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Shot peening FEM simulation: A novel approach based on crystal plasticity

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Introduction

Shot peening is widely used in automotive and aerospace industries to induce compressive residual stresses in the near surface of treated metal parts. These compressive stresses enhance the fatigue life of shot peened parts. Understanding how the stress state is created and how it changes depending on some process' parameters is essential to optimize fatigue life.

The *Finite Element Method* (FEM) has been extensively used to simulate the shot peening process at a macroscopic scale [1-3]. However, simulating shots impacts at the microscopic scale, to the best of our knowledge, has not been done yet. This might be related to the fact that *Crystal Plasticity* (CP) requires significant computer resources. In this work, a microscopic approach was explored to study the role of different microstructural features, like grain-to-shot size ratio or the local texture, on the residual stresses distribution.

Objectives

The objectives of this work were to

1. Set-up a FEM framework in which the shot peening process can be simulated using crystal plasticity within a manageable simulation time.
2. Study the heterogeneities and variations on the residual stress profile produced by different local textures and grain-to-shot size ratio.
3. Attempt to link the local crystal misorientation after shot peening to the grain refinement observed experimentally [4-5].

Methodology

The simulated shot peening process relied on CW14 shots to achieve a full coverage at an Almen intensity of 8A. Shots initial velocity and impact points were obtained through *Discrete Element Method* (DEM) simulations [1]. An impacting volume of $2R$ x $2R$ x $3R$ (*length* x *width* x *thickness)*, where R is the radius of the CW14 shot, was chosen. *Periodic Boundary Conditions* (PBC) were applied to the sides of the volume as well as to the shots (virtual shots were created to satisfy this condition) and the microstructure as shown in Fig. 1. The bottom's surface normal displacement was constrained and shots hit on the top surface. These boundary conditions allowed to reduce the number of shots needed to achieve full coverage. Also, a high damping coefficient was used to reduce the interval between two hits. Once the last shot rebounded, a certain amount of time was simulated without any new impact. This step was added to damp down all the dynamic effects before extracting the residual stress distribution.

The material under study was a precipitated hardened IN718 alloy. Crystal plasticity constitutive theory parameters were previously fitted using tensile and Hopkinson's tests. A power law was used for the plastic flow and a Voce's law was used for the hardening [6]. Also, an isotropic macroscopic model was simulated to compare the two different approaches.

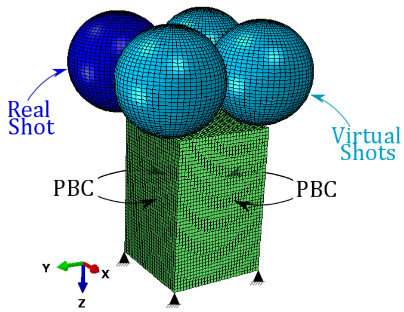


Fig. 1: Periodic boundary conditions FEM. Shots added to satisfy the PBC are in light blue. They were linked to have the exact same displacements and rotations as the original shot (dark blue).

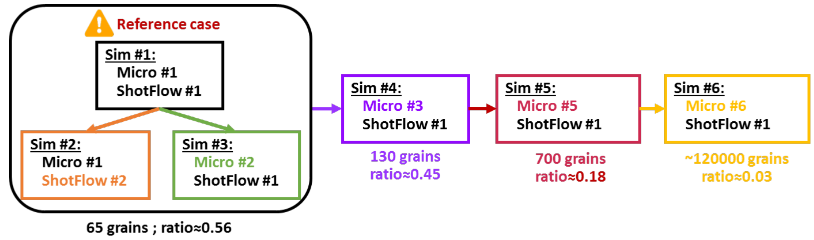


Fig. 2: Simulation plan followed in this work. Having previously fixed the shot type, the number of grains in the volume has been changed to satisfy the ratio between grain and shot size.

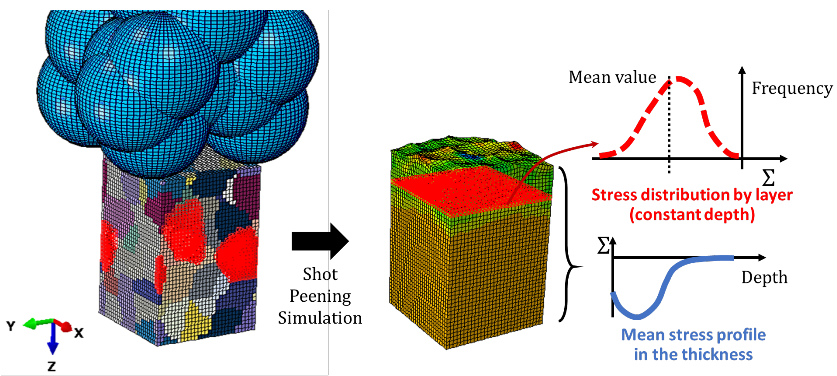


Fig. 3: Procedure followed to study the residual stress distribution. After shot peening, for each layer of the mesh, the mean, the maximum and the minimum value of stresses were extracted to characterize their evolution in the thickness (blue full line). Also, for each layer, the stress distribution is characterized to study how homogenous it is (red dashed line). Highlighted parts represent a grain split in four to satisfy the PBC (left) and a layer of elements at a constant depth from the surface (right).

A simulation plan was set in order to analyze the effect of different parameters, as shown in Fig. 2. At first, the study was focused on a grain-to-shot size ratio that was kept constant. Under this condition, several *Representative Volume Element* (RVEs) were tested to estimate the statistical variation of residual stresses due to local texture. Then, other parameters like the shot flow (order in which the shots impact to achieve full coverage) were varied and their impact on the residual stress field was quantified.

The grain-to-shot size ratio was subsequently changed (smaller grains with a constant shot size) and the same analysis was carried out. For each shot peening simulation, residual stress profile on the thickness and also the residual stress distribution for given depths were computed, as explained in Fig. 3.

Results and analysis

The first part of the analysis was focused on the highest grain-to-shot size ratio of 0.56. Fig. 4 and Fig. 5 show that the modification on the shot flow did not have a strong impact on the mean residual stress profile, even though the surface topography and the stress concentration points were different. Both shot flows were carefully chosen in such way that the total kinetic energy at the beginning of the simulations was the same. Given the small effects of the shot flow, only one (shot flow #1) was used for the rest of simulations.

These figures also show that the microstructure modification, which leads to a local texture evolution and different grain-to-grain interactions, had a strong impact on the residual stress distribution through the thickness. This variation can reach up to 100MPa (around 10% of the maximum residual stress value). According to these results, shot peened parts with big grain-to-shot size ratio could exhibit large residual stresses distribution on the surface depending on the local texture. However, residual stress measurement techniques usually average over small surfaces or volumes. As a result, these local variations could be smoothed and eluded. The extreme values are partially due to the dimple's geometrical concentrations that also created high tensile stresses on the surface, as shown in Fig. 6. It is important to note that these extreme values are much higher in the crystal plasticity based simulation than in the isotropic macroscopic case because of the heterogeneities and anisotropy introduced by the grain behavior. Unexpectedly, stress distribution for the polycrystal simulation is narrower, as shown in Fig. 7. Even if the distribution is larger (more extreme values), it is more homogeneous than the isotropic case.

The second part of the study focused on the residual stresses sensitivity to the grain-to-shot size ratio. To illustrate the evolution of the microstructure with this ratio (keeping the shot size constant), Fig. 8 shows some RVEs representations. It can be seen that for the smaller ratios the mesh has been adapted. The aim of this modification was to increase the number of elements and grains on the near surface region to reduce the simulation time. The elements on the bottom layers remained in the elastic regime and their impact on the simulation results is deemed to be negligible.

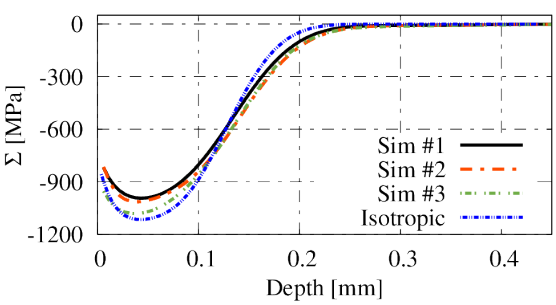


Fig. 4: Mean residual stress evolution in the depth for a same grain-to-shot ratio.

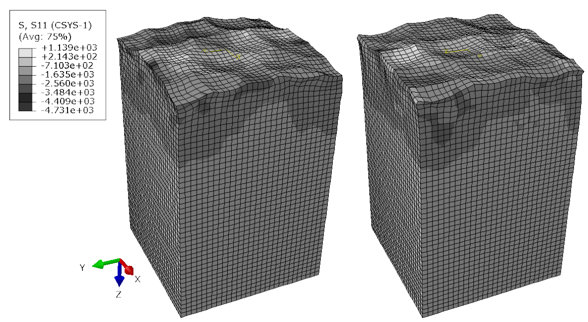


Fig. 5: Residual stresses distributions for two polycrystal simulations. Microstructure was kept constant (same grains, same orientation), only the shot flow was changed.

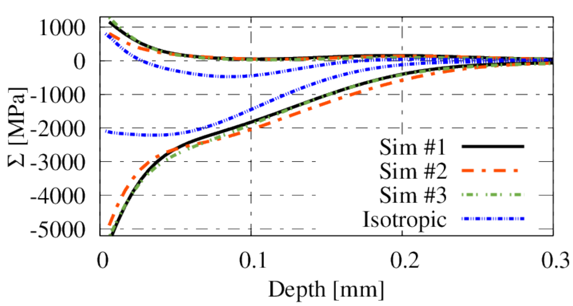


Fig. 6: Maximum and minimum residual stresses evolution in the depth for a same grain-to-shot size ratio.

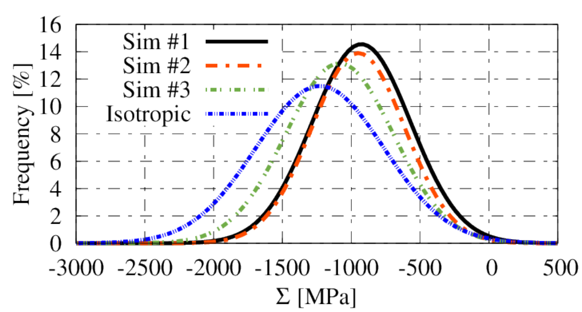
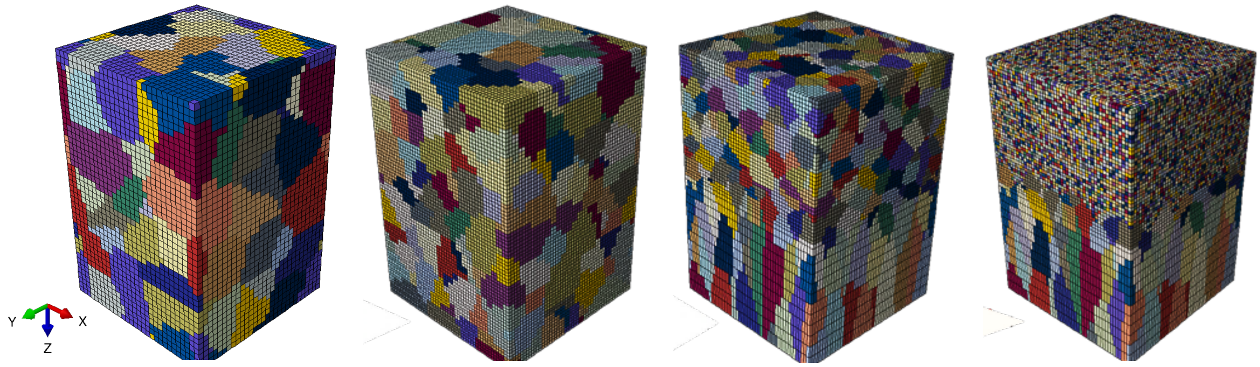


Fig. 7: Residual stress distribution under the surface for a same grain-to-shot size ratio (depth≈20µm). Trends were fitted using a gaussian function.



ratio≈0.56 Sim#1 ratio≈0.45 Sim #4 ratio≈0.18 Sim #5 ratio≈0.03 Sim #6

Fig. 8: Different RVEs used depending on the fixed grain-to-shot size ratio.

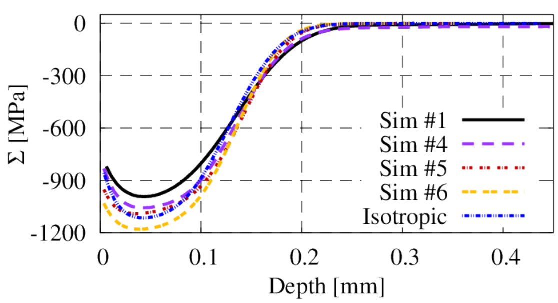


Fig. 9: Mean residual stress evolution in the depth for different grain-to-shot ratio but the same shot flow.

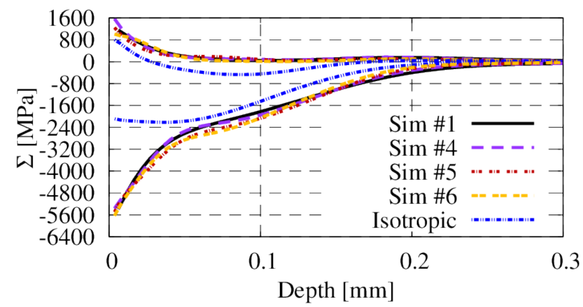


Fig. 10: Maximum and minimum residual stresses evolution in the depth for different grain-to-shot ratio but the same shot flow.

Fig. 8 shows that there is a significant difference between the two smallest ratios. The model evolved from a polyhedral subdivision of the volume into grains (following a Voronoi tessellation) to another approach that consisted in assigning a random orientation to each element. This last formulation was adopted because the mesh density needed to accurately describe small grains could not be handled.

The mean residual stress profiles show a clear trend, as seen in Fig. 9. The lower the ratio was, the more intense the residual stresses were under the surface. This increase in the maximum residual stress was accompanied with a small reduction of the depth of compressive stresses. No significant variation was observed on the extreme values, as shown in Fig. 10. The stress distribution at a constant depth also showed a clear evolution: the lower the ratio was, the closer to the isotropic case became the distribution, as shown in Fig. 11. This evolution was to be expected since, as the behavior of more grains was smoothed under the impact of the shots, the local texture became closer to a random texture and so the response of the material is closer to the isotropic case.

These simulations suggest that, given that the grain-to-shot size ratio is small enough to ensure an isotropic media response, stress localization in the volume is mainly driven by the shot flow, as depicted in Fig.12. The global trend is quite similar although small local variations related with the microstructure can be seen.

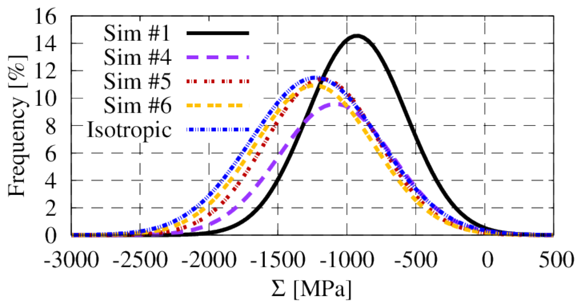


Fig. 11: : Residual stress distribution under the surface for a same grain-to-shot ratio (depth≈20µm). Lines were fitted using a gaussian function.

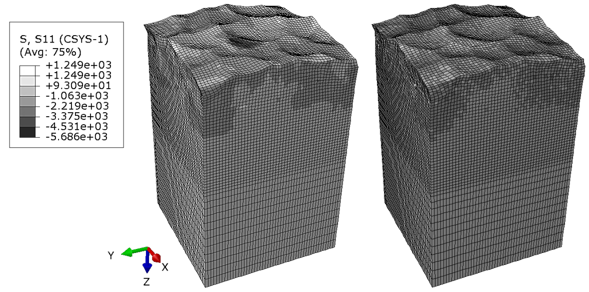


Fig. 12 : Residual stress in the volume. From left to right, ratio≈0.18 and ratio≈0.03. Surface and under surface stress concentrations related with the shot flow are present in both models without a major variation due to grains size or subdivision method used.

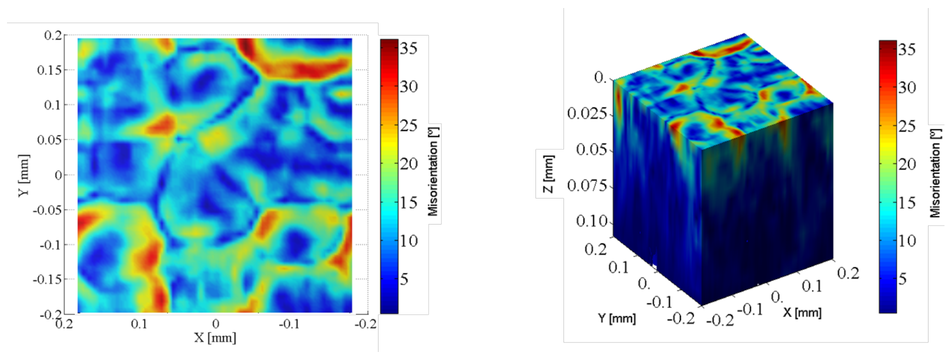


Fig. 13: Misorientation distribution on the surface (left) and in the volume (right).

The third part of the analysis made use of all the crystal plasticity framework capabilities to explore a first approach towards the grain refinement after shot peening. Indeed, during the crystal deformation, the crystal lattice rotates and a misorientation angle from the reference configuration can be computed. If the misorienation was high enough and was extended in a certain volume, it could be considered that a new grain was created.

For this analysis, the RVE with the biggest grains was used. Misorienations were computed both in the shot peened surface and in the volume, as shown in Fig. 13. These trends agree with experimental observations in which grain refinement is confined to the shot peened sub-surface and can reach high values.

Local crystal reorientation after shot peening can also be read into a virtual EBSD map, as shown in Fig. 14. The dark lines represent grains boundaries before shot peening. It can be clearly seen that some grains are split into separate zones (colored with different hues). This means that different sub-grains regions were created, although the frontiers are not clear in all the cases.

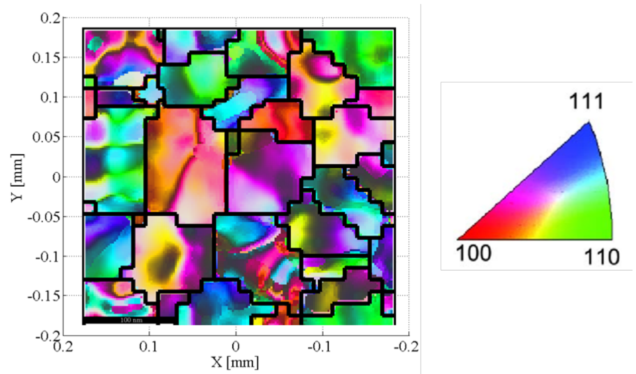


Fig. 14: Reconstructed EBSD map of the shot peened surface. Projection over the normal direction to the surface was used (along Z axis).

Conclusions

A microscopic approach based on crystal plasticity has been set up to simulate the shot peening process. Several microstructures and shot flows were tested. For big grains-to-shot ratio size, microstructure plays an important role in the residual stress profile associated with the variation of the local texture. Once this ratio became smaller, results become closer to those obtained through macroscopic approach. Nevertheless, more simulations are needed to create a larger database and so a solid statistic treatment that reinforces the assessment made in this work.

The microscopic approach could be used to estimate the grain refinement. To achieve a better estimation, deformation by twinning should be added in future work.

References

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