3D FE analysis of shotpeening process for simulation and research on shotpeening process parameters

A. Manoucherifar[1] and K. Rezvani[2]

1 Assistant Professor of Mechanical Engineering, Islamic AZAD University, Khomeinishahr Branch, IRAN
2 MSc Student, Islamic AZAD University, Khomeinishahr Branch, IRAN

Abstract
The present research aims at describing a simplified 3D finite element dynamic and static analysis of shot impacting on metallic target plates to clarify and for better understanding of the effect of several key parameters such as shot velocity, shot size, incident angle, coefficient of friction and multiplicity of shot on compressive residual stress created by the shot-peening process. The finite element package ABAQUS 6.9 is used to simulate the procedure corresponding to the experimental operations. The geometry of the target plate is assumed to be a deformable plate with 2×2×1 mm dimensions. Also, for simplicity, shot is assumed to be fully spherical, discrete and rigid with a mass positioned at its centre. For the convergence model, several preliminary runs were conducted to establish the appropriate mesh design. Each result consists of two runs for which the first run contains an explicit dynamic step using initial mesh and configuration. The second run contains a static general step by using an import part and an update reference configuration from the output first run for considering the spring-back effect. The material models used was an aeronautical-based nickel base super alloy material, Waspaloy. The model is first validated by comparison of residual stress profiles obtained by simulation and the result of the X-Ray diffraction technique published in the literature. The results of the simulation showed that an increase in shot velocity and shot size largely increases the magnitude and depth of the residual stress field created in the target plate. Also the maximum magnitude of residual stress created in the surface layer is reduced after spring-back. The present work also indicates that the proposed finite element analysis is capable for investigating the influence of various parameters on the shot peening process and this process can successfully be simulated by the finite element package ABAQUS.

Keywords: Shot peening, Residual stress field, Finite element Simulations, Spring-back, Shot impact.

Introduction

Shot peening, as a cold-working process, is one of the many techniques available to mechanically improve surface properties of components. Other techniques include grinding, lapping, super-finishing, and burnishing. The process creates strain hardening and compressive residual stress at the metallic target plate surface by plastic deformation. The objective of that compressive layer is to offset the applied stress, resulting in a benefit in terms of the fatigue surface characteristics of metal components such as fretting fatigue, stress corrosion, and corrosion fatigue. The main advantage of the shot peening process is that all surface stresses generated are of a compressive nature. It is well known that cracks will not initiate or propagate in a compressively stressed zone. Since, nearly all fatigue and stress corrosion failures originate at the surface of a part, compressive stresses induced by shot peening provide considerable increases in structural component life. Also, shot

peening has proven to be successful in retarding detrimental damage such as cavitation damage, galling, pitting, crack arrest, and stress corrosion cracking. For these reasons shot peening is mainly used in industry, particularly in the manufacture of parts as different as gears, helical springs, rockers, welded joints, aircraft parts, turbine and compressor discs, connecting rods cam shafts, torsion bars, etc. The shot-peening process consists of multiple repeated impacts of a structural component by hard spherical media. As a result of these impacts, the structural component undergoes local plastic deformation. The elastic subsurface layers should theoretically recover to their original shape during unloading. However, continuity conditions between the elastic and the plastic zones do not allow for this to occur. Consequently, a compressive residual stress field is developed in the near-surface layer of the structural component, to maintain equilibrium in the peened component, a tensile residual stress field is developed through the depth of the component. There are a significant number of parameters involved in shot peening which need to be controlled and regulated in order to produce a more beneficial compressive residual stress distribution within the component. These parameters can be sorted into three groups relating to the shot, the workpiece and the process. In order to control the resulting residual stress pattern in a peened part, it would be highly profitable to set up quantitative relationships between these parameters and residual stress characteristics. The evaluations of the shot peening mechanism are largely based on experimental work that is very difficult, tedious, costly and time consuming. The appearance of powerful finite element codes ,such as ANSYS, LS-DYNA and ABAQUS, allow simulation of dynamic processes, also modeling and numerical simulations that are not easy to perform but can provide as insight into the mechanism of shot peening during the impact of shot on the target material. The present paper aims at describing a simplified 3D finite element dynamic and static analysis of shot impacting on metallic target plate for clarifying and better understanding of the effect of shot velocity, shot size, incident angle, coefficient of friction and multiplicity of shot on compressive residual stress created by the shot-peening process. For this purpose, the finite element package ABAQUS 6.9 is used to simulate the procedure corresponding to the experimental operations.

Research Background

The shot peening process is significantly complex; the system is dynamic and includes contact mechanics. Study of contact problems of the elastic and elastic-plastic materials resulting from the loading of circular contact area of a sphere with a plane (or more generally between two spheres) was presented by Hertz [1]. Li, et al. [2] proposed a simplified analytical model for calculating the compressive residual stress field due to the shot peening process which cannot take the velocity of the shot into account and, in addition, depends on empirical parameters to develop a theoretical model. Hardy et al. [3] was the first to solve the contact problem of a rigid sphere indenting an elastic–perfect plastic half-space using the FE method. The first FE analysis of shot peening using the commercial FE program was presented by Edberg et al. [4]. Meguid et al. [5] used the ANASYS computer program and developed a three-dimensional finite element model of dynamic elasto-plastic analysis, single and twin spherical indentations using rigid spherical shots and metallic targets. He examined the effects of shot velocity, size and shape, and target characteristics on residual stress distribution in the target. Their results indicated that the effects of shot parameters were more profound than the strain-hardening rate of the target. M. Frija et al. [6] published a numerical simulation of the shot peening process using a finite element method and obtained the residual stress, the plastic deformation profiles and the surface damage. In their model, the shot was supposed to be a rigid sphere. The mechanical behavior of the subjected material was assumed to be elastic plastic coupled with damage, using an integrated form of the Lemaître and Chaboche model [7]. The shot peening loading was simulated by a static indentation, obtained by an energetic equivalence with the dynamic impact. Al-Hassani et al. [8] presented a numerical simulation of single shot impact on a component and examined single shot impacting with an oblique angle but very limited results were presented and their results verified the significant role played by non-linear

work hardening and strain rate dependency of the target on residual stress profile and extent of surface hardening. Majzoobi et al. [9] have investigated multiple shot impacts and the effect of the shot velocity on the residual stress profile by using LS-DYNA code. Their results showed that, residual stress distribution was highly dependent on impact velocity and multiplicity.

Model Description

The 3D FE model of for simulation of the shot peening process was developed using the commercial finite element code ABAQUS 6.9. The main model used in this research consisted of two parts that involved a square-shaped deformable plate and a ball. In this modeling for simplicity, also due to non-necessity analysis stress on shot body; this shot is assumed to be a fully spherical, discrete, and rigid. These assumptions greatly bring down the computing analysis time. Figure 1 shows the 3D Finite element model that was used to simulate single shot impact on a workpiece in the present paper. The geometry of the workpiece which is constant in all analysis is considered to be 1 × 2 × 2 mm. To simulate the procedure corresponding to the experimental operation, diameter and mass of shot used in the model chosen was in accordance with the standard J444 [10]. The boundary condition on the workpiece was bottom end fixed by encastre constraint. The meshes of the workpiece consist of 30056 eight-node linear brick elements with reduced integration and hourglass control (C3D8R) were used with no uniform distribution of elements along the depth by using biased seeding. Shot is meshed by using a sweep technique and quad-dominated discrete rigid element shape. Method Master-Slave algorithm contact with penalty property was chosen for contact between the shot and workpiece. The shown results consist of two runs model. The first run contains an explicit dynamic step by using an initial mesh and configuration and another run contains a static general step by using import part and update reference configuration from output first run for considers spring-back effect. The material models chosen used [6], an aeronautical-based nickel base super-alloy material, Waspaloy (based on Ni–0.04C–19.55Cr–1.37Al–2.95Ti–13.51Co–4.25Mo–0.0063B–0.06Zr (wt.%)). The mechanical properties of the material are: initial Young's modulus E = 210,000 MPa, the Poisson's ratio v = 0.3, the yield stress at 0.2% is 1000 MPa, the ultimate tensile strength is 1275 MPa, and the plastic material behavior law was determined by using the Holloman law [11] that is given by:

$$\sigma = A\varepsilon^{n} \tag{1}$$

where A and n are two material constants, identified by using the initial and ultimate stress strain values.

Figure 2 shows the stress plastic strain curve with coefficients A = 1367.11 MPa and n = 0.05 that were used for the modeling material in this paper. By exploiting symmetry in the geometry of the model only one half of the workpiece was used to simulate it, but in all of the analysis model, fully analyzed.

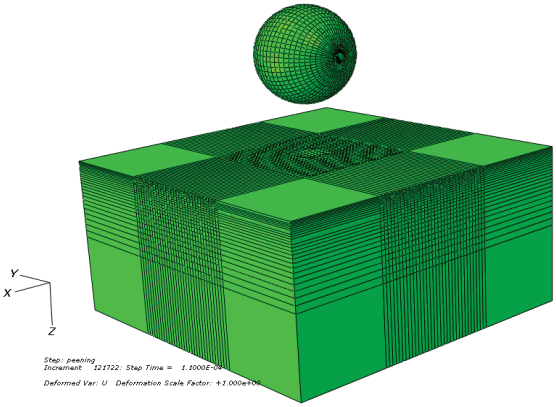

Figure 1. 3D finite element model for single shot impact on a workpiece.

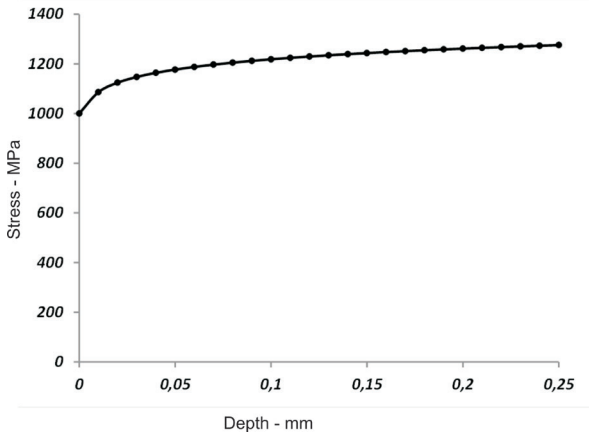

Figure 2. The used stress profile strain curve for finite element calculations [6].

Model Validation

Unfortunately, direct validation of the finite element model is not possible, because of the complexity of the process and the large number of variables associated with the peening process. So to validate the proposed model, the residual stress profile is compared with experimentally and numerically obtained data from the literature. M. Frija et al. used the following in their analysis; geometry of the part 1×1×5 mm is made of an aeronautical nickel base super alloy material with the aforementioned mechanical properties. The diameter of S230 shot was 0.6 mm with a constant velocity 52 m/s, and friction coefficient μ= 0.01 was considered between the shot surface and workpiece surface during contact. In this paper, the target and shot characteristics considered for verification were the same as those selected by M. Frija et al. and performed an explicit dynamic analysis. The mass of shot assumed m = 0.82055 mg is derived from SAE J444 and shot is dropped with a distance of 5mm from the surface workpiece. Figure 3 shows the variation of residual stress with depth along the central axis in the workpiece obtained by this modeling and also this X-ray diffraction technique and numerical results published by M. Frija et al. Figure 4 shows the result of several preliminary runs that were conducted to establish the appropriate mesh design for a convergence test model. It shows that the model using 30056 mesh elements gives more accurate results.

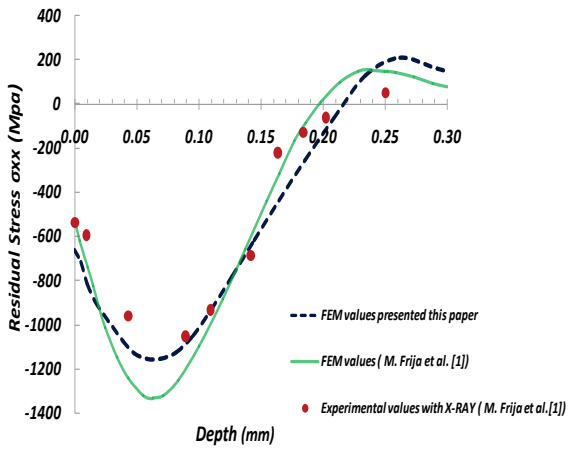

Figure 3. Validation of modeling

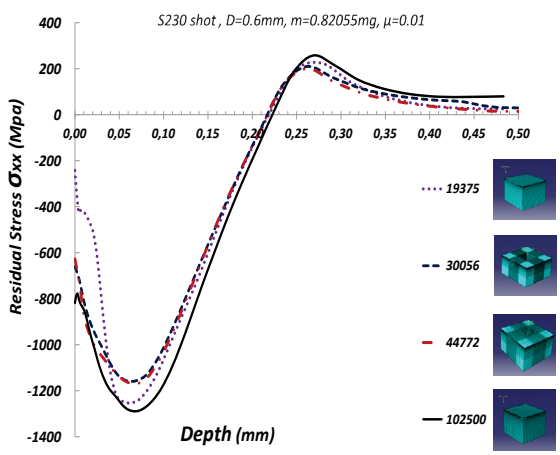

Figure 4. Convergence test model

A good correlation is observed between the three sets of results (present FE simulation, experimental and FEM values by M. Frija et al.) providing some limited validation for the

accuracy of the present analysis. The slight difference between experimental and simulation result may be attributed to the errors which may originate from the simplified modeling of a variety of parameters such as geometry of the model, one rigid shot impact, interaction type, ball constant velocity, material behavior and etc.

Shot Impact Parametric Study

The effects of key parameters: shot velocity, shot size, incident angle, coefficient of friction and multiplicity of shot on the shot peening process were examined. In all of these models the workpiece was assumed to be an elastic-plastic with isotropic hardening material.

The reference case for the study uses the identical Young's modulus, initial yield stress, ultimate tensile strength and Poisson's ratio adopted in [6] and using the density of 7800 kg/m^3 for the workpiece. Unlike the experimental process, the results of the simulation are independent of distance between center shot and workpiece surface. Therefore this distance is assumed to be 5 mm for a swift running model. The velocity of shot media is assumed to be in the vertical direction and applied to a reference point for each shot as an initial condition to the predefined field. All results were obtained from a variation of residual stress σ_{xx} along the path that is created by selecting nodes along the central axis in target plate.

Effect of Shot Velocity

The single shot finite element analysis is performed to investigate the influence of shot velocity. Five different impact velocities was used: 20, 35, 52, 80 and 125 m/s. This analysis used a rigid shot (S230) with radius R= 0.3 mm and mass M=0.82055 mg. Figure 5 shows the variation of residual stress σ_{xx} after spring-back along the mentioned path for the five impact speeds selected. Figure 5 shows that increase in the velocity of shot results in an increase in magnitude of the maximum residual stress but the maximum residual stress for the three velocities 20, 35 and 52 are very close to each other. An increase in the velocity of shot media results in an increase in the of depth of the compressed residual stress and this increase is sensible in layer with depth 0.10 to 0.30 mm of target plate.

Effect of Shot Size

The single shot finite element analysis was performed to investigate the influence of shot size by varying the shot sizes from S-170 to S-330. In this analysis rigid shot was used with diameter, mass, global size seed and number of element as shown in table 1. The impact velocity of each shot media was assumed to be a constant 52 m/s and friction coefficient μ= 0.01 was considered to exist between each shot surface and material target surface during contact. Figure 6 shows the variation of residual stress σ_{xx} after spring-back along the mentioned path for the five shot types selected. Figure 6 shows that an increase in the size of the shot media results in an increased magnitude of the residual stress created in the target plate surface and an increased depth of the compressed residual stress and also an increase in magnitude of the maximum residual stress. This increase is sensible in layers of target plate with depth of 0.1 to 0.2mm.

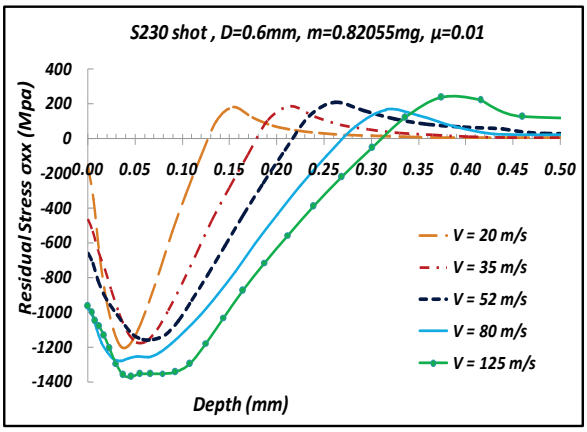

Figure 5. Residual stress profiles for 5 shot size model at velocity 52m/s.

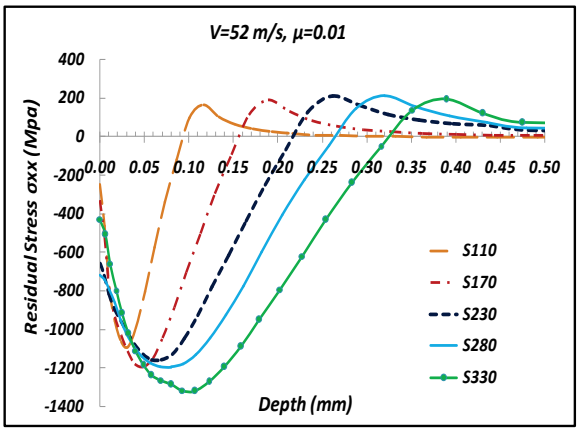

Figure 6. Residual stress profiles for 5 shot size models at the center of the workpiece.

Table 1. Shots Type Properties Used For Simulation Effect of Shot Size

Shot type	Shot Diameter (mm)	Shot Mass (mg)	Global Size Seeds of shot
S110	0.2794	0.08976	$2e^{-5}$
S170	0.4318	0.33134	$2.5e^{-5}$
S230	0.5842	0.82055	$3e^{-5}$
S280	0.7112	1.48046	$3e^{-5}$
S330	0.8382	2.42362	$3e^{-5}$

Effect of incident angle

The single shot finite element analysis was performed to investigate the influence of the incident angle. The impact velocity of shot in the X and Z direction used for simulation effects of the incident angle are shown in Table 2. Figure 7 shows the variation of residual stress σ_{xx} after spring-back along the mentioned path for five incident angles selected. It can be seen that as the incident angle decreases, the magntude of compressive surface residual stress and the compressive residual stress penetration depth decreased. These effects are becoming more evident in smaller angles.

Table 2. Velocity in the X and Z direction Used for the simulation Effect of Incident Angle

V_z (m/s)	V_x (m/s)	Incident Angle (°)
23.9848	46.1413	30
35.61	37.887	45
44.3088	27.2163	60
49.985	14.333	85
52	0	90

Effect of coefficient of friction

The residual stress profile along the mentioned path against the variable coefficient of friction is plotted in figure 8 for shot S230 with constant velocity of 52 m/s. The figure clearly shows that an increase in the coefficient of friction results in an increased magnitude of the maximum residual stress and for coefficients of friction μ ≥0.3 and depths more than 0.05 mm the effect of friction is negligible.

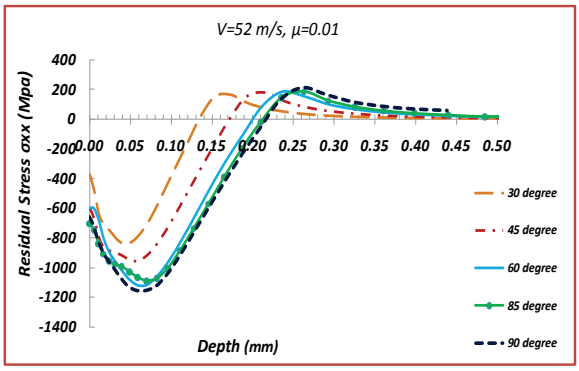

Figure 7. Residual stress profiles for 5 varying Incident Angle modes

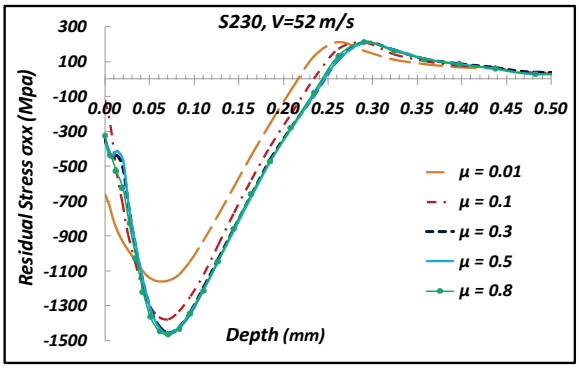

Figure 8. Residual stress profiles for 5 varying coefficient of friction models.

Effects of multiplicity shot

Investigation of the influence of the effects of multiplicity shot was carried out using models consisting of 1, 2 and 3 shots with a diameter of 0.6 mm, constant velocity of 52 m/s and friction coefficient μ= 0.01 between the shot surface and material target surface during contact. With each shot in model 2 and 3 shot was equal distance 1mm with another and with the osculate in the center of the target plate. Figure 9 shows the arrangement simulation of 2 shots and 3 shots modeling.

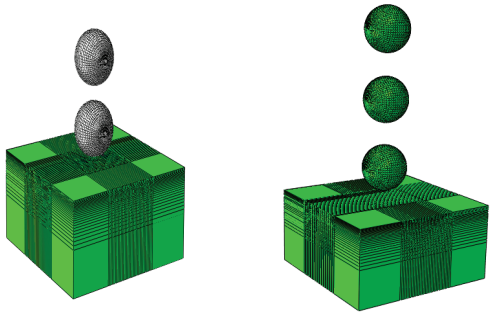

Figure 9. Arrangement simulation of 2 shot and 3 shot modeling

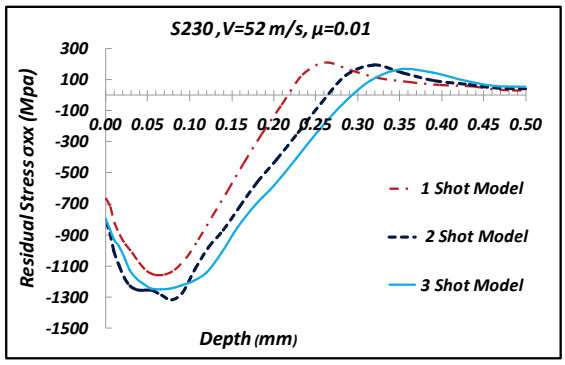

Figure 10. Residual stress profiles for 3 different shot models.

Figure 10 shows the variation of residual stress, σ_{xx} after spring-back along the mentioned path for the 3 models selected. It shows that an increased number of shot impacts on the target plate results in a moderate increase in compressive residual stress in the surface target plate and also an increase in depth of residual stress.

Discussion and Conclusions

A comprehensive 3D finite element dynamic analysis with consideration of the spring-back effect was conducted to simulate the shot peening process. The model was validated by comparison of the residual stress profiles obtained by simulation and the X-Ray diffraction results that were proposed by [6]. The effect of shot velocity, shot size, incident angle, coverage by multiplicity of shot and coefficient of friction upon the variation of residual stress, σ_{xx} after spring-back have been examined and discussed. The results reveal that increase in shot velocity largely increases the magnitude and depth of the residual stress field created in target plate. Also the increase in the shot size results in increased magnitude and depth of the residual stress field. The magntude of the compressive surface residual stress and the penetration depth of that decreased with a decrease of incident angle. Multiplicity of shot impact at the same location on the target plate gives an increase in the magnitude and depth of the compressive residual stress. An increase in the coefficient of friction between the shot surface and the target plate results in an increased magnitude of the maximum residual stress field created in the target plate. The present work also

indicates that the proposed finite element analysis is useful for the investigation of the influence of various parameters on the shot peening process. This process can successfully be simulated by the finite element package ABAQUS**.**

References

[1] Hertz H. Uber die Beruhrung fester elastischer Korper (*On the contact of elastic solids*). J Reine Angewandte Mathematik 1882; 92:156–71.

2] Li J et al. *Mechanical approach to the residual stress field induced by shot peening*. Mater Sci Eng 1991;A147:167–73.

[3] Hardy C, Baronet CN, Tordion GV. *The elasto-plastic indentation of a half-space by a rigid sphere*. Int J Numer Methods Eng
1971;3:451–62.

[4] Edberg J, Lindgren L, Mori K. *Shot peening simulated by two different finite element formulations*. In: Shen S, Dawson E, editors.
Simulation of materials processing: theory, methods and applications –NUMIFORM95; 1995. p. 425–30.

[5] S.A. Meguid, G. Shagal, J.C. Stranart, J. Daly, *Three-dimensional dynamic finite element analysis of shot-peening induced residual stresses*, Finite Element Anal. Des. 31 (1999) 179–191.

[6] Frija M, Hassine T, Fathallah R, Bouraoui C, Dogui A. *Finite element modeling of shot peening process*: prediction of the compressive residual stresses, the plastic deformations and the surface integrity. Mater Sci Eng A 2006; 426:173–80.

[7] J. Lemaˆıtre, J.L. Chaboche, *M´ecanique des mat´eriaux solides*, Dunod, 2`eme Edition, ISBN 2 10 005662X, 2002.

[8] Al-Hassani STS, Kormi K, Webb DC. *Numerical simulation of multiple shot impacts*. In: Proceedings of ICSP-7, Warsaw, Poland, 1999. p. 217–27.

[9] Majzoobi, G.H., Azizi, R., Alavi Nia, A., 2005. *A three-dimensional simulation of shot-peening process using multiple shot impacts*. J. Mater. Process. Technol. 164–165, 1226–1234.

[10] SAE J444, *Cast Shot and Grit Size Specifications for Peening and Cleaning***,** SAE Standards, May 1993.

[11] R.W. Hertzberg*, Deformation and Fracture Mechanics of Engineering Materials*, New York, 1996, p. 17, ISBN 0-471-01214-9.

[12] *ABAQUS User's Manual*, Version 6.9.1

[13] MIL-S-113165C, *Shotpeening of metal parts.*