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Analysis of the impact of a shot at low velocity using the finite element method. Application to the ultrasonic shot-peening process.

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Keywords: ultrasonic shot-peening, finite element simulation, coefficient of restitution, residual stresses, low energetic impact, Al 2017A alloy.

Abstract. Shot-peening is a surface treatment widely used in the industry to improve fatigue life of mechanical components by introducing compressive residual stresses. Ultrasonic shot-peening is a recent development of this process. While the classical shot-peening process uses pneumatic energy to project the shots, ultrasonic peening uses high-power ultrasounds. This energy source allows the use of larger shots projected at lower velocity as compared to classical shot-peening. This work aims at studying the mechanical response (restitution coefficient, residual stress field) of a surface impacted by a shot at low velocity using the finite element method and experimental analysis. This paper presents the simulation of a single elastic steel shot normally impacting an Aluminum alloy plate considered to exhibit a linear-elastic behavior and non-linear isotropic work hardening characteristics. The numerical simulations are carried out for different impact velocities in order to take into account the heterogeneous shot velocity field observed in an ultrasonic shot-peening chamber. We compare the simulated rebound energy and the indentation profiles obtained for different impact velocities to experimental results. The simulated residual stress field topology shows a strong dependence on the shot velocity. While numerical results obtained at high impact energy agree well with literature results, the residual stress distribution simulated for low impact energies shows a tensile layer below the impacted area. The restitution coefficients and the indentation profiles compare well with the experiments.

Introduction

Ultrasonic shot-peening is a recent development of the well established shot-peening process. It consists of impacting the surface of the part to be treated with shots generally bigger than the shots used in classical shot-peening processes (0.3-1.2 mm). The projection of the shots is assured by high-power ultrasounds that generate a randomly distributed shot velocity field in the shot-peening chamber. The repartition of the impact sites in the ultrasonic shot-peening chamber has been modeled previously using a Molecular Dynamics simulation [1]. It was shown that the restitution coefficient of the impact had a strong influence on the results; the restitution coefficient is defined here as the ratio of the speed of the shot before the impact to the speed of the shot after the impact. This study thus aims at understanding the kinetic behavior of a steel shot impacting on an Aluminum plate at several velocities using both numerical and experimental approaches. An experimental set-up was made to measure the rebound behavior of a shot impacting on a thin plate at different velocities in order to evaluate the energy dissipated during the impact, and thus evaluate the restitution coefficient. Numerical models are proposed for resolving the problem; first a validation approach that gives general interesting results and then a finite element model validated experimentally. The results obtained in terms of restitution coefficient, dent profiles and residual stress fields are presented. Once the numerical model is properly validated, it can be applied to the shot-peening of other materials.

Numerical procedure

The finite element simulations were run using the ZéBuLoN FE package. We limited the study to normal impacts and thus treated the problem as an axisymmetric system (Fig. 1).

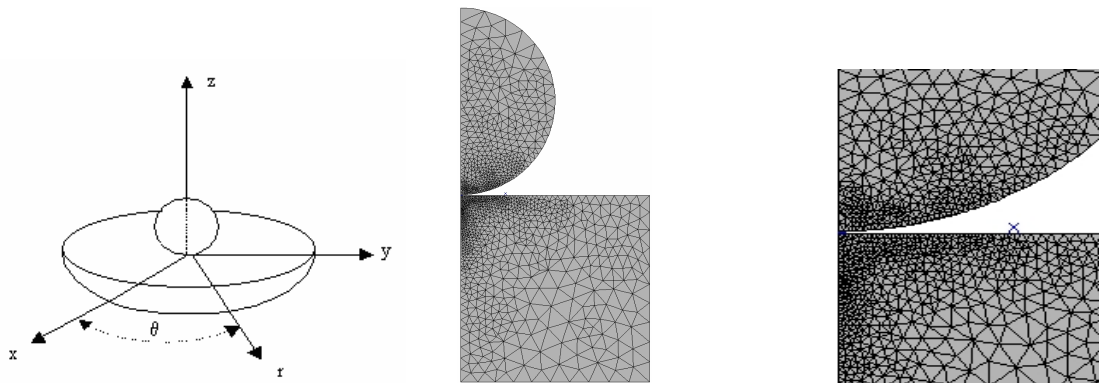


Figure 1: Axisymmetric model, cylindrical reference frame (O,r,θ,z) and typical mesh adopted.

The lower surface of the substrate is fixed in the z -direction as a geometrical boundary condition, and the impact velocity is imposed. The geometry is meshed using quadratic triangular elements with reduced integration. A dynamic implicit scheme is used to solve the finite element problem. The contact algorithm is a stress formulated one based on the flexibility method [2], and the friction effects are neglected. A typical mesh is presented in Fig. 1. The geometrical and numerical parameters of the computation (mesh, size of the geometrical model, convergence ratios, global convergence of the solution, numerical damping parameters, contact parameters...) have been optimized to guarantee the best results.

Validation of the model

A particular attention was paid to assure the precision and the validity of the numerical calculations. The contact problem of a rigid sphere impacting on an elastic semi-infinite substrate is first treated as a validation process to evaluate the geometrical, kinematical and the contact parameters. The elastic-plastic impact problem is then treated to validate the dynamic simulation.

Elastic impact simulation. The problem of a rigid shot impacting on a semi-infinite *elastic* body is treated in order to confront the numerical results to the theoretical solutions of Hertzian contact mechanics [3-5]. The substrate is assumed semi-infinite. The radial stress profiles $\sigma_{rr}(z)$ calculated on the symmetry axis ($r = 0$ mm) for different impacting velocities (0.2 m/s and 20 m/s) are compared to the results of Hertz [3] and Davies [4] under the large and small strain assumption for the numerical computation (see Fig. 2). Note that the values of the stresses obtained are rather unrealistic, this corresponds to an elastic solution of the contact problem made to validate the numerical model. For an impact velocity of 0.2 m/s, no difference is observed between the three solutions: large and small strain formulation solutions and the analytical solution. However, the results obtained for an impact velocity of 20 m/s show that the small strain assumption is no longer valid for large penetrations, as one might expect. Under the small strain hypothesis the numerical results deviate by up to 12% from the theoretical Hertzian values, and up to 5% with the large strain formulation. Note that there is also a small displacements hypothesis underlying the Hertzian values. It is interesting to see that the analytical solutions of Hertz and Davies give results that are very close to the numerical solutions obtained with a smaller number of approximations.

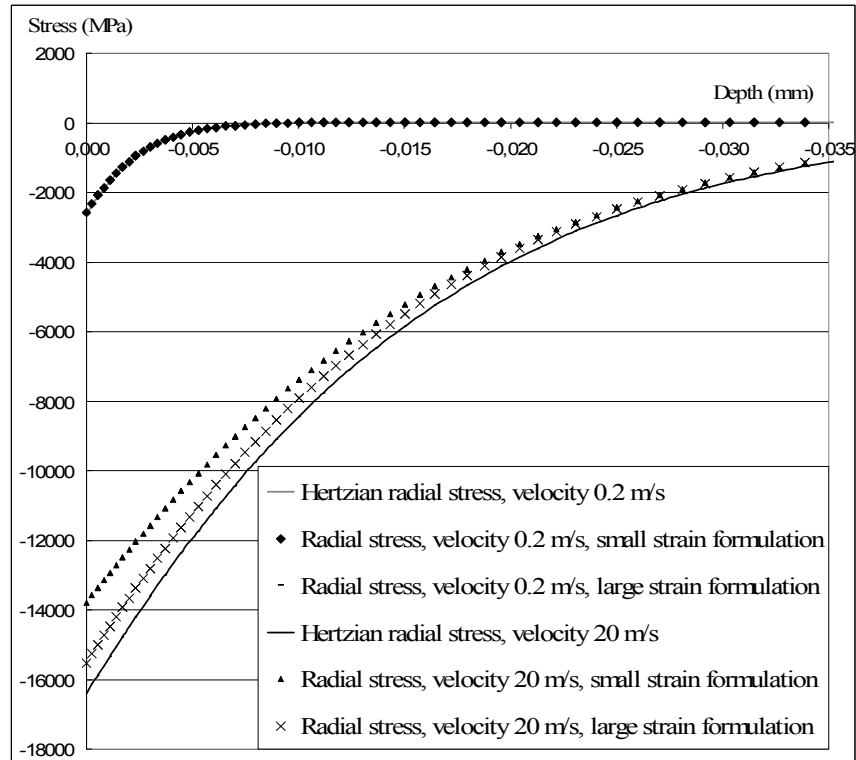


Figure 2: Radial stress profiles $\sigma_{rr}(z)$ at $r = 0$ mm calculated under large and small strain assumptions for the elastic impact of a rigid shot (diameter 0.6 mm) at 0.2 m/s and 20 m/s.

Elastic-plastic impact simulation. Static and dynamic resolution schemes have been compared by running impact simulations for an elastic-plastic shot impact on an aluminum 7075T13 alloy also studied by Deslaef [5]. The static scheme is possible if equivalence is assumed between the strain energy of the impacted region and the initial kinetic energy of the shot [6]. Fig. 3 compares the results of Deslaef (obtained by resolving the equivalent static problem using the Abaqus software) with our results (obtained with the ZéBuLoN FE software, using both a static and a dynamic implicit resolution scheme). The results obtained by the two resolution schemes coincide perfectly, which validate the different approaches.

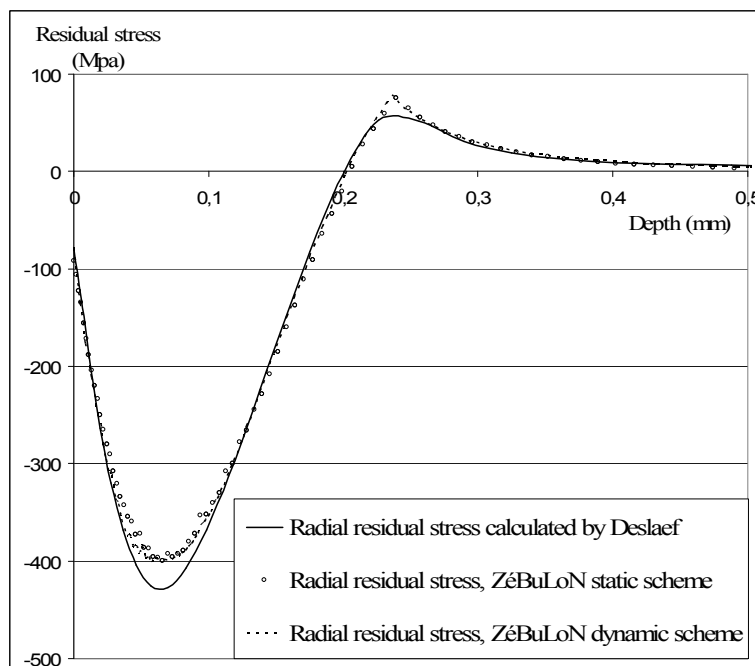


Figure 3: Comparison of the residual stress $\sigma_{rr}(z)$ at $r = 0$ mm, obtained by static and dynamic computations, Al 7075T13 impacted by an elastic shot (diameter 0.6 mm) at 20 m/s.

Experimental set-up and numerical model

The application of the FE model to usual ultrasonic shot-peening impact case is now treated to compare numerical and experimental results.

Restitution coefficient and measurement of the impact dent diameter. An experimental setup was realized for measuring the rebound of a shot (3 mm diameter) impacting under the influence of gravity on an Al 2017A alloy sheet for different velocities varying from 2 to 6 m/s. The height of the rebound was measured using a digital camera and the diameters of the impact indentations were estimated under an optical microscope.

Numerical model. The substrate studied is an aluminum 2017A alloy laminated plate impacted by a hard steel shot that is considered to deform only elastically. Strain rate effects were neglected and the impacted region is supposed to exhibit a non-linear isotropic work hardening behavior. The latter is modeled by a double exponential equation to obtain a good agreement with the experimental work hardening curve:

$$R = R_0 + Q_1(1 - e^{b_1 p}) + Q_2(1 - e^{b_2 p}). \quad (1)$$

The parameters $\{Q_1, Q_2, b_1, b_2\}$ of the hardening law were identified with respect to an experimental monotonic tensile test curve using an optimization algorithm. The yield stress R_0 was taken as the stress measured at $\varepsilon_{0.2\%}^p$. The optimum parameters are given in Table 1. The simulations were carried out using the optimized geometry described in the section above, for impact velocities varying from 2 to 20 m/s.

Young's modulus [MPa]	73500	Q_1	[MPa]	226.3
Poisson's ratio	0.32	Q_2	[MPa]	76.74
Density [kg/m ³]	2800	b_1		13.62
R_0 [MPa]	200	b_2		318.98

Table 1: Optimum parameters for the constitutive law (1) of the Al 2017A alloy.

Results

Restitution coefficient and impact indentation profile calculation. The impact simulation was carried out for velocities varying from 1 to 20 m/s, representing the order of magnitude of the shot velocities generally occurring in an ultrasonic shot-peening chamber. Fig. 4 shows the restitution coefficients calculated in the experimental velocity range, as well as the experimental results and the Thornton theoretical results [7]. The yield stress value used in the Thornton model is chosen arbitrary to compare experimental and theoretical velocity dependence of the restitution coefficient. The theoretical Thornton prediction closely follows the experimental curve for shot velocities less than 4 m/s. The measured restitution coefficients sharply decrease for shot velocities higher than 4 m/s and the Thornton prediction does not follow anymore. This might be explained by the fact that the support of the sheet used in the experimental setup was rudimentary and was not sufficient to transmit the total impact energy. The numerical simulation overestimates the measured restitution coefficients, which can be explained by the same argument. The impact was indeed simulated on a totally constrained sheet, which is a highly constraining boundary condition with respect to the sheet in the actual experimental setup. The numerical simulation seems also to overestimate the measured indentation profiles (Fig. 5). Fig. 6 shows the impact mark observed under the optical microscope and the simulated indentation profile for an impact velocity of 6 m/s. The indentation diameter is taken as the distance between the z-axis and the top of the deformed surface. The indentation diameter overestimation can be explained by the uncertain relation between the optical observation and the calculated indentation profile. A complete measure of the impact profiles would have been more efficient to compare numerical and experimental results but the small impact marks made it difficult to realize.

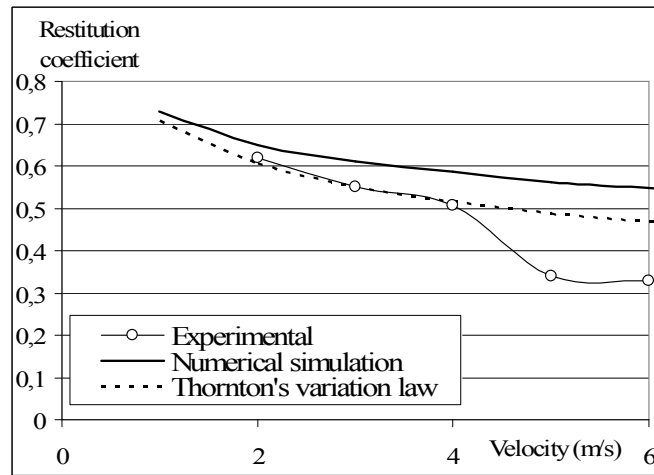


Figure 4: Comparison between numerical and experimental restitution coefficients, shot diameter 3 mm impacting on an alloy 2017A sheet. The Thornton's variation law was set with arbitrary material yield stress to fit the experimental results.

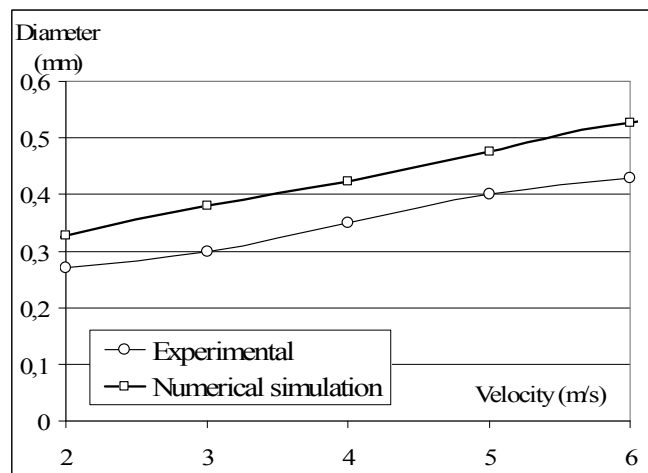


Figure 5: Comparison between numerical and experimental indentation diameters, shot diameter 3 mm impacting on an Al 2017A alloy sheet.

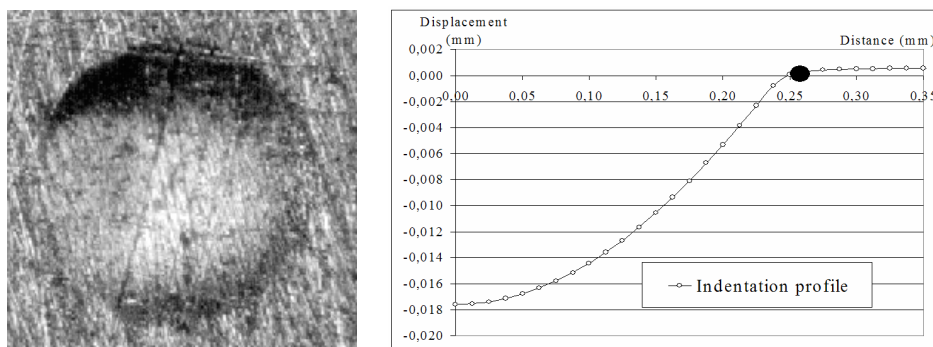


Figure 6: Measurement and evaluation of the numerical and experimental indentation diameter, shot diameter 3 mm impacting on an Al 2017A alloy sheet at 6 m/s.

Residual stress profile calculation. Fig. 7 shows the simulated residual radial stress profiles $\sigma_{rr}(z)$ at $r = 0$ mm. For high impact velocities, the residual stress profiles show good agreement with the literature results [6]. A tensile residual stress state is observed just below the top surface for velocities below 15 m/s. This residual stress field topology is explained by the high influence of the hydrostatic pressure in this subsurface layer during the contact for such a small relative penetration. The calculations confirm that the stress distribution in the subsurface layer is quasi-hydrostatic, while the plastic flow appears at greater depths. The incompatible straining then has to be accommodated by a tensile residual stress nearer to the surface.

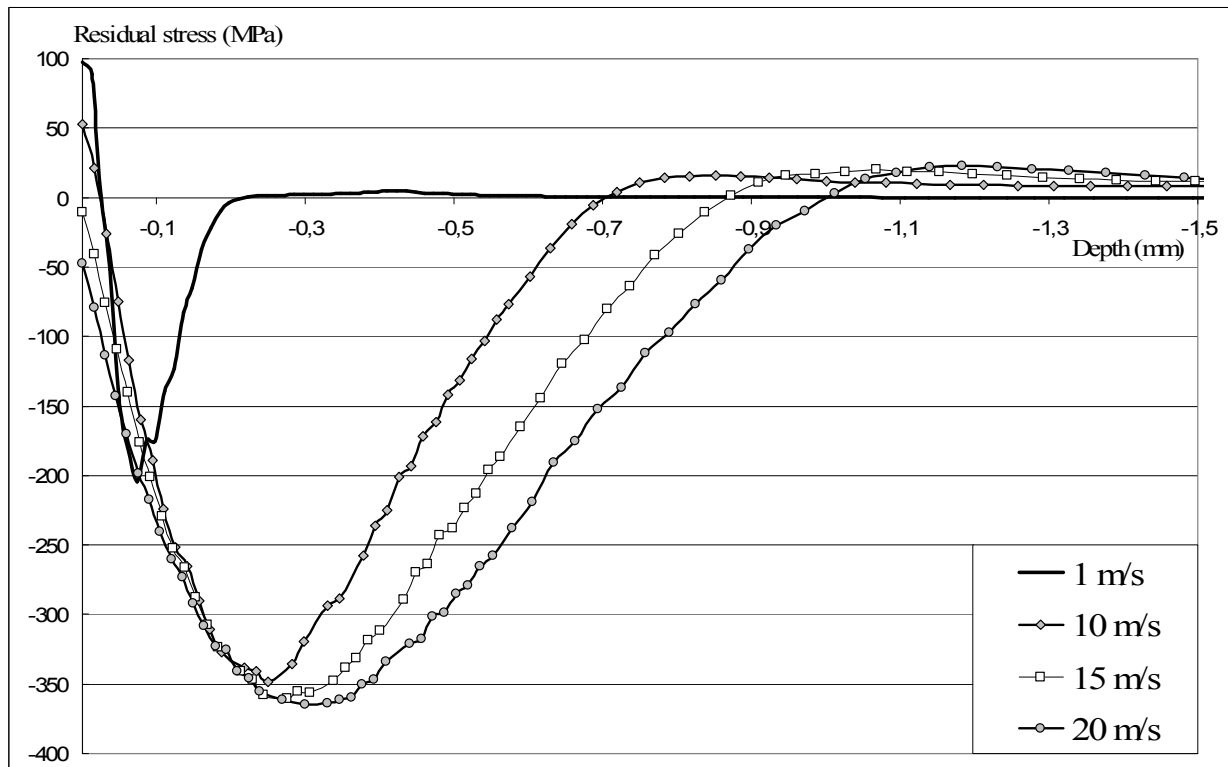


Figure 7: radial residual stress profiles $\sigma_{rr}(z)$ at $r = 0$ mm simulated for different impact velocities, shot diameter 3 mm impacting on an Al 2017A alloy sheet.

Conclusion

This paper presents a numerical impact simulation with the goal of predicting the elastic-plastic mechanical response of an impacted aluminum 2017A alloy sheet. Its elastic validation with respect to the Hertzian predictions gave us good results for low shot penetrations. It also showed that the geometric effects are to be taken into account for modeling correctly the stress distribution. The elastic-plastic simulations overestimated the experimental results in term of restitution coefficient and diameter of the impact dents. A more refined experimental setup would be necessary to validate the numerical results more accurately.

Residual stress profiles as a function of the impact velocity were calculated. These residual stress profiles simulated for low impact velocities present a subsurface tensile residual stress state, which is yet to be validated experimentally. It would be indeed interesting to show that the numerical simulation is sufficiently accurate to model the stress repartition in the first penetration instants to ensure the consistency of modeling the material by taking into account the kinematics hardening effects. We finally obtained numerical data to support a Molecular Dynamics simulation of the ultrasonic shot-peening process. The proposed finite element simulation is to be adapted to other materials to take the sonotrode, the chamber and the sample restitution coefficients into account.

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