Residual Stress Measurement Correction on Shot Peened AA2024 by Finite Element Analysis

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Abstract

X-Ray diffraction is the most widely used technique to measure the residual stresses produced by shot peening. In this process, electropolishing is needed to access the in-depth residual stress state. Consequently, the measures must be corrected to take into account the ensuing stress relaxation. Moore and Evans (M&E) [1] proposed an analytical method for correcting the residual stress measurements in simple geometry components by relying on several simplifying assumptions that are not easy to validate in real life. Finite element analysis (FEA) approaches have to be developed and applied on complex geometries. Savaria *et al.* [2] improved the work from the Lambda research laboratory [3] based on the calculation of a so-called FEA relaxation correction matrix which quantifies the layer removal relaxation. However, this method highly depends on the component and removed pockets geometries. This paper investigates the dependency of the assumed removed layer geometry on the ability for the FEA approach to properly estimate the initial residual stress gradient. Moreover, the relaxation correction matrices are validated through numerical analysis and are applied to an actual AA2024 part. The results show a non-negligible difference between the M&E method and the FEA approaches.

Keywords Residual stress, layer removal technique, finite element analysis, stress relaxation correction.

Introduction

The penetration depth of X-Rays, in common engineering metals, is relatively small (few microns). Therefore a layer removal process, by electropolishing in practice, is used to obtain the in-depth residual stress state. However, this process implies material relaxation by the redistribution of the residual stress profile after each layer removal step. For this reason, a correction has to be provided in order to get the residual stress profile that was initially present.

An analytical method has been developed by Moore and Evans (M&E) in 1958 and can be applied to simple geometries such as thick cylinders and large plates if the proper polishing method is used [1]. For example, Eq. 1 below gives the correction by M&E in the case of a flat plate in x-direction (the same stands for y-direction):

$$\sigma_x(z_1) = \sigma_{xm}(z_1) + 2\int_{z_1}^{H} \frac{\sigma_{xm}(z)}{z} dz - 6z_1 \int_{z_1}^{H} \frac{\sigma_{xm}(z)}{z^2} dz \qquad (1)$$

where σ_x and σ_{xm} are the corrected and measured stresses in x-direction, H is the original thickness of the plate, while z is the thickness of the plate and z_1 the distance from the lower surface to a point in which we are interested to get the stress state after layer removal.

In fact, this method, although widely used in the industry, relies on some assumptions which made it inaccurate for many cases. Four of these assumptions are the following: the stresses must remain elastic during relaxation and redistribution, the M&E equations are only valid for large geometries (long tubes or large plates) and for measurements far from the edges, the layer removal process is supposed to be applied to the full part and not restricted to a little area, and the stress field to be measured has to be symmetric (axial or planar). The three last

assumptions are rarely true and consequently, errors can be introduced by the M&E corrections.
The use of a correction based on finite element analysis (FEA) has the advantage to overcome most of the restrictions listed above since it is a computational method which can take into account the real geometry of the part, the non-symmetric stress field, and the geometry of the electropolished pocket.
The aim of this paper is to apply the FEA correction method on a shot peened plate (made in AA2024-T351). This method is based on the calculation of a relaxation correction matrix, proposed by the Lambda-Research Laboratory [3] and improved by Savaria *et al.* [2]. The validation of the correction has been discussed, in particular, the influence of the removed layers geometry on the results has been studied.
This article is divided into 5 sections. Following this introduction, section 2 reminds the FEA-based correction method which is applied here. Section 3 presents three models simulating the layer removal process used for the validation of the FEA correction method and discusses the obtained results. Section 4 shows the application of the method on an actual case. Section 5 concludes this work.

The FEA relaxation correction matrix method
In the original method presented by the Lambda-Research Laboratory [3], the principle of the FEA-based correction is to model the layer removal process in a part subjected to a known residual stress profile in order to calculate correction matrix K coefficients. These coefficients are used to correct the actual measured residual stresses. Similar to the M&E correction method, some assumptions have to be respected while applying this FEA method. The main are: relaxation remains elastic during the layer removal process, none new residual stresses are introduced by the layer removal process itself, the thickness of the polishing pocket is small compared to the in-depth stress gradient, the relaxation and redistribution of the stress in one direction are not affected by the stresses in other directions i.e., the stresses are uncoupled. A consequence of these assumptions is that the correction matrix should be independent of the stress profile selected to calculate it [3]. In practice, it is suggested to use a linear stress profile to calculate the K matrix. Savaria *et al.* [2], when working on induction harden parts, have introduced the notion of stress gradient in the removed layers (see equation 3 below). They have also pointed that some errors minimized the initial stress profile used for the calculation of the K matrix are close to the actual expected real profile, especially if sharp stress gradients are expected (it is not the case in the present work) and an iterative method is then necessary for proper and accurate calculations. Moreover, the geometry of the material pocket removed by electropolishing also has an influence and should be well documented at each step of the process, at least in term of dimensions.
The abstract of the application of the FEA method is as follows. A stress profile is virtually introduced in the part and the layer removal process is simulated at each step of removal. The stresses remaining in the part are computed and recorded at various depths below the surface. Then, the coefficients K_{ds} of the correction matrix are calculated for each stress direction according to Eq. 2 below.

$$(\Delta\sigma_d)_s = (\sigma_d)_s - (\sigma_d)_{s-1} = -K_{ds} \cdot \sigma_{avg,s} \qquad (2)$$

where $(\Delta\sigma_d)_s$ is the local stress variation observed at a certain depth d after the removal step s; K_{ds} is the correction coefficient at the depth d associated with the removal step s; $(\sigma_d)_s$ and $(\sigma_d)_{s-1}$ are the actual stresses in one direction after removing layers s and $s-1$, respectively; $\sigma_{avg,s}$ is the average of the two stresses measured on upper sides of the removed layers s and $s+1$ as defined in Eq. 3 (as proposed in [2]).

$$\sigma_{avg,s} = \tfrac{1}{2}(\sigma_{m,s} + \sigma_{m,s+1}) \qquad (3)$$

where $\sigma_{m,s}$ and $\sigma_{m,s+1}$ are the residual stresses measured on the upper sides of layers *s* and *s+1*, respectively.

It is interesting to note that a correction matrix *K* has to be calculated independently for each stress direction. It is also worth noting that for the calculation of this matrix, the values $\sigma_{m,s}$ referred to the fictive residual stresses introduced numerically.
Then, the corrected residual stress $\sigma_{c,d}$ at the depth *d* can be calculated using the coefficients of the correction matrix determined above, as Eq. 4 shows.

$$\sigma_{c,d} = \sigma_{m,d} + \sum_{s=1}^{d-1}\left(K_{ds} \cdot \sigma_{avg,s}\right) \qquad (4)$$

Introduction and validation of three FEA matrix correction models
An actual shot peened plate made of aluminum alloy AA2024-T351, 15 mm in thickness, was used for the modeling. The isotropic elastic properties were selected as: a Young's modulus of 74.2 GPa and a Poisson's ratio of 0.33.
As shown in Figure 1, three models were studied to simulate the geometry of the layer removal process: a full polishing over all the part, a square-parallelogram-like polishing, and a semi-sphere-like polishing.

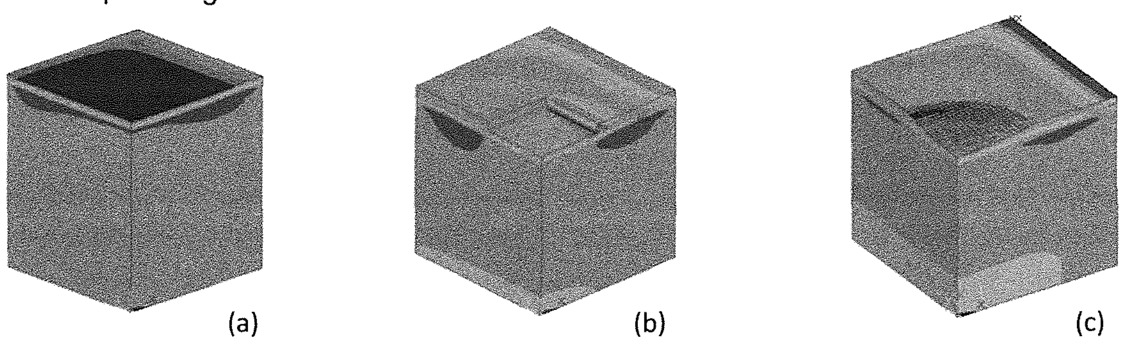

Figure 1. models used for the simulation of the layer removal process: (a) full polishing over the part, (b) square-parallelogram-like polishing and (c) semi-sphere-like polishing. The grey levels represent the different stress levels in the x-direction.

The full polishing model is respectful of the M&E assumption which states that the layer removal process is done over the entire surface of the part (however, the full planar symmetry of the part is not respected). The square-parallelogram-like polishing model is a simple way to simulate a local layer removal process, as it is kind of respect of the actual pocket's dimensions Finally, the semi-sphere-like one takes into account the actual geometry obtained when performing a layer removal process by jet electropolishing.
As shown in Figure 1, each model was simulated using symmetric boundary conditions to reduce the computation time. Convergences as per the size of the part to be modeled and the size of the finite elements were checked: the models were meshed with 86436 elements.
Since isotropic material properties were assumed, the residual stresses in both directions of the plane of the surface are the same. Hence, only the results in x-direction are computed. The simulations were run with ANSYS APDL 14.0 [4] on a 64-bit operating system using an Intel Xeon CPU processor of 2.27 GHz (2 processors).
For the calculations of the *K* matrices for each model, linear stress profiles were virtually introduced in the parts via the application of thermal gradient and using a coefficient of thermal expansion of 23.10^{-6} °C^{-1}. The thermally induced stresses were computed with ANSYS and the layer removal processes were simulated step by step using a "do loop". Thereby, the matrices containing the stresses at each step in column and each depth in row were built. The *K* matrices were so calculated as per Eq. 2 and 3 described previously using a MATLAB program [5].

The validation of the FEA correction method was performed next. Firstly, a stress profile similar to the ones generated during shot peening was introduced into the ANSYS models, using the INISTATE command into nodes, layer by layer. Then the static mechanical equilibrium states were computed as a first step and the resulting stress states were recorded as the "σX Initial" curves in Figure 3. Afterwards, the layer removal processes were simulated step by step by unselecting the elements corresponding to the polished pockets. Together, the virtually "σX Measured" stresses were recorded for the remaining depths for each removal. These measured values were finally corrected using the *K* matrices previously determined. If the correction method do not introduce errors, the "σX FEA corrected" values are expected to be the "initial" ones.

It is interesting to note that the "measured values" of σX are different for the three models. They are compared in Figure 2.

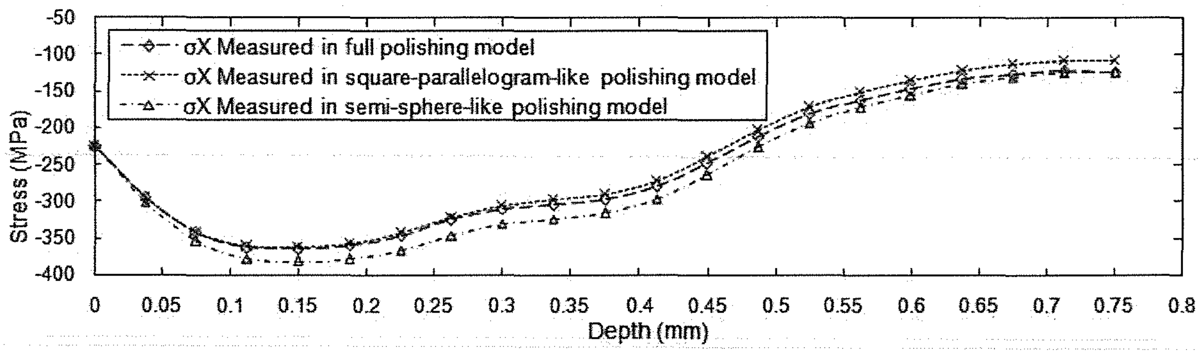

Figure 2. Comparison of the measured values for the three models.

Now, the results of the numerical correction methods are shown in Figure 3 for each model and they are compared with the analytical M&E ones (see curves called "σX M&E corrected"). The results show that the corrections by M&E and by FEAs are quite close, but still, several remarks could be made:

1. The three FEA corrections gave values very close to the actual values although the correction matrices are not numerically equals, thus validating the numerical method.
2. For the first model (using a full surface polishing method), the M&E correction is closer to the initial stress state than the FEA correction, however the differences are very small with an average difference of slightly more 4%. This could be explained by the fact that the most important assumption of the M&E method is observed in this model and that no numerical errors are introduced.
3. In the model where square-parallelogram-like polishing is assumed, the FEA correction is more accurate than the M&E one, but again, the discrepancies are rather small with an average difference between the two corrections of 2.33%.
4. The model using a layer removal process by semi-sphere-like polishing shows that the FEA correction is better than the M&E one to predict the initial values of the stress field. Actually, average errors of about 1.14 MPa in stress intensities are found. As this kind of spherical polishing is the one usually encountered in practice, The FEA correction method is worth using when accurate values of the stress field is required (for fatigue models for examples).

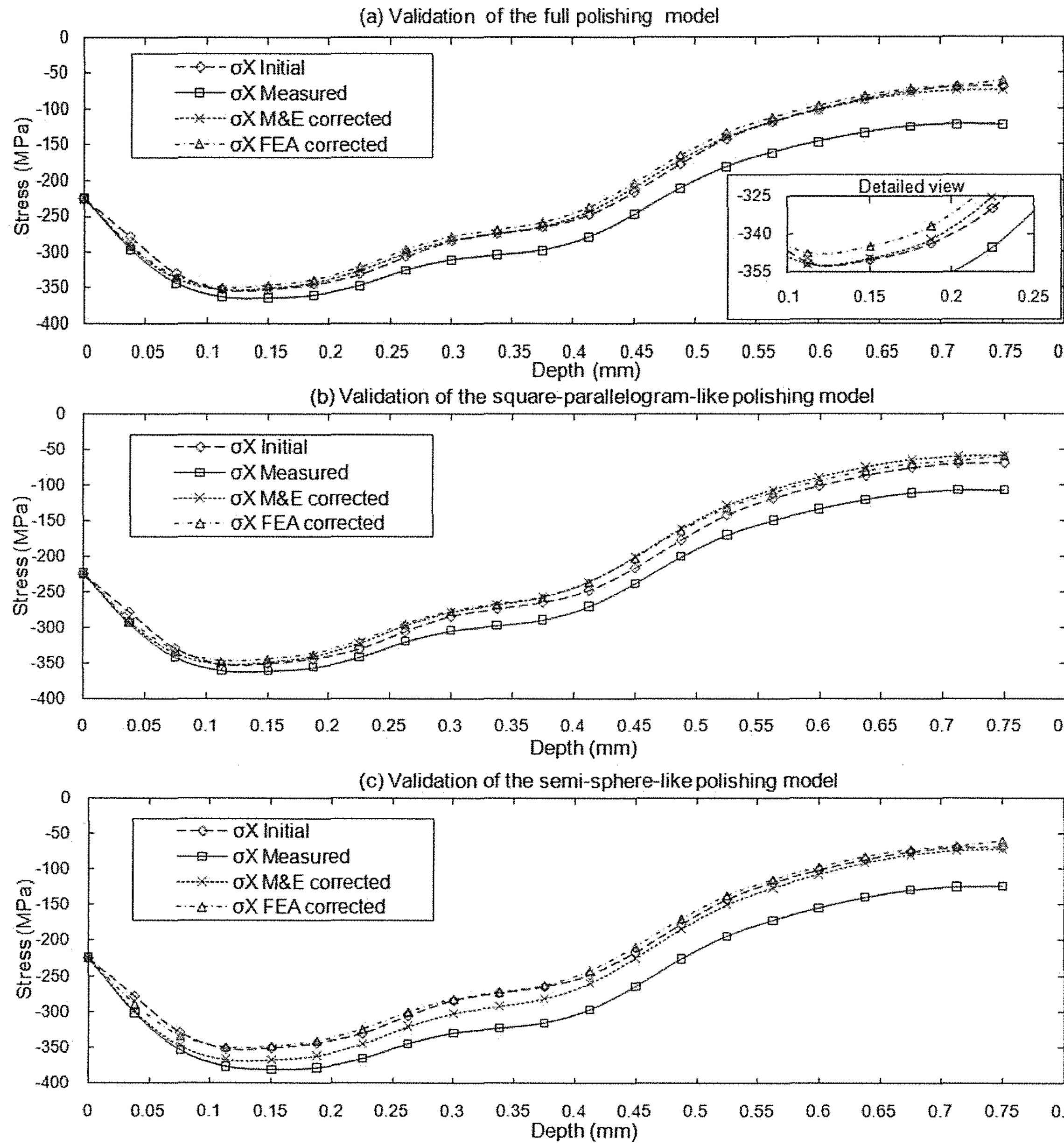

Figure 3. Correction of a virtual residual stress profile by M&E method and by FEA method: (a) full polishing, (b) square-parallelogram-like polishing, and (c) semi-sphere-like polishing.

Application of the FEA method for the correction of an actual case

The K matrix of the third model was used to correct an actual stress profile measured by X-Ray diffraction on a shot peened AA2024-T351 plate. Results are shown in Figure 4. The media type used was cast steel shots S230 and the plate was shot peened at full coverage (100%).

Due to the fact that 20 layers were used for the calculation of the K matrix and that only 6 layers were actually removed experimentally, the measured stress profile was extrapolated using the Piecewise Cubic Hermite Interpolating Polynomial method in MATLAB [5]. Then it was this extrapolated stress profile which was corrected as per the FEA method.

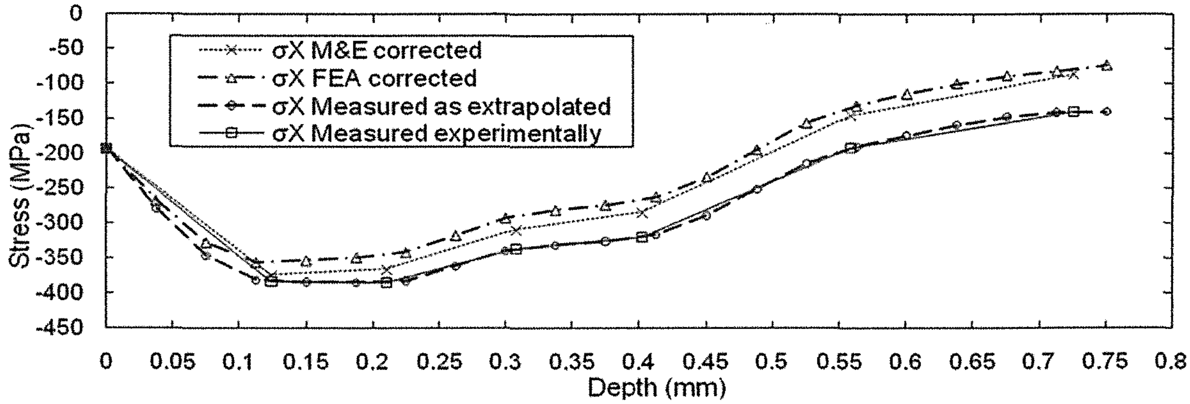

Figure 4. Correction of an actual residual stress profile in a shot peened AA2024-T351 plate.

The FEA method gave a fairly different correction than the M&E one. As expected from the results obtained while validating the method with the third model (semi-spherical-like polishing), the M&E analytical method cannot capture the real geometry of the electropolishing method and errors are introduced (or full correction cannot be obtained to be more precise).

Conclusions

In this work, an improved finite element analysis method for correcting the residual stresses after relaxation was presented and validated through a case study. It served to correct an actual stress profile of a shot peened AA2024-T351 plate.

It has been shown, in agreement with Savaria *et al.* [2], that stress variations due to relaxation and redistribution depend on the layer removal geometry. Using (complex) geometries close to real geometries and the FEA matrix relaxation correction method, one can obtain accurate results. On the other hand, using the M&E method can lead to significant errors if a semi-sphere-like polishing pocket is used. Actually, in the proposed example, the correction brought by the FEA is greater than the one predicted by M&E method.

References

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