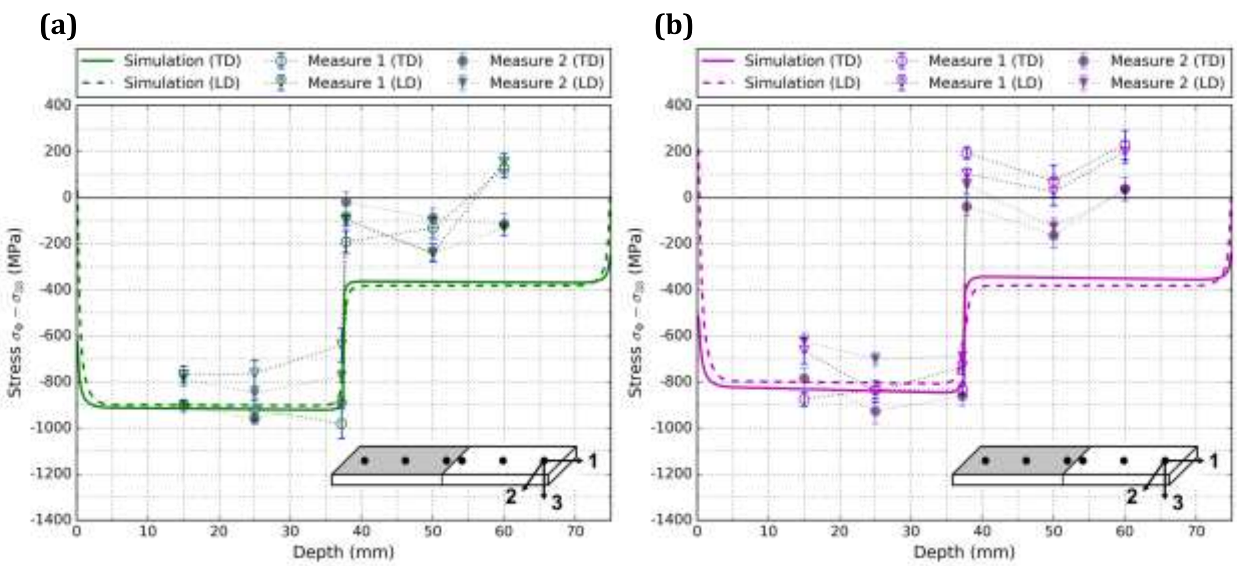

Fig. 2: residual stresses distributions along the longitudinal direction (4 μm depth) for samples of 5 mm thickness: a) partially shot-peened SP1, b) and partially shot-peened SP2

Comparison of curvatures

The profile height is also a characteristic parameter which is interesting to link with the effect of the RS rebalancing. With greater rebalancing comes greater deflection. For totally and partially shot-peened samples, the profile height is characterized in the longitudinal direction of the half-width. The considered data are displayed in (Fig. 3).

The results for the modelling approach are in a reasonably good agreement with the experimental data. The deviation between the maximum values is due to the sensitivity of the model to the Young modulus and the RS profile for the milled state. Those parameters have been fixed to apply the modelling approach whereas experimental dispersions are observed. When the Young modulus value decrease and/or the compression near the back milled surface is higher, then the simulated deflection becomes greater.

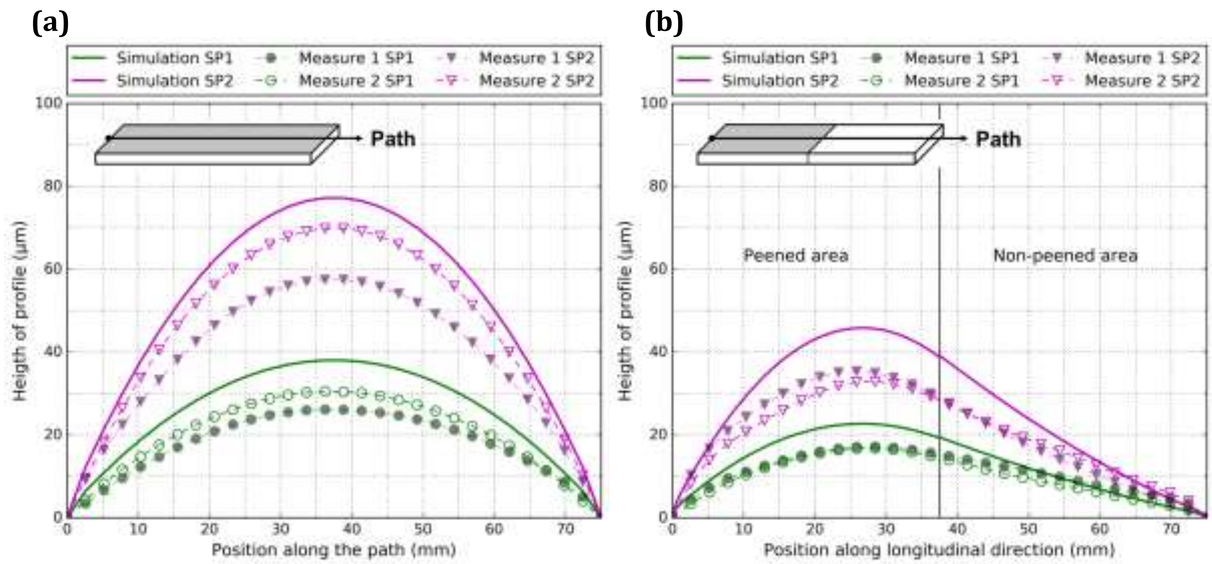

Fig. 3: Height of profile along the longitudinal direction for samples of 5 mm thickness: a) totally shot-peened, b) and partially shot-peened (SP1 and SP2)

Conclusions

The feasibility and the potential of the approach for RS modelling have been demonstrated through the comparison with experimental data for totally and partially shot-peened flat sample of 5 mm thickness. The method provides the RS state and the deflection due to shot-peening, and takes into account the rebalancing of RS due to the geometry. Hence a perspective is to lead the comparison with experimental results for curved surfaces.

In addition, the final objective is to use the redistributed RS field to the estimation of the fatigue life of the shot peened part submitted to cyclic loadings in service. Thus, using a Crossland criterion for high cycle fatigue regime, the study aims to propose a complete methodology in order to investigate the influence of shot peening on fatigue strength of mechanical components with complex geometry.

Acknowledgments

This work is part of the industrial collaborative CONDOR project coordinated by IRT M2P and consisting in developing a methodology for fatigue life prediction of shot peened structures. It is a pleasure to acknowledge all the industrial partners: Airbus Helicopters, ArcelorMittal, Areva, Mistras group, PSA Peugeot Citroën and Safran.

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