Simulating Shot Peening: Application on leaf springs

Christos Gakias[1], Georgios Savaidis[1]

[1] Aristotle University of Thessaloniki, Laboratory of Machine Elements and Machine Design, Greece

Abstract

Shot peening (SP) is a widely used process of surface treatment, based on the impact of small spheres (shots) on the surface of a component. The impact results on a localized plastic deformation and the development of a compressive residual stress field, that can extend up to a depth of 300-400 μm. This stress field significantly improves the fatigue life of components and prevents the initiation of small cracks. SP treatment can be influenced by various parameters, such as the velocity of shot peening media, many of them, governed by stochasticity. 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. Explicit calculation scheme and sophisticated plasticity modelling algorithms are used, that are implemented in LS-Dyna solver. A validation of the model is presented, including a comparison with experimentally derived residual stress profile. These results demonstrate the efficiency of the proposed model and highlights the capabilities of the model to capture accurately the effect of the process. Furthermore, the model was also shown to be capable of examining the effect of the process parameters, such as the shot velocity. Overall, the structured and modular modelling approach that is proposed in this study can provide valuable information of the results of the SP treatment and can lead to a further understanding and optimization of the process in general.

1 Introduction

Shot peening (SP) stands as a valuable technique in enhancing the durability and reliability of components exposed to repetitive loading, including leaf springs. A qualitative depiction of the shot peening process is illustrated on Figure 1 below. Two rotating wheels are illustrated, which they throw multiple number of shots on the leaf spring, under high velocity. By inducing controlled plastic deformation and compressive residual stresses on the surface of leaf springs, SP substantially elevates their fatigue life, overall strength, resistance on crack propagation [1], [2]. Computational simulation tools like Finite Element Analysis (FEA) have been honed to replicate the SP process, enabling the projection of residual stress distributions and material retorts [3], [4]. However, there are still some obstacles when it comes to making an exact 3D SP FEA model. These include things like setting realistic values and dealing with the randomness of the process [5]. This paper dives into a detailed investigation of creating a precise 3D SP FEA model. It deals with these issues and brings in new approaches.

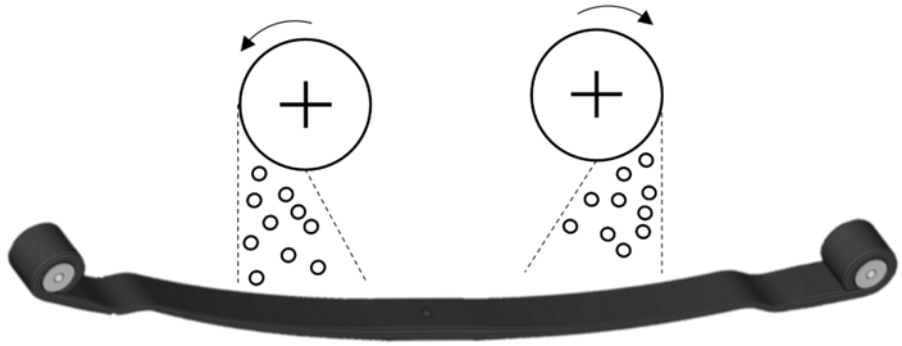

Fig.1: Qualitative illustration of shot peening process on leaf spring.

2 FEA Model description

The 3D FEA simulation depicts a part of the leaf spring, with dimensions selected thoughtfully to find a compromise between computational efficiency and accurate results. The object's volume is divided into finite elements, utilizing elements of varying sizes to improve computational efficiency. This process begins with a finely meshed region (with element length of 40 μm) where peening occurs. The sample is constrained on both ends and exposed to semi-infinite boundary conditions (**`*BOUNDARY_NON_REFLECTING`**) [6] to ensure the stress wave dissipation. Moreover, in Figure 2 below, is presented the full developed model.

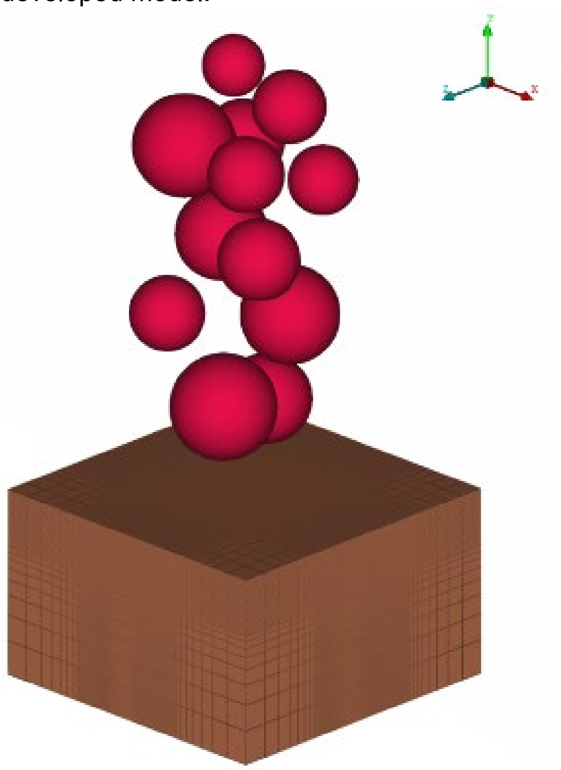

Fig.2: The developed 3D SP model.

2.1 Shots geometry generation

Precise simulation of shots is critical for enhancing overall model accuracy. It is evident in Figure 2 above, that the shots are neither equal in size, nor allocated in predefined positions. The study employs a strategy that integrates diverse shot diameters, informed by sieve analysis data from an automotive spring manufacturer (detailed in Table 1). This integration accounts for the random spatial distribution of shots in a designated rectangular space, while accommodating variable shot diameters [7]. The discretization process employs hexahedron elements.

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

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

To address heightened computational demands, a distinct and more adaptable tool was developed using the Python programming language and fundamental statistical packages [8]. Consequently, it enables swift generation of spherical geometry, creation of finite element (FE) meshes, and application of boundary and initial conditions. The algorithm chiefly centers on two key aspects: first, generating spheres with diameters aligned with the provided sieve analysis data, and second, randomly situating these spheres within the specified rectangular domain. Furthermore, the algorithm handles the mesh generation for the generated spheres, further refining the simulation's accuracy and efficiency.

2.2 Material modelling

The research centers on the utilization of 51CrV4 spring steel as the component material and cast steel for the shots. Stress-strain graphs for both materials are acquired from prior investigations and current literature [9]. The plastic deformation characteristics of the 51CrV4 material are simulated through a mixed hardening rule of Chaboche and Voce and strain rate sensitivity, conforming to the Cowper-Symonds model (**`*MAT_DAMAGE_3`**)[6]. A damping ratio of 0.5 is chosen to account for damping effects during SP. Moreover, the shots are assumed to be elastic-plastic, so their plastic deformation characteristics were simulated using a simple multilinear plasticity material model (**`*MAT_PIECEWISE_LINEAR_PLASTICITY`**)[6].
Stress-Strain curves for both spring and shot material are presented in Figure 3 below, and key-parameters in Table 2.

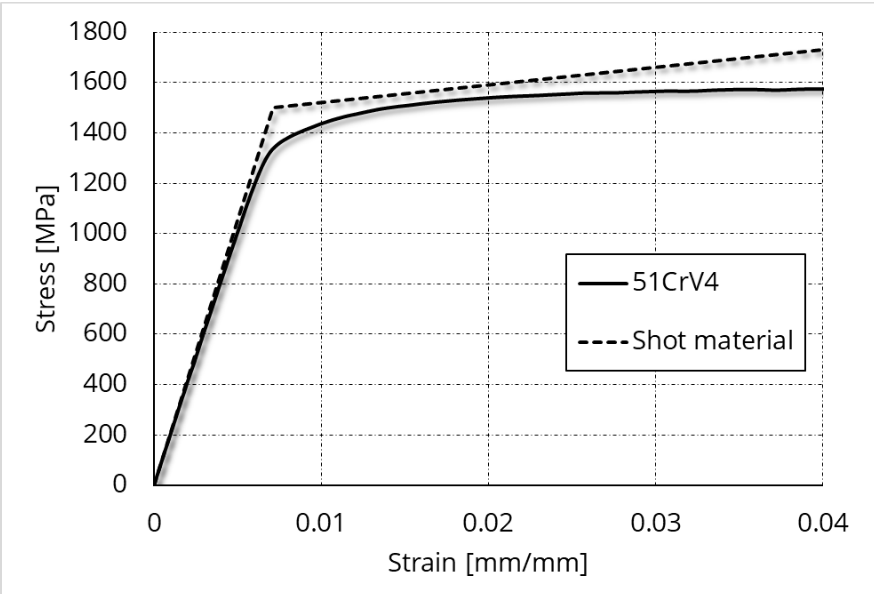

Fig.3: Stress-Strain curves for 51CrV4 and cast steel shots.

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

Table 2: Material mechanical properties.

3 Results

Parametric investigations and simulations are carried out to recreate shot peening conditions on samples of leaf springs. Profiles of residual stress and surface roughness are computed and then juxtaposed with empirical measurements. A visual representation of residual stresses, along X axis and the rough, peened sample can be observed in Figure 4 depicted below.

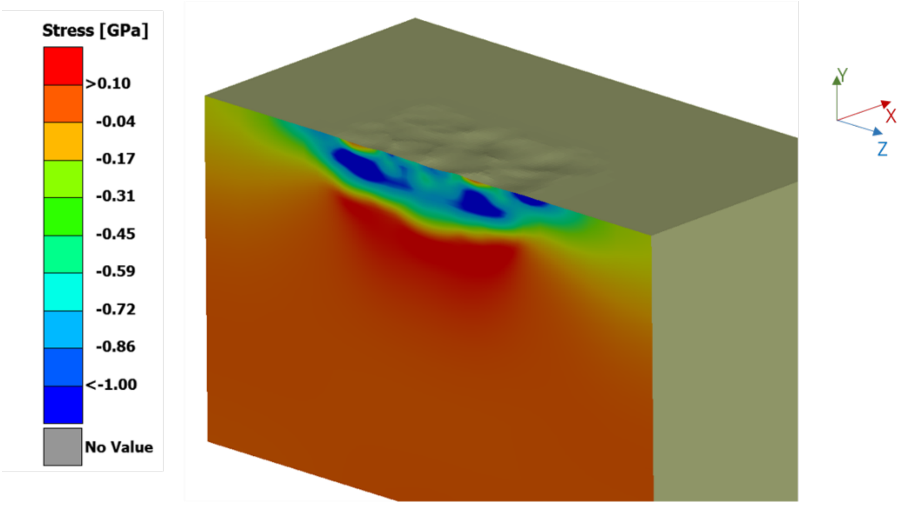

Fig.4: Visual representation of the calculated stress of SP modelling.

Two different peening speeds, specifically 77 m/s and 64.5 m/s, were investigated, while maintaining an approximate impact angle of 80 degrees in relation to the vertical axis. Figure 5 below provides a visual representation of the residual stress profiles obtained from the FE model, along with the corresponding profiles obtained through measurement, as they vary with depth from the surface.

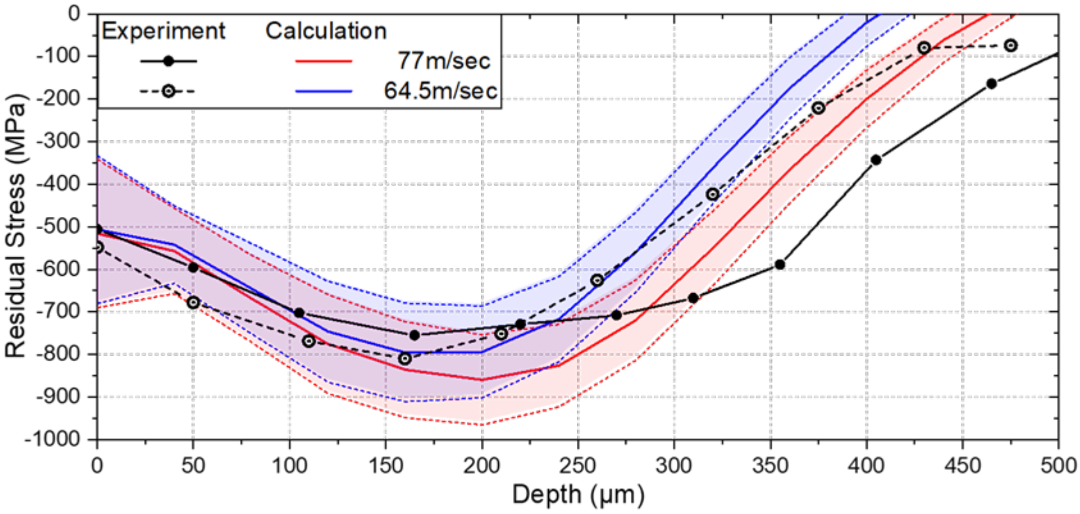

Fig.5: Experimentally determined versus calculated residual stress profiles for two different impact velocities.

The findings indicate that the impact velocity has a notable impact on the profiles of compressive residual stress. Elevated velocities lead to greater depths and increased stress levels in these profiles. The stress profiles derived from calculations precisely anticipate the highest stress levels and the depths at which they occur. Calculated stress values at greater depths are diverging from the corresponding measured values, but the difference is considered negligible.

The evaluations of surface roughness reveal that heightened impact velocities correspond to greater roughness levels. The precision of the calculated roughness parameters varies. A synopsis of this comparison is provided in Figure 6 displayed beneath.

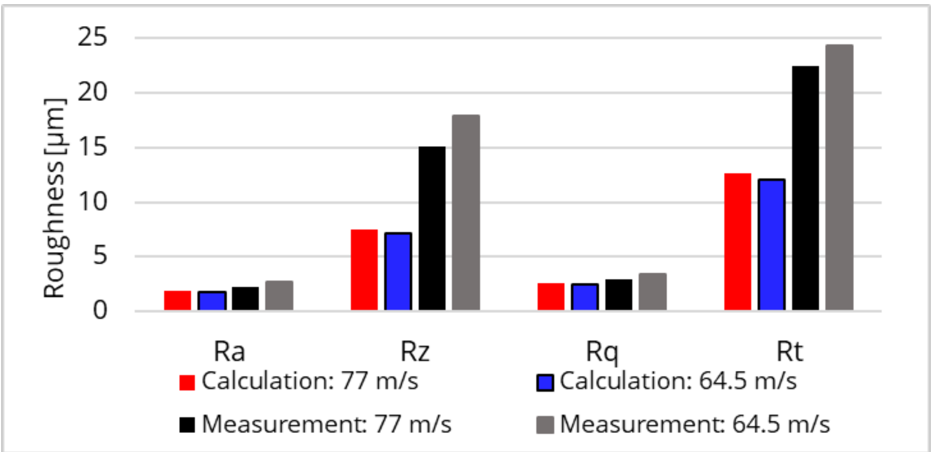

Fig.6: Experimentally determined versus calculated roughness parameters for two different impact velocities.

4 Summary

Based on the data displayed in Figures 5 and 6, a reasonable deduction can be made that the proposed model exhibits an adequate level of precision. Moreover, the model illustrates its capacity to integrate lifelike stress conditions for shot peening, accurately representing the impacts of shots in intricate and uncertain processes. The modular arrangement of the models also facilitates the recreation of various uncomplicated shot peening scenarios.

Furthermore, the role of shot peening bears great significance in industries, especially in fabricating leaf springs, gears, and other automotive or aerospace parts, due to its substantial impact on the final product's quality and fatigue endurance. Consequently, the inclusion of such a modeling approach in leaf spring development holds pivotal importance and has the potential to considerably economize time otherwise expended on intricate experimental assessments.

5 Funding

This research was funded by Research Fund Coal & Steel, grant agreement number 799787 [10]. The author would like to gratefully acknowledge the Research Fund Coal & Steel.

6 Acknowledgments

The Center for Interdisciplinary Research and Innovation (CIRI AUTH – KEDEK, DRAM Group) is gratefully acknowledged.

BETA CAE is gratefully acknowledged for the provision of ANSA and META software.

7 Literature

References should be given in the last paragraph of your manuscript. Please use following scheme:
[1] Name, Abbreviation of first name: "publication", issue, year, pages
'

[1] Almer, J., Cohen, J., & Moran B. “The effect of residual macrostresses and microstresses on fatigue crack initiation.” Materials Science Engineering, 17, 2000, 286-279.
[2] De los Rios, E., Walley, A., & Milan, M. “Fatigue crack initiation and propagation on shot peened surfaces in A316 stainless steel”. International Journal of Fatigue,” 284, 1995, 493-499.
[3] Al Hassani, S. T. S. “Numerical simulation of multiple shot impact. 7th International Conference on Shot Peening, Warsaw, Poland, 1999
[4] Hong, Y. M. “Numerical and Theoretical Study of Shot Peening and Stress Peen Forming Process.” Montreal, Canada: Universite de Montreal, 2010
[5] Luo, P., et al. “Literature Review on State of the Art in Shot Peening in the Last Decade (2006–2015)”. Advanced High Strength Steel and Press Hardening, ,2017, 406-419
[6] LS-DYNA Manual R11.0, Vol I/II/III, October 2018
[7] Gakias, C., Maliaris, G., & Savaidis, G. “Investigation of the Shot Size Effect on Residual Stresses through a 2D FEM Model of the Shot Peening Process”. Metals, 12, 2022, 956.
[8] sFEre package for generation and FE mesh of spheres, https://github.com/lmemd/sFEre, 2022
[9] Maliaris, G., Gakias, C., Malikoutsakis, M., & Savaidis G. “A FEM-Based 2D Model for Simulation and Qualitative Assessment of Shot-Peening Processes.” Materials, 14, 2021, 2784.
[10] 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/