SIMULATION OF SHOT PEENING IMPLEMENTING STOCHASTIC ASPECTS

[1]Christos Gakias*, [1]Georgios Savaidis
[1]Aristotle University of Thessaloniki, Laboratory of Machine Elements and Machine Design, Greece

KEYWORDS –
shot peening, finite element method, residual stresses, stochasticity.

ABSTRACT –
Shot peening (SP) is a widely used surface treatment process that involves the use of small spheres to impact the surface of a component, resulting in a localized deformation and the development of a compressive stress field within the surface layer. This compressive stress field can extend up to 300-400 μm in depth and significantly improve the fatigue life of the component. However, the effectiveness of the SP process can be influenced by various stochastic parameters such as the variability of shot diameters and shot velocity.
In this study, a structured modelling approach based on the Finite Element Method (FEM) is introduced to account for these stochastic parameters alongside with elastic-plastic behavior and accurately simulate the SP process. The modelling process is semi-automated, with discrete stages including problem definition, setup, simulation, and results extraction using ANSA and META software.
The validation of the model is also presented and includes comparison with experimentally determined data. The results demonstrate the effectiveness of the proposed approach in capturing important process parameters and highlighting the impact of stochasticity on the SP process. Moreover, the model was shown to be capable of examining the effect of various process parameters on the resulting surface residual stress field, which is crucial for the fatigue life of the component.
Overall, the structured modelling approach introduced in this study can provide valuable insights into the SP process and aid in the optimization of SP parameters for different applications, leading to improved fatigue life and durability of components.

TECHNICAL PAPER -

1. INTRODUCTION

Shot peening (SP) is a technique used to enhance the durability and reliability of components subjected to cyclic loading. It induces plastic deformation and compressive residual stresses on the component's surface, improving its fatigue life, strength, and resistance to crack propagation (1), (2). Computational simulation tools, such as Finite Element Analysis (FEA), have been developed to simulate the SP process and predict residual stress profiles and material responses (3), (4). However, there are still challenges in accurately modelling SP, including the implementation of realistic parameters and addressing the stochastic nature of the process (5). This paper presents a comprehensive investigation on the development of an accurate 3D SP FEA model, addressing these challenges and incorporating innovative approaches.

2. FEA MODEL DESCRIPTION AND METHODOLOGY

2.1 Computational basis

The explicit solver LS-Dyna is used for the SP process simulation due to its ability to handle high strain rates and velocities (6). Explicit analysis is necessary for dynamic events like high-velocity impacts involved in SP and offer a faster solution in events where there is a dynamic equilibrium, or otherwise:

$$\text{Sum of all forces} = \text{mass} \times \text{acceleration}$$

2.2 Shots geometry generation and FE discretization

Accurate modelling of the shots is crucial for improving the overall accuracy of the model. The study adopts an approach that incorporates different shot diameters based on sieve analysis data obtained from an automotive spring manufacturer, which are presented in Table 1 below. The random spatial distribution of shots in space and variable shot diameters are considered (7). The discretization of shots is carried out using hexahedron elements.

Table 1 – Sieve analysis for shots, obtained from automotive spring manufacturer.

Sieve opening [mm]	**Sieved out mass [%]**
1.7	7
1.18	72
0.85	11
0.6	10

During the development of the model, the need arose to develop a different and more flexible tool for the generation of the shots, due to its more demanding nature, in terms of computational power. This tool was developed using the Python programming language alongside with basic statistical packages (8). The implementation of this tool in the Application Programming Interface (API) of ANSA© pre-processor (9) led to a fast generation of the geometry of the spheres, an FE mesh creation and the application of any boundary and initial conditions. The two main points that govern this algorithm are:

- The sphere generation, with a diameter that follows the given sieve analysis data.
- The random allocation of these spheres inside a specified rectangular space domain.
- The mesh generation of the created spheres

Figure 1 provides a closer examination of the non-uniform shot diameters and their random spatial arrangement.

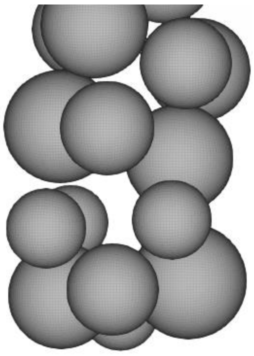

Figure 1 – Generated and meshed spheres with random position and diameter

2.3 Material modelling

The study focuses on 51CrV4 spring steel for the component and cast steel for the shots. Stress-strain curves for both materials are obtained from previous studies and current literature (10). The plasticity behaviour of the 51CrV4 material is modelled using a mixed hardening rule and strain rate sensitivity according to the Cowper-Symonds model. A damping ratio of *0.5* is chosen to account for damping effects during SP. Stress-Strain curves for both spring and shot material are presented in Figure 2 below, and key-parameters in Table 2.

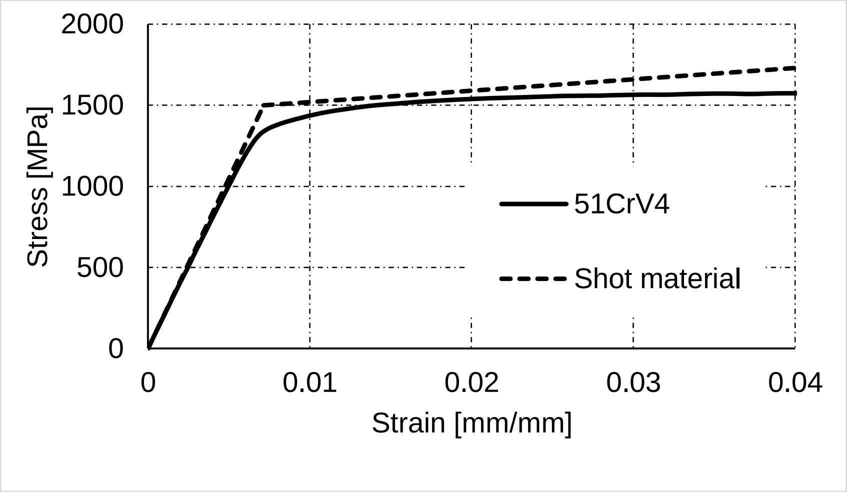

Figure 2 – Stress-Strain curves for 51CrV4 and cast steel shots.

Table 2 – Material mechanical properties.

Material Parameter	51CrV4	Shots
Young's modulus (GPa)	206	206
Yield stress (MPa)	1450	1500
Ultimate Tensile Strength (MPa)	1645	1800

2.4 Model details and FE discretization

The 3D FEA model represents a portion of the peened component with carefully chosen dimensions to balance computational cost and accurate results. The volume is discretized using finite elements, with a variable element size scheme to optimize computational time and result accuracy, starting from a fine meshed (element length of 40 μm) peened area. The specimen is fixed on each side and subjected to semi-infinite boundary conditions to simulate stress wave dissipation.

2.5 Workflow and evaluation

Moreover, in Figure 4 below, is presented the full developed model, after the setup of any above-mentioned parameter in ANSA pre-processor. Random allocate shots are also visible.

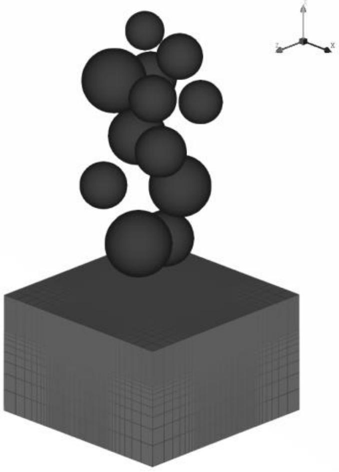

Figure 3 – The developed 3D SP model

Another crucial aspect of the present study is the integration of the developed 3D model into a semi-automated simulation process utilizing ANSA and META APIs (9), (11). This process involves meticulously gathering all parameters that impact the shot peening process and its outcomes. The comprehensive set of input data, including FE parameters such as mesh size, configuration, and boundary conditions, is then fed into the ANSA pre-processor. The model is automatically and modularly established and subsequently passed to the LS-Dyna explicit solver. Primary output parameters, such as the stress and strain tensor, are processed automatically using the META post-processor, and the relevant results are extracted.

This semi-automated process represents a significant advancement in the developed model and the overall shot peening modelling process. It possesses the flexibility to adapt to a wide range of industrial applications of shot peening and can be utilized with diverse input parameters and conditions. The flowchart depicting the modelling process is presented in Figure 4 below.

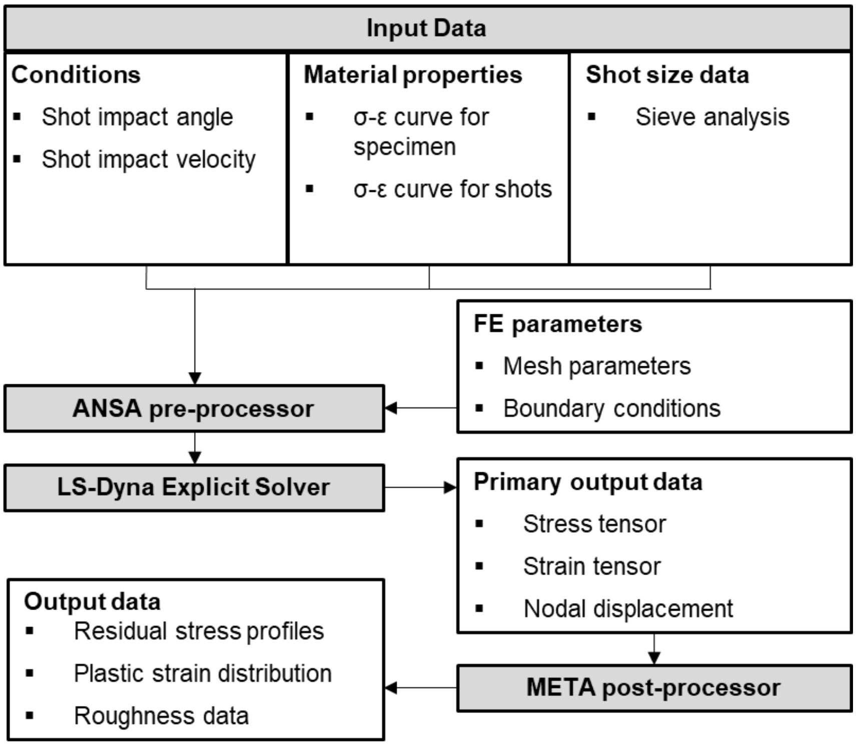

Figure 4 – Flowchart of the SP simulation procedure

3. RESULTS AND VALIDATION

Parametric studies and simulations are conducted to replicate shot peening scenarios on leaf spring specimens. Residual stress profiles and surface roughness are calculated and compared with experimental measurements. A visual example of the residual stresses and the rough, peened specimen, on META is illustrated on Figure 5 below.

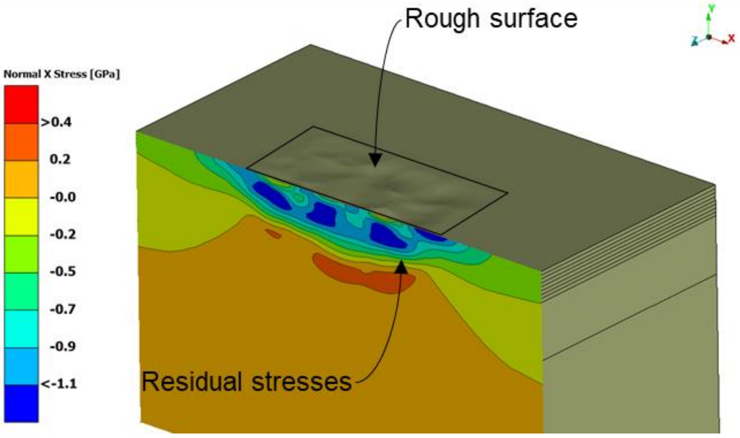

Figure 5 –Visual representation of the calculated results of SP modelling.

Two distinct peening velocities, namely 77 m/s and 64.5 m/s, were examined, with an approximate impact angle of 80 degrees relative to the vertical axis. Figure 6 below presents a qualitative illustration of the residual stress profiles, extracted from META, and the corresponding measured profiles, towards the depth from surface.

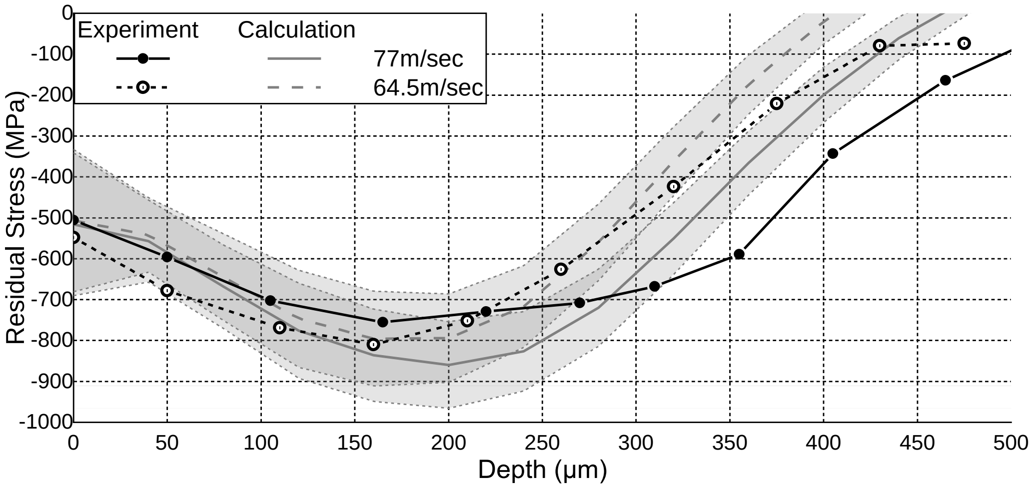

Figure 6 – Experimentally determined versus calculated residual stress profiles for two different impact velocities.

The results show that the impact velocity significantly affects the compressive residual stress profiles, with higher velocities resulting in deeper and higher stress profiles. The calculated stress profiles accurately predict the peak depth and maximum stress. Errors occur at greater depths but are considered insignificant.

The surface roughness measurements show that higher impact velocities result in higher roughness, and the calculated roughness parameters have varying degrees of accuracy. The comparison is summarized in Figure 7 below.

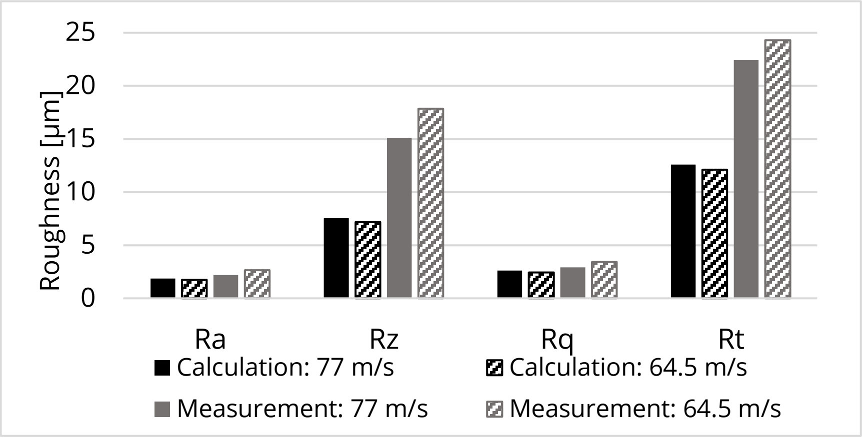

Figure 7 – Experimentally determined versus calculated roughness parameters for two different impact velocities.

4. CONCLUSIONS

Based on the evidence presented in Figures 6 and 7, it is reasonable to conclude that the proposed model demonstrates a sufficient level of accuracy. Additionally, the model showcases the capability to incorporate realistic stress shot peening conditions, faithful representation of shot impingements within complex and stochastic processes. The modular structure of the models further enables the reproduction of numerous simple shot peening scenarios.

Furthermore, shot peening plays a pivotal role in the industry, particularly in the production of leaf springs, gears and other automotive or aerospace components, as it significantly influences the quality and fatigue life of the final product. Consequently, incorporating such a modelling approach in the development of leaf springs holds crucial importance and can potentially save substantial time that would otherwise be spent on intricate experimental measurements.

FUNDING

This research was funded by Research Fund Coal & Steel, grant agreement number 799787 (12). The author would like to gratefully acknowledge the Research Fund Coal & Steel.

ACKNOWLEDGMENTS

The authors would like to gratefully acknowledge the Research Fund Coal & Steel.
BETA CAE is gratefully acknowledged for the provision of ANSA and META software.

REFERENCES

(1) Almer, J., Cohen, J., & Moran B. (2000). The effect of residual macrostresses and microstresses on fatigue crack initiation. Materials Science Engineering, 17, 286-279.
(2) De los Rios, E., Walley, A., & Milan, M. (1995). Fatigue crack initiation and propagation on shot peened surfaces in A316 stainless steel. International Journal of Fatigue, 284, 493-499.
(3) Al Hassani, S. T. S. (1999). Numerical simulation of multiple shot impact. 7th International Conference on Shot Peening, Warsaw, Poland.
(4) Hong, Y. M. (2010). Numerical and Theoretical Study of Shot Peening and Stress Peen Forming Process. Montreal, Canada: Universite de Montreal
(5) Luo, P., et al. (2017). Literature Review on State of the Art in Shot Peening in the Last Decade (2006–2015). Advanced High Strength Steel and Press Hardening, 406-419
(6) LS-DYNA Manual R11.0, Vol I/II/III, October 2018
(7) Gakias, C., Maliaris, G., & Savaidis, G. (2022). Investigation of the Shot Size Effect on Residual Stresses through a 2D FEM Model of the Shot Peening Process. Metals, 12, 956.
(8) sFEre package for generation and FE mesh of spheres, https://github.com/lmemd/sFEre, 2022
(9) ANSA version 21.1.3 User’s Guide, BETA CAE Systems, May 2021
(10) Maliaris, G., Gakias, C., Malikoutsakis, M., & Savaidis G. (2021). A FEM-Based 2D Model for Simulation and Qualitative Assessment of Shot-Peening Processes. Materials, 14, 2784.
(11) META version 21.1.3 User’s Guide, BETA CAE Systems, February 2021
(12) LIGHTTECH—Innovative Approaches of Stress Shot Peening and Fatigue Assessment for the Development of Lightweight, Durability-Enhanced Automotive Steel Leaf Springs. Research Fund Coal & Steel, GA 799787. https://lighttechproject.com/