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Shot peening modeling and simulation for RCS assessment

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Abstract

The application of shot peening to components and structures induces residual compressive stresses (RCS) on the surface. It has also been identified that fatigue, corrosion fatigue (CF) and stress corrosion cracking (SCC) are lifted by RCS. However, failures still occur in local areas of shot peened components under service conditions at stresses below the yield strength of the material. This calls for a real assessment of the distribution of stresses in the shot peened component for enhanced prediction of induced RCS. This report is the first part of an ongoing research aimed at establishing a simplified methodology for a realistic simulation of the shot peening process and the accompanying residual stress by combined DEM-FEM approach. In this paper, the authors have replaced the transient analysis used in past DEM-FEM approach with a simpler static structural analysis. The results obtained are validated with similar experimental results available in literature. This will serve as a reliable tool for more accurate analysis/prediction of the service life of shot peened components and for enhancement of shot peening application as a life-extension remedy to critical engineering components.

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Keywords: discrete element method(DEM), finite element method(FEM), modelling and simulation, residual compressive Stress (RCS), shot peening (SP).

1. Introduction

The shot peening (SP) process is a mechanical surface treatment in which the creation of a beneficial residual compressive stress state is produced by an imposed cold working with accompanying tiny surface dents due to

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random impact of small balls as shown in figure 1 below. Its application results in improved fatigue / corrosion fatigue resistance, by eliminating / reducing steady tensile stress at the surface of the component when load is applied. This reduces severe causes of cracking by fatigue, corrosion fatigue and stress corrosion cracking. Generally, there is an enhanced service life of the component. As a result of the highlighted benefits indicated above much experimental work, analytical and numerical modeling has been carried out to attempt the optimization of the SP process, and to proffer better understanding of its stochastic nature. Yet questions as to what extent the SP parameters influence the depth/magnitude of the induced compressive stress/surface hardening, and how stable is the RCS under service conditions are still not clear. Also the issue of coverage when complex geometry such as the root of a turbine blade is shot peened and how it affects the service performance of the component are yet to be answered.

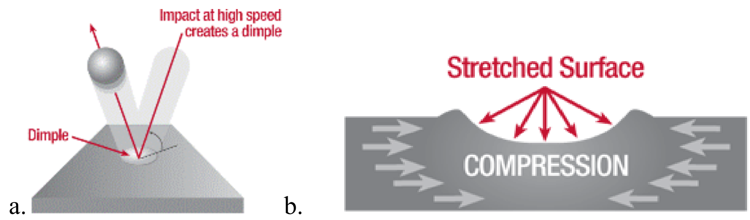

Fig. 1. (a) Interaction of shot peening ball and a metallic surface; (b) resulting compressive stress and deformation of target surface.

Nearly all fatigue and stress corrosion failures originate at the surface of a part, but cracks will not initiate or propagate in a compressively stressed zone, as represented schematically in Fig. 1. Due to overlapping dimples from shot peening, a uniform layer of compressive stress is created at metal surfaces, thus enhancing service life of the component, however, shot peened components still fail at operating conditions below their fatigue strength. There are other related surface enhancement processes such as laser peening and low plasticity burnishing which induces deeper greater residual compressive stresses without the associated pitfalls with shot peening application, notwithstanding shot peening is still the most economical and practical method of ensuring surface residual compressive stresses, especially with large components.

Research and development for shot peening is focused on two areas. The first area is devoted to researching the effects of coverage, saturation, and intensity on the fatigue behaviour of a shot peened structure and surface forming capability. The second is prediction and measurement of the residual stress via analytical, numerical or experimental research. Coverage is simply the fraction of area peened during a specified time. Saturation is reached when doubling the shot peening time does not result in more than 10% increase in arc height (deflection of a metal strip). The intensity is directly related to the energy of the shot stream. An intensity measurement corresponds to how much a standard metal strip, known as an Almen strip, will deflect (bow) depending on the chosen parameters such as pressure, shot velocity and size. An understanding of the influence of these parameters on the SP process is needed for its optimization and control in the manufacturing of components.

A large number of studies have been performed on shot peening experimentally [1, 2]. In this approach, parts are shot peened with a set of peening parameters for a certain coverage. Then these parts are subjected to fatigue testing. If the fatigue performance is adequate, then the subsequently manufactured parts are also subjected to the same peening conditions. However, the determination of peening parameters needs to be repeated through further experimentation if the part does not meet the expected fatigue life, which is very expensive. This made way for analytical study of the process [3,4]. These analytical methods involve complex mathematical analysis which are less expensive but difficult to implement due to much simplified assumptions which compromises their effectiveness when applied to complex geometry. Good enough, with numerical simulations making use of computers, the shot peening process has become a very attractive subject leading to a vast number of proposed models [5-9], with better understanding of the complex phenomenon. Very recently, wonderful attempts have been made [8,10] to bring these models and their simulation very close to reality. It is therefore the objective of this paper to further simplify previous DEM-FEM approaches [7,8] by replacing the transient structural analysis with a static structural analysis. This effort which is the first part of an ongoing research will easily make way for further analysis of shot peened components and structures during their manufacture, and implementation of life-extension strategy such as re-peening during service-life of a peened component.

2. Proposed DEM-FEM approach

The DEM-FEM approach proposed herein is an offshoot from the work reported in [8], but using static structural analysis with Ansys (load-steps approach) instead of transient analysis which takes more time and computer hard disc space. A simplified work-flow of the proposed approach is shown in figure 2.

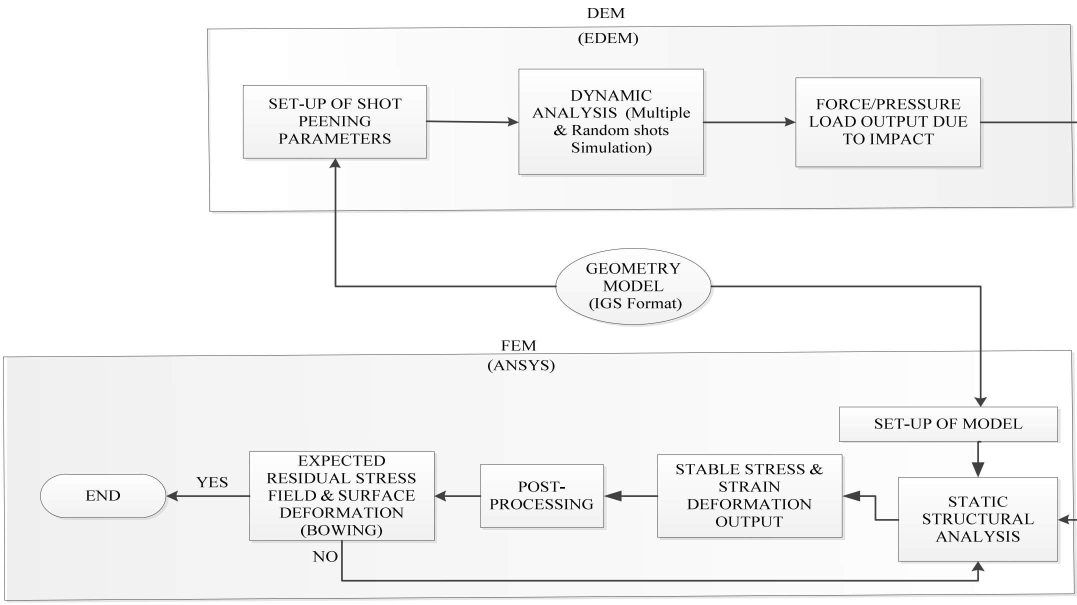

Figure 2. Data flow between DEM and FEM simulation

2.1. Almen strip for SP simulation

In line with the purpose of this study, which is to demonstrate the applicability of the proposed DEM-FEM approach for a simplified SP simulation, the Almen strip type-A whose properties are shown in Table 1 along-side with that of the shot used has been considered because of the importance of the strip in determining the intensity and saturation of the peening process.

Table 1. Material properties of shot and Almen Strip.

Property	Almen Strip (SAE 1070)	Rigid Shot (Cast Steel)
Size (mm)	76x19x1.29	0.6
Elastic modulus (GPa)	205	N/A
Density(kg/m*3)	7800	7800
Hardness (HRC)	44-50	40-55
UTS (MPa)	1270	N/A
Yield Strength (MPa)	1120	N/A
Poisson's ratio	0.3	0.3

2.2. DE Model

The Edem commercial code was used in performing the DEM simulation based on its capability for dynamic impact process as obtained in shot peening being considered, without the limitations associated with the FEM in the area of random and multiple shots. Though, its material base is purely elastic, the elasto-plastic material response of typical metals is being captured with the definition of variable co-efficient of restitution (CoR) or the use of an average value in the Edem model. It has been shown in [8] that CoR is not constant, but varies with velocity of impact and the hardening effect of cold working. The strain hardening effect of the process is captured by assigning an average value of 0.57 for CoR, the strain-rate effect was accommodated by assigning different types of shots with different CoRs for corresponding velocities in the Edem nozzle/factory design, that is 0.6 – 0.45 corresponding to 25 m/s – 100m/s [12]. The system flexibility for multiple nozzles design, all at 90^{o} target angle but with different shot parameters assigned made this possible. A total mass flow rate of 42 kg/min with average spray velocity of 70 m/s equivalent to that of an industrial air-pressure peening machine was utilized. Peening was done for a total of 7 seconds comprising of two passes along the length of the strip to and fro.

2.3. FE Model

Since Edem cannot analyse the Almen strip response to the surface impacted force/pressure, the captured force is therefore exported to surface of the same geometry in Ansys for static structural analysis so as to quantify the induced residual compressive stress and the resultant bowing of the strip, which plays a major role in the quality control of the shot peening process. Assuming elasto-plastic material model for the strip with isotropic hardening behaviour, the residual compressive stress was developed by applying appropriate boundary constrains to the geometry, which depicts the real situation of shooting an Almen strip constrained by the Almen holder. The applied constrains were technically released to simulate the removal of the strip from the holder, whereby allowing the bowing of the same after the peening process. Figure 3 shows a plan view of an Almen strip held by four pretension bolts to the Almen holder, ready for shot peening. The force load was imported with time corresponding to DEM peening time, unto the top face of the constrained geometry similar to the effect of shot peening the strip in its holder, followed by structural analysis carried out in steps for 7.5 seconds with removal of the constrains after the loading time of 7 seconds, to obtain the resultant spring back of the strip (bowing) and the RCS.

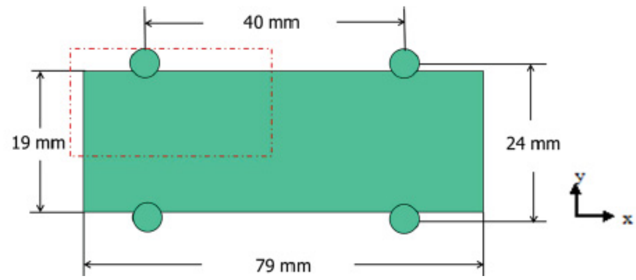

Figure 3. Plan view of strip under constrained condition in its holder [10]

All four vertical surfaces were constrained only to be displaced along x and z-axis throughout the simulation time, while displacement of the shot peened face (top-face) is allowed only along the x-axis, and the bottom face in contact with the holder was fixed for the peening time duration of 7 seconds but released thereafter. The imported force load (Minimum 36.886 N and Maximum 76.989 N) was analysed in steps of 0.5 seconds while the complete geometry was meshed with 0.3 mm rectangular mesh size.

3. Validation of result

The residual stress profile obtained with Ansys (FEM simulation) was compared with experimental results of similar shot peening parameters - mean shot velocity of 70 m/s, 0.6 mm shot size, 90° Nozzle target angle, 20 mm stand-off distance, and two passes of a total time of 7.2 s, along the length of the strip. The figure 4 shows the Almen strip spring-back of an approximate height 0.3mm, and the figures 5 and 6 are the stress profiles of both numerical and experiment results being compared.

Fig 4: vertical deflection of the Almen strip of a total of height of 0.2625mm.

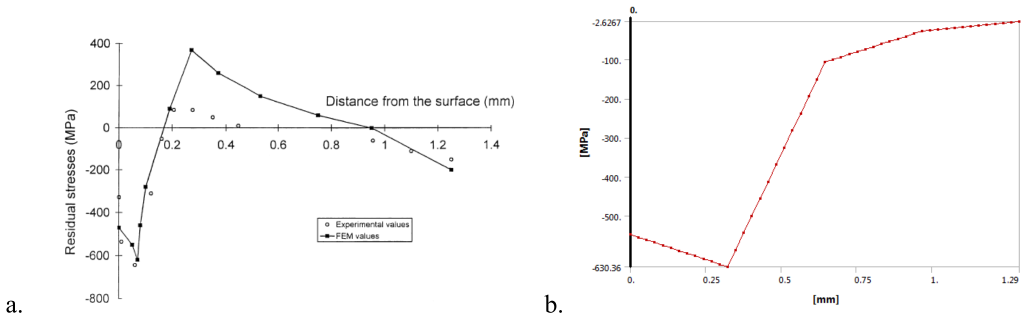

Fig 5: Residual stress profile obtained on Almen strip A, with shot size 0.6mm, at intensity 12A: (a). Published experimental result [11]. (b). Numerical result obtained with the proposed FEM-DEM simulation.

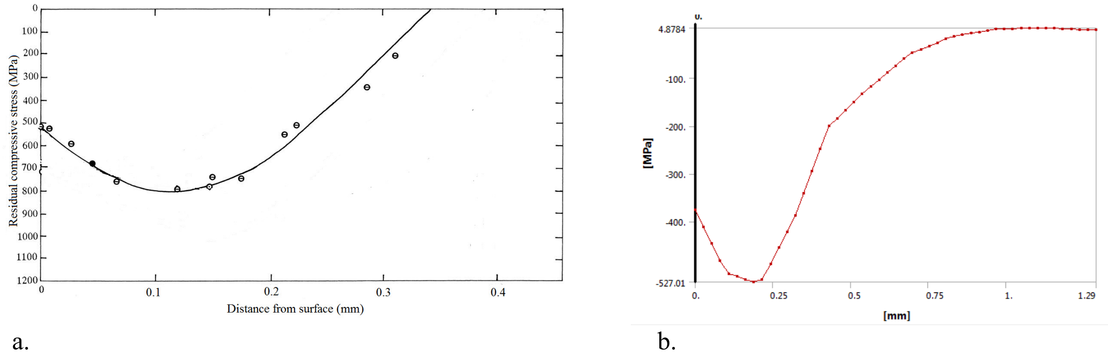

Fig 6: Residual stress profile obtained on Almen strip A: (a). Published experimental result, with shot size 0.8mm, at intensity 16A, [1]. (b). Numerical result obtained with the proposed FEM-DEM simulation with shot size 0.8mm, at intensity 12A.

Figure 5a and 5b show results of stress profile obtained with the same peening parameters from published experimental work in literature and the proposed DEM-FEM method, respectively. There was no significant difference between both results. The same applies to figure 6a and 6b with a slight difference in the magnitude of the residual compressive stress both at the surface and the maximum below the surface. This is due to the difference in the intensities (that is 16A and 12A) applied in these two cases.

4. Conclusion

A DEM-FEM approach has been described in detail for the simulation of a realistic shot peening process. The simulation consists of two distinct parts which include a dynamic analysis using EDEM and a static analysis using Ansys. This approach which is simpler with lesser computer simulation time when compared with previous techniques, proves capable of predicting the residual compressive stress and cold worked depth for a specified process parameter. This work which is the first part of an on-going research, attempt to develop a robust method for shot peening optimization and application in the design, manufacturing and integrity management of components and structures, thereby enhancing further investigation of their response to service conditions such as fatigue, corrosion fatigue typical of turbine blades materials. The ease of applying this technique to shot peening simulation makes room for effective integrity management of critical assets where re-peening is an option for life extension.

References

[1] S. Wang, Y. Li, M. Yao, R. Wang. Compressive residual stress introduced by shot peening. Journals of Materials Processing Technology, 73 (1998) 64–70.

[2] M. Kobayashi, T. Matsui, Y. Murakami. Mechanism of creation of compressive residual stress by shot peening. Int. J. Fatigue. 20(5), 1998, 351-357.

[3] H.Y. Miao, S. Larose, C. Perron, M. Levesque. An analytical approach to relate shot peening parameters to Almen intensity. Surface & Coating Technology. 205(2010) 2055-2066.

[4] J.K. Li, Y. Mei, W. Duo. Mechanical approach to the residual stress field induced by shot peening. Materials Science and Engineering. A 147(1991) 167-173.

[5] T. Hong, J.Y. Ooi, J. Favier, et. al. A Numerical Simulation to Relate the Shot Peening Process Parameters to the Induced Residual Stresses, in V. Schulze & A. Niku-Lari, ed.,'Proc. of the 9th Int. Conf. on Shot Peening', iitt, Noisy-le-Grand, (2005) pp. 100-106.

[6] S.A. Meguid, G. Shagal, J.C. Stranart. Development and Validation of Novel FE Models for 3D Analysis of Peening of Strain-Rate Sensitive Materials', J. Eng. Mater. Tech. 129(2), (2007), 271-283.

[7] K.Murugaratnam, S. Utili, N. Petrinic, A combined DEM-FEM numerical method for shot peening parameter optimization, Advances in Engineering Software 79 (2015) 13–26.

[8] B. Bhuvaraghan, S. Srinivasan, B.Maffeo, R.McCLain, Y. Potdar, O. Prakash, Shot peening simulation using discrete and finite element methods, Advances in Engineering Software 41 (12) (2010) 1266–1276.

[9] B. Bhuvaraghana, S. Srinivasanb, B. Maffeo, Numerical simulation of Almen strip response due to random impacts with strain-rate effects, International Journal of Mechanical Sciences 53 (6) (2011) 417–424.

[10] Z. Chen, F. Yang, S.A. Meguid. Realistic finite element simulations of arc-height development in shot-peened Almen Strips, J. Eng. Mater. Tech. vol 136 / 041002, (2014), Transactions of the ASME.

[11] M. Guagliano. Relating Almen Intensity to Residual Stresses Induced by Shot Peening: A Numerical Approach. J. Mater. Process. Technol., 110(3), (2001) pp. 277–286.