An approach to relate shot peening finite element simulation to the actual coverage

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1. Introduction

Among the common fatigue life improvement techniques, shot peening is widely used due to its simplicity, economical cost and applicability to variety of targets. Shot peening is carried out by firing small spherical shots with a velocity of 20–100 m/s against a target surface. Tensile residual stress developed during the manufacturing process can be completely converted to a compressive one by shot peening and stress rising due to notches could be fully counterbalanced using optimum process parameters.

The beneficial effects of shot peening on fatigue life are attributed to compressive residual stress and surface work hardening [1–3]. With the variety of processing parameters in shot peening however, selection of the most suitable and optimum ones to achieve a given degree of improvement is always a matter of question in the designers' mind. An accurate analytical or numerical assessment could be an inexpensive and at the same time reliable method to answer.

"There is still a huge lack of knowledge. We are only just entering the area of mechanics of shot peening." Al-Hassani used these words at the end of his analytical analysis of a target impinged upon by a single sphere, three decades ago, to emphasize on the complexities of the process involving many disciplines of static and dynamic elasticity and plasticity [4]. At that era shot peening was not known to everyone and also very limited works and researches were available. His simple formulas and those published by Al-Obaid [5,6] were the first relations which correlated depth of plastic zone and residual stress to density of shot, velocity of impact, thickness and hardness of the target.

Noteworthy differences of dent shape and residual stress in static and dynamic indentation test [7] demonstrated that dynamic effects of shot peening cannot be ignored. This issue increases the complication of analytically analyzing the process. Numerical methods such as finite element, thanks to rapid progress of computer power in the last decade, have been efficiently utilized for analyzing of involved process. Simulation of one spherical shot Impingement on an elasto-plastic target has been widely used for determination of the shot peening induced residual stress [8–13]. A cube of 7R width (R is the shot radius.), 4R height and 5R breadth [8] and a cylinder of 8R radius and 3R height [13] have been proposed as suitable geometries of an arbitrary target upon which impingement of one shot takes place. Although these single shot impingement models could not simulate a realistic peening, they drew a preliminary good perception of shot velocity and size effects on plastic zone development, its growth and unloading residual stress. Examination of twin spherical indentation using the finite element model [14] revealed the significant effect of separation distance between two shots upon residual stress field which in turn introduced multiplicity of shots as a serious topic to be considered in finite element simulations. Situation of a large number of identical shots impinging a metallic target has been envisaged by symmetry cell approach [15]. The dimensions of the proposed symmetry cell were $C \times C \times H$ where C is one half of separation distance between adjacent shots and could be considered as representative of the coverage in the peening. Shot peening of the symmetry cell can be regarded as the impingement of identical shots with a symmetry layout inside each row. These rows were further combined in series of four rows that in each impingement

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upon the target surface one single shot comes into contact with one corner of the symmetry cell. A general realistic residual stress induced by shot peening has been successfully and efficiently calculated [16] by application of the four impacts symmetry cell combined with the idea of averaging the nodal residual stresses at each depth. Using another shot sequence, Majzoobi et al. [17] developed a nine impacts symmetry cell model and studied the variation of in depth residual stress profile in different points of the target. Increasing the number of impacts, they found that a uniform state of in depth residual stress could be achieved in different points of target at particular number of shots. However, this particular number of shot impact is certainly a problem dependent parameter and would change for different peening conditions. More recently, a random location of shots in finite element model has been utilized to simulate nano-crystallization by shot peening [18]. Good agreement between simulated and experimentally measured residual stress distribution affirmed that random locations for shot can be a good alternative for simulation of more realistic shot peening process.

A brief look on the way in which numerical simulation goes through as compared by that of practical shot peening, discloses a lack of straightforward terminological correlation between simulation and practice. Numerical simulators are presenting their own results in terms of shot velocity and size while shot peening industries are more interested in other parameters. There are two important practical parameters that have been universally accepted and adopted by engineers in order to ensure repeatability of the process: I) intensity and II) coverage. Intensity is an index of transferred kinetic energy from stream of shots to the target and coverage indicates the amount of target surface that is treated by shots. If a reliable selection of shot peening parameters to meet a given function is supposed to be a mission of numerical simulation, there is no escape but incorporation of intensity and coverage into numerical simulation of shot peening.

A procedure to relate the values of Almen-scale, which is indicator of intensity, to the residual stresses in metal parts have been established [19]. Such a correlation can guide the designer towards the optimal selection of process parameters while minimizing the cost of necessary experimental assessments. Such an incorporation however, for the other important parameter i.e. coverage has not been investigated yet. In fact most of the 3D multiple impact simulation models, recently developed, did not focus on coverage but on the general understanding of how the stress state develops during successive impacts [18].

Coverage, the most important measurable variable of shot peening, the most important parameter in the so called severe shot peening [18] and one of the most affective parameters on fatigue life of treated parts, either improvement or deterioration, is at the same time the most missing one in the finite elements simulations. It is therefore the purpose of this study to first examine if the former finite element models can take coverage into account and then to characterize a suitable random simulation to accommodate coverage.

2. Finite element models

Reviewing all finite element models published so far is neither in the scope of the paper nor necessary. As far as shots are interested, shot peening simulations can be classified into prior and random positioning of shots. When target is regarded, there are one symmetry plane [12,13], two symmetry planes [19] and four symmetry planes [15–17,20]. Among these kinds of targets, more attention was given to those containing four planes of symmetry, in another words symmetry cells. Therefore, two main symmetry cells Meguid & Kim [15,16] and Majzoobi [17] that made an effort to simulate a realistic shot peening have been selected from literature. A finite element re-simulation of them is carried out in this section. These models are considered to be a representative of prior shot positioning since both of them have assigned prior positions to shots. The capability of these models to capture a realistic peening is evaluated and discussed. A random finite element simulation of shot peening is also developed and presented in this section in order to overcome the inadequacies of former models.

2.1. Symmetry cell#1 (Meguid & Kim)

Kim et al. [16] applied the idea of area average solution on a symmetry cell to obtain a realistic distribution of shot peening residual stress. In this approach the average nodal residual stress in all nodes forming the cross section at specific depth, is introduced as the amount of shot peening induced residual stress at that depth. The impingement of four shots on each corner of a symmetry cell target which was developed by Kim is re-simulated in this work. However, on behalf of a

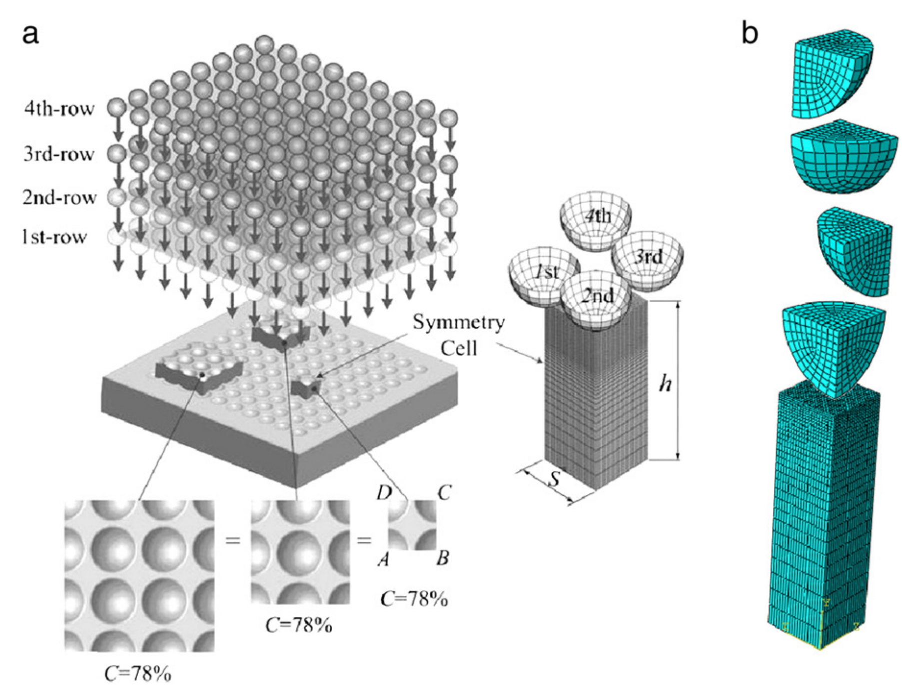

Fig. 1. a) Symmetry cell used by Meguid & Kim [16]. b) Finite element mesh of Meguid & Kim symmetry cell used in the present study.

Table 1
Material properties and shot peening parameters used in the re-simulation of two symmetry cell.

	Density (kg/m^3)	Young modulus (GPa)	Poission's ratio	Yield stress (MPa)	UTS (MPa)	Plastic modulus (MPa)	Dimension (mm)	Strain rate sensitivity	Initial velocity (m/s)
Shot (Majzoobi)	7800	210	0.3	–	–	–	0.4 Radius	–	50
Target (Majzoobi)	7800	210	0.3	1500	–	1600	$0.8 \times 0.8 \times 1.6$	Cowper–Symonds	–
Shot (Kim)	7850	210	0.3	–	–	–	0.4 Radius		55
Target (Kim)	7850	205	0.25	1510	1860	–	$0.4 \times 0.4 \times 1.5$	–	–

great contribution of Meguid in developing the concept of this symmetry cell [15,20], it is named Meguid & Kim symmetry cell in this paper. The finite element models used by Kim and that of the present work in order to assess his model are illustrated in Fig. 1. A brief material characteristics and shot peening parameters applied in the simulation are given in Table 1. For detailed information about material behaviour and modelling readers are referred to the original paper. In addition to re-simulation of the original model, the impingement of a single shot on the same target has been also constructed. Using the result of the single impact, the estimation of multiple impact coverage could be possible.

2.2. Symmetry cell#2 (Majzoobi)

The impingement of nine shots on a target which was developed by Majzoobi et al. [17] is re-simulated in this work. Fig. 2 shows the finite element model used by Majzoobi and that of the present work in order to assess his model. Although he did not apply the word "symmetry cell" to present his model, the symmetry boundary condition were applied on all lateral sides. Therefore, the mode is recalled Majzoobi symmetry cell in this paper. A brief material characteristics and shot peening parameters applied in the simulation are given in Table 1. For detailed information about material behaviour and modelling readers are referred to the original paper. In addition to re-simulation of the original model, the impingement of a single shot on the same target has been also constructed. Using the result of the single impact, the estimation of multiple impact coverage could be possible.

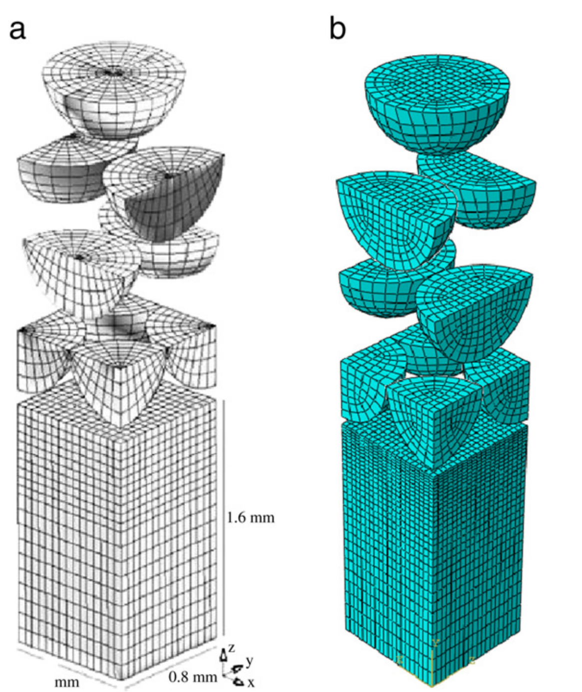

Fig. 2. a) Symmetry cell used by Majzoobi [17]. b) Finite element mesh of Majzoobi symmetry cell used in the present study.

2.3. Random finite element simulation of shot peening

A two steps finite element simulation of shot peening is presented here in order to acquire full coverage. First, an impingement of a single shot on a target surface is examined. The output of first analysis is the indentation radius introduced by each separate shot. Knowing the amount of treated part by each shot, the problem is now to arrange the shots configuration and target dimension in such a way that a reasonable interaction between residual stresses and also 100% coverage to be achieved.

Three-dimensional FE model was constructed using the commercial finite element code ABAQUS Explicit 6.10.1 [21] in order to investigate single/multiple shots impingement on a target. A target in the form of a cylinder was thought to be appropriate for random shot impingements and was given the following geometric properties: radius = 3C and Height = 6R where C is the radius of treated area and R is the shot radius. The cylinder height was selected after some preliminary analysis to ensure that boundary condition exerted on the cylinder bottom has no considerable effect on the residual stress field after shot peening as it has been applied before in the literature [12,13]. The cylinder radius (3C) or let say radius of treated area (C), however, is a matter of question. The sensitivity of simulation to the bigness of treated area has not been investigated yet. Hence three different radiuses of C = R, C = 2R and C = 3R for treated area are examined here keeping all other processing parameters the same in order to simulate actual interaction and coverage development.

To achieve a realistic model of shot peening, a large number of identical shots should impact target at random locations and in random sequences. Surface coverage is defined as the ratio of the area covered by plastic indentation to the whole surface area treated by shot peening expressed in percentage. The method suggested by Miao et al. [22] based on distribution of plastic equivalent strain (PEEQ) to evaluate percentage of coverage was used in the present simulation to compute coverage. In this definition coverage is approximated as the ratio of the number of nodes with PEEQ larger than the PEEQ at the boundary of the indentation, to the total number of nodes on the representative surface. PEEQ at the boundary of indentation is extracted from the single impingement simulation. The multiple impingements model was constructed by assigning two random numbers in r–θ plane for each shot. Random numbers were produced using the rand function in MATLAB which returns pseudorandom values drawn from the standard uniform distribution on the open interval (0,1). The first random number is the distance of shot from center of treated area and can be any randomly distributed value in the range of zero and C. The second number which indicates the angular location of shot is any randomly distributed value in the range of zero and 2π. After each impingement the resulted coverage is calculated and this process continues till the full coverage is acquired. SAE J2277 [23] has defined full coverage as being equivalent to 98% actual coverage. Hence this level of coverage was considered as full coverage in the present study.

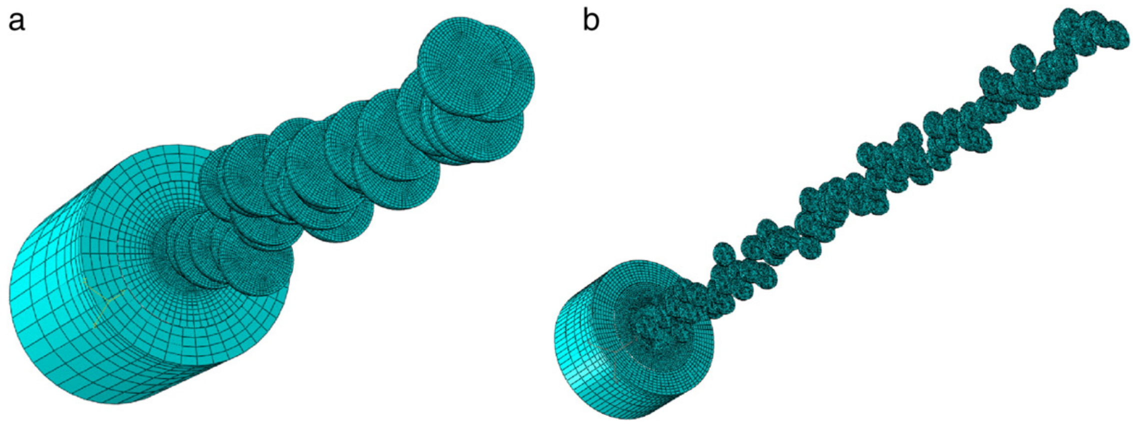

Fig. 3. a) Finite element mesh for C = R. b) Finite element mesh for C = 2R.

The cylindrical target was restrained against all displacements and rotations on the bottom. 45200, 182840 and 412920 C3D8R eight node linear brick elements with reduced integration and hourglass control were used to discretize the target for C = R, C = 2R and C = 3R respectively. Element size at the contact region was $0.02 \times 0.02 \times 0.02\ mm^3$. This element size has been selected in such a way that no more significant change in the result occurs by further refinement in mesh sensitivity analysis. 8192 same elements were also used to discretize each shot. Finite element meshes for three random simulations and a close view of impact zone for C = 3R model are illustrated in Figs. 3 and 4.

0.4 mm radius shots were used in this simulation by assuming isotropic linear elastic behavior with density of 7800 kg/m^3, Young modulus of 210 GPa and Poisson's ratio of 0.3. The target material used in this study was steel AISI 4340 which is frequently treated by shot peening. Plastic behavior and strain rate sensitivity have been implemented by Johnson–Cook equation. This constitutive equation is stated as follows:

$$\sigma = (A + B\varepsilon^n)\left(1 + CLn\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)(1 - T^{*m}) \quad (1)$$

where A, B, n, C and m are material constants and are measured by experiments. $\dot{\varepsilon}$ and $\dot{\varepsilon}_0$ are the current and reference strain rate ($\dot{\varepsilon}_0 = 1$). T^* is the homologues temperature defined as $(T - T_{room})/(T_{melt} - T_{room})$ where T_{melt} and T_{room} are melt and room temperature. A = 792, B = 510, n = 0.26, C = 0.014 and m = 1.03 were used to simulate the behavior of AISI 4340 in this simulation [24]. Thermal effects have been neglected in the present simulation. In order to prevent residual oscillations material damping was introduced into the model using equation 2 where C is damping matrix, M is mass matrix and K is stiffness matrix. α was calculated according to equation 3 where ω_0 is initial frequency and ξ is damping ratio ($\xi < 1$). The value $\xi = 0.5$ which is adequate for rapid damping of low frequency oscillations was used in the model [15]. ω_0 was estimated by equation 4 where E is the target's Young Modulus, ρ is its density and h is the height of symmetry cell. After some trial runs it was observed that a mass proportional damping is satisfactory for vanishing residual oscillations. Therefore, the stiffness proportional damping factor, β was set to zero. The initial velocity of 70 m/s has been exerted on all nodes of shots. The contact between shots and target surface were simulated using the penalty algorithm with no limit on shear stress, infinite elastic slip stiffness and isotropic coulomb friction coefficient of 0.2.

$$C = \alpha M + \beta K \quad (2)$$

$$\alpha = 2\omega_0\xi \quad (3)$$

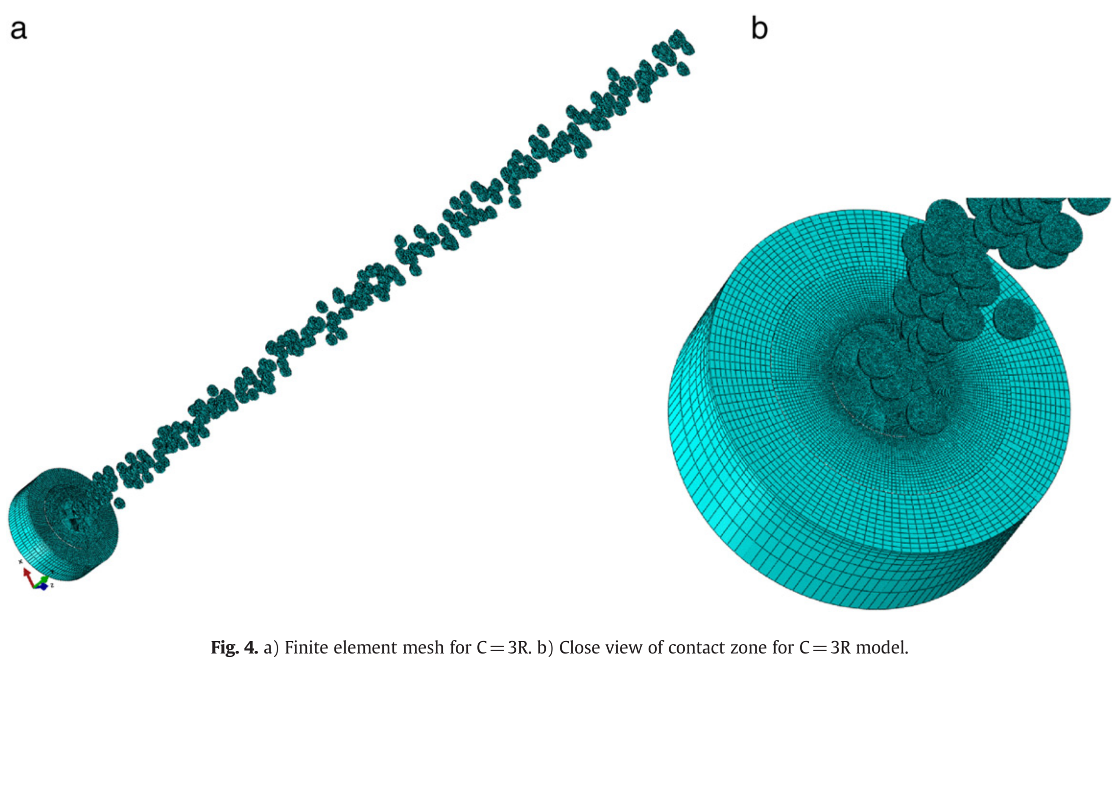

Fig. 4. a) Finite element mesh for C = 3R. b) Close view of contact zone for C = 3R model.

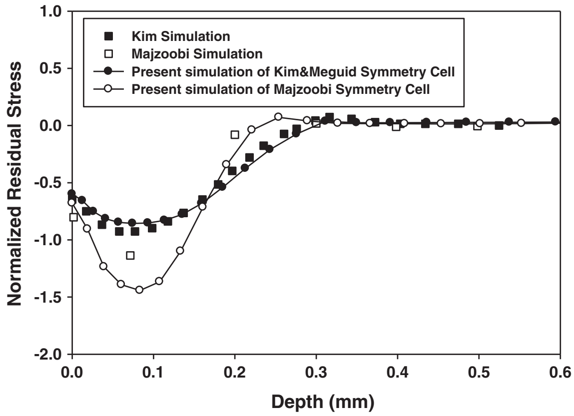

Fig. 5. Comparison of the former and present simulations.

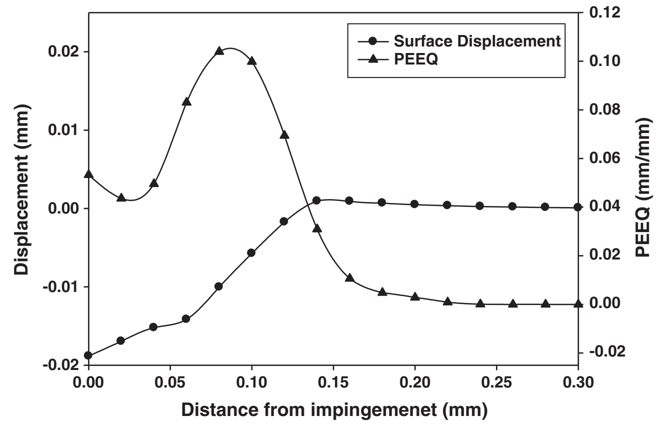

Fig. 7. Indentation profile and plastic equivalent strain for Meguid & Kim symmetry cell.

$$\omega_0 = \frac{2\pi}{h}\sqrt{\frac{E}{\rho}} \tag{4}$$

3. Results and discussion

3.1. Coverage assessment of former simulations

In order to verify the accuracy of present re-simulations, in depth residual stress profiles are compared with those of original simulations in Fig. 5. It should be noted that Majzoobi extracted the distribution at the center of target while Kim calculated the average nodal residual stress in each depth. Values were normalized by corresponding yield stress. Satisfactory agreement between the original and present simulations enabled authors to leave some comments regarding the coverage of these models.

As described earlier, it has been proposed that coverage can be numerically estimated as the ratio of the number of nodes with PEEQ larger than the PEEQ at the boundary of the indentation to the total number of nodes in the treated surface. This definition was employed to estimate the amount of coverage. Therefore, a single impingement analysis of both Majzoobi and Meguid & Kim symmetry cell has been accomplished in order to obtain the amount of critical PEEQ above that the finite element node is supposed to be treated by shots. Boundary of indentation can be realized, extracting the amount of displacement around the impingement center.

Figs. 6 and 7 demonstrate the displacement perpendicular to the surface cross section along with PEEQ around the impingement center for both symmetry cells. The indentation radiuses formed after a single impingement, were 0.12 mm and 0.14 mm for Majzoobi and Meguid & Kim symmetry cells respectively. The amounts of PEEQ at the boundary of indentation were 0.032 and 0.03 respectively. Having in hands this critical amount of PEEQ, a simple manipulation of PEEQ at all surface nodes of multiple impact models revealed that Majzoobi and Meguid & Kim symmetry cell have just simulated 20% and 43% coverage respectively. These amounts are much less than the real coverage of experimental procedure that their models were supposed to simulate. Kim considered these 4 impacts as 100% coverage and derived the equations which correlate Almen height, shot velocity and coverage. Application of those correlations is gone under question by the result presented in this paper.

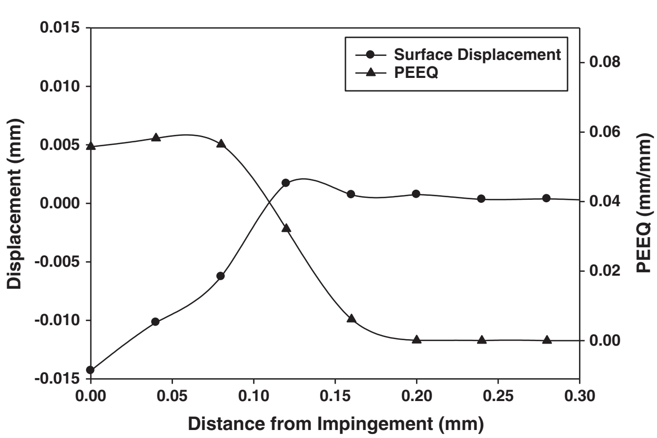

Fig. 6. Indentation profile and plastic equivalent strain for Majzoobi symmetry cell.

3.2. Random impacts

In the most of presented finite element models the number of shots and their configuration were considered as a prior. However, coverage is a problem dependent parameter and its realistic simulation could not be captured by a unique finite element model. There should introduce an indexing parameter in a simulation that can reasonably be variable for each specific shot peening process. Based on the simple idea of the larger impacts, the greater coverage, the first parameter that may come into mind is the number of shots. More recently, Avrami equation (Eq. (5)) was employed to calculate the number of random impacts needed to develop full coverage in finite element simulation [18]. Here, C% is the coverage percentage, and A_r is the ratio of total indent area to the target area. In this case A_r can be defined by equation 6 where N is the number of shots, d is single impingement diameter and D is diameter of treated area. The application of Avrami equation which is based on empirical observation of real peening on the finite target area of a simulation has not been either affirmed or assessed yet. Hence, present simulation was begun assuming that the number of impact to reach a full coverage level is not known. After each impact the resulted coverage were recorded and simulation went on till the full coverage level reached.

$$C\% = 100\left(1 - e^{-A_r}\right) \tag{5}$$

$$A_r = \frac{N \times \pi\left({}^{d}/_{2}\right)^2}{\pi\left({}^{D}/_{2}\right)^2} \tag{6}$$

Illustrated in Fig. 8 is surface displacement and PEEQ produced after a single impingement. It is clear that the radius of indentation is 0.17 mm and the critical amount of PEEQ above which the treatment of surface can be ensured is 0.053. Afterwards, the random multiple

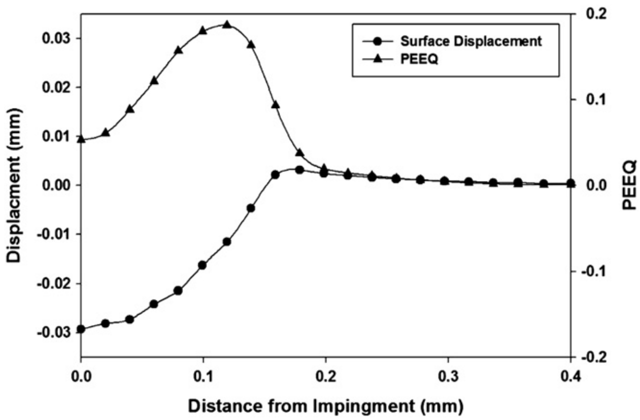

Fig. 8. Indentation profile and plastic equivalent strain after single impingent.

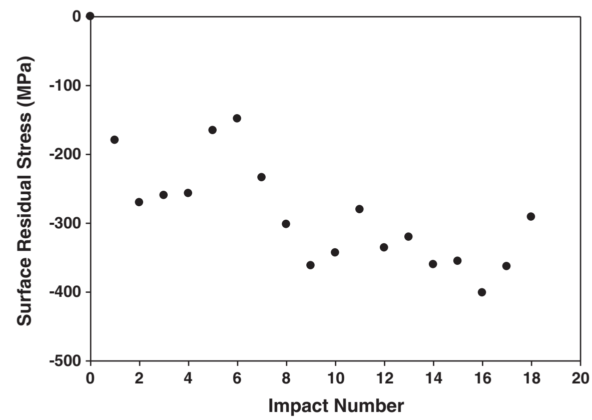

Fig. 10. Surface residual stress development for the treated radius of C = R.

impacts were allowed to take place. Using the aforementioned amount of PEEQ, surface coverage after each impact was calculated.

Variation of surface coverage with number of impacts for the treated radius of C = R is shown in Fig. 9. In the early stages impacts are most likely to occur without overlaps. Hence, coverage should develop more or less linearly in this stage. As the surface is covered more and more the probability of overlap increases and therefore the progress rate decreases. Development of coverage predicted by Avrami equation is also superimposed in Fig. 9. The number of impacts needed to acquire full coverage is calculated 44 according to Avrami equation. However, full coverage occurred after 15th impact in random impingement simulation.

Computing the average residual stress at each depth is an accepted technique to estimate the residual stress distribution after shot peening [16,18,25]. Development of surface average residual stress for the treated radius of C = R is illustrated in Fig. 10. It can be seen from the figure that residual stress is not converged to a specific amount as it is supposed to happen in reality.

Variation of surface coverage with number of impacts for treated radius of C = 2R is shown in Fig. 11. Comparing with treated radius of C = R, the exponential nature of coverage development is more evident here. Avrami equation was also superimposed in Fig. 11. According to Avrami equation full coverage should occur after 128 Impacts. However, in the random simulation of multiple impacts it happened after 88th impingement. Development of surface average residual stress after each impingement for treated radius of C = 2R was depicted in Fig. 12. Surface residual stress is converging around −600 MPa.

Variation of surface coverage and residual stress with number of impacts for treated radius of C = 3R are given in Fig. 13. Predicted coverage development by Avrami equation was also superimposed in Fig. 13. There is still an overestimation of the Impingement number predicted by Avrami in comparison with that of observed by random simulation at which full coverage occurs. Avrami equation predicts 254 impingements while full coverage acquired after 214th impingement in the simulation. Demonstrated in Fig. 14 it can be readily realized that, convergence of surface average residual stress around −600 MPa is also occurred for the treated radius of C = 3R as well as for C = 2R.

As far as residual stress after shot peening is regarded, a comparison of results for different treated areas affirmed that a target radius of C = R could not captured a realistic residual stress distribution. In contrast, a target radius of C = 2R is sufficiently suitable to reflect a realistic development of residual stress. It should be noteworthy that even for C = 2R after 11th impingement or in another words, after 35% coverage the resulted surface residual stress is −530 MPa which has just 11% error as compared with its amount after full coverage. That's why the examined simulations of Meguid & Kim and Majzoobi or many former simulations have reported a reasonable residual stress distribution while they have not simulated a realistic shot peening process. A realistic shot peening simulation should be capable of precisely simulate not only a correct residual stress field but also a correct coverage development. A realistic development of coverage in simulation is a necessary step to acquire an actual work hardening as well as an actual surface roughness induced by shot peening. It will be even more meaningful when very high coverage in shot peening is of interest. This is the situation that nowadays takes place in severe shot peening or peening to obtain nano-crystalline surface. Plastic equivalent strain is accumulated after each impact in severe shot peening and nano-crystallization occurs when the amount of plastic equivalent strain exceeds a critical value.

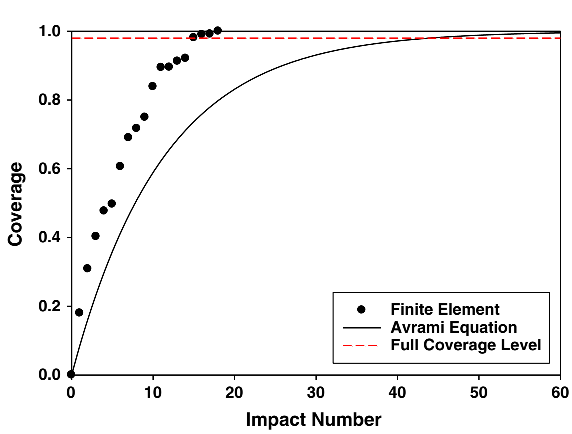

Fig. 9. Coverage development for the treated radius of C = R.

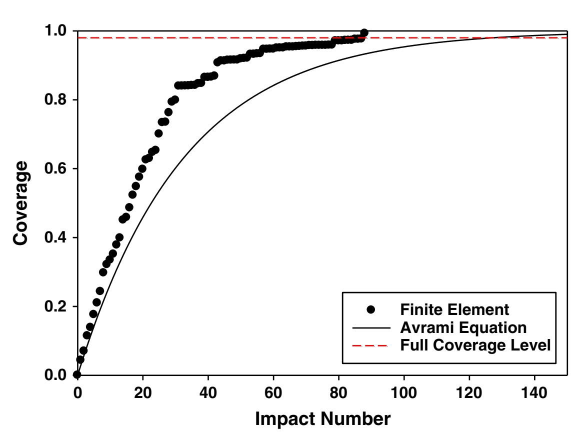

Fig. 11. Coverage development for the treated radius of C = 2R.

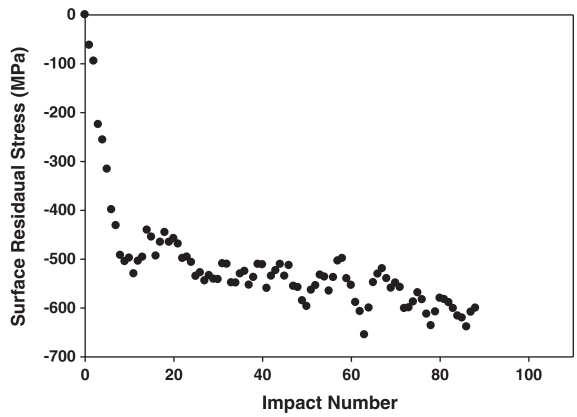

Fig. 12. Surface residual stress development for the treated radius of C = 2R.

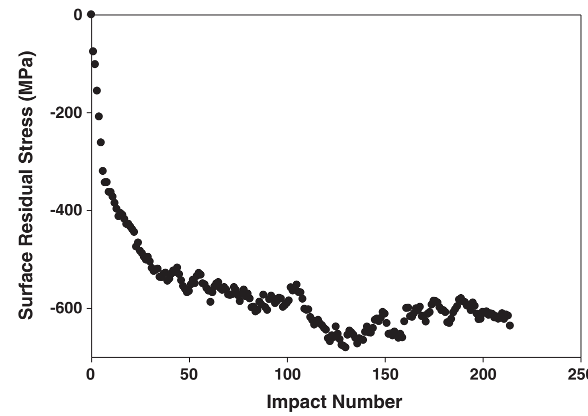

Fig. 14. Surface residual stress development for the treated radius of C = 3R.

Random finite element is a suitable method to get a realistic coverage development. More recently it has been applied to simulate a severe shot peening using Avrami equation to find out the required impingement number in order to make full coverage. It has been shown in this paper that Avrami equation overestimate the number of impacts that is required to get a full level of coverage in a finite treated area. In fact, Avrami equation requires that an infinite area of surface is being considered [26] which is a reasonable assumption for the case of a real shot peening and not for the target areas usually used in simulations. As discussed earlier, Avrami equation led to 66% error in estimating the number of impact at full coverage when the radius of treated area is C = R. The errors were 31% and 16% in the cases of C = 2R and C = 3R respectively. Assuming a linear trend, the amount of error would be less than 10% if the radius of C = 4R is considered for treated area. In order to make this finding more general and independent of the shot peening parameters applied in this study, it would be more convenient to express the appropriate dimension of treated area in term of the indentations radius induced by a single impingement. The reason is that the effect of shot size, shot velocity, shot and target material are also taken into account using this parameter. Accordingly, a treated area in a random impingement simulation of shot peening, on which Avrami equation is applied should have a radius at least 10 times of the single indentation radius. Otherwise, development of coverage should be assessed after each impingement to find out when full coverage reaches.

4. Conclusion

Existing finite element simulation of shot peening have been assessed in terms of their resulted coverage which is practically one of the most important measurable variable of the shot peening process. A random finite element simulation of shot peening was adapted to reflect a realistic process. The following conclusions can be made:

- Residual stress is the necessary but not sufficient parameter that a realistic simulation of shot peening should be verified with.
- An actual coverage development should be included in simulation of shot peening.
- Existing simulations of shot peening have the deficiency of not capturing an actual coverage development.
- Random finite element simulation would be capable of reflecting a realistic shot peening process if a suitable treated area is selected. Neither actual coverage development nor accurate residual stress interaction could be demonstrated by radius of treated area equal to shot radius.
- A procedure based on step by step examination of treated surface was adopted to simulate an actual coverage development during shot peening.
- Avrami equation leads to overestimation of impingement numbers at full coverage level in simulation unless the radius of treated area is at least ten times of the single indentation radius.

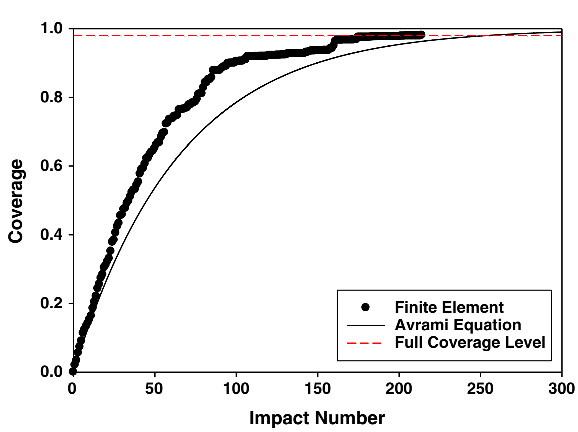

Fig. 13. Coverage development for the treated radius of C = 3R.

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