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Finite Element Simulation of Shot Peening Coverage with the Special Attention on Surface Nanocrystallization

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Abstract

The present study aims to challenge the existing finite element models in terms of one of the most important practical parameters, i.e. coverage. Important models from the literature are re-simulated and their resulted treated surfaces are carefully examined. Result of this study shows that existing finite element models could not reflect the realistic coverage. A variable dimension symmetry cell is developed in order to acquire full coverage and at the same time not increasing the computational cost. This model can successfully simulate the surface nanocrystallization by severe shot peening in which the amount of coverage is much higher than conventional shot peening.

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Keywords: Shot Peening; Finite Element; Coverage; Nanocrystallization.

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. Having in hands an accurate assessment of shot peening effects is a necessary step in the subsequent design consideration and life prediction of treated parts.

Many experimental investigations have shown that beneficial effects of shot peening on fatigue life were attributed to compressive residual stress and surface work hardening peening [1-5]. There are also huge attempts to illustrate this beneficial effect numerically. Impingement of one rigid spherical shot on

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an elasto-plastic target has been widely used for determination of the shot peening induced residual stress [6, 7]. Although parametric studies carried out using one impact model could provide a fairly good qualitative perception of plastic zone and unloading residual stress development, its shortcomings in capturing realistic peening effects are self evident. Basic symmetry cell [8], enhanced symmetry cell [9], criterion of achieving a uniform residual stress in all over the target area by increasing the shot numbers [10], area average solution [11, 12] and random finite element modelling [13, 14] were the main attempts to simulate more real condition.

A brief look on numerical simulation and the experimental assessments is showing a lack of straightforward terminological correlation between simulations and experiments. 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 for a given service condition is supposed to be 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 [15]. Such a correlation can guide the designer towards the optimal selection of process parameters while minimizing the cost of necessary experimental assessments. Such a incorporation for the other important parameter i.e. coverage has not been investigated yet. With the ever increasing application of a process including high coverage which is often called severe shot peening, the incorporation of coverage into finite element simulation would be meaningful and necessary. It is therefore the purpose of this study to examine if the former finite element models can take coverage into account. A new model with the special attention to coverage is also presented.

2. Finite Element Models

Reviewing the all finite element models published so far is neither in the scope of the paper nor necessary. Therefore, three finite element models that made an effort to simulate a realistic shot peening have been selected. A finite element re-simulation of two different symmetry cells (Meguid&Kim [8, 11] and Majzoobi [10]) has been carried out in this section. Examination of the third one which has been published by Bagherifard et al. [14] has been left for the discussion. The developed finite element model which is believed to be a straightforward solution for the problem of coverage is also illustrated in this section.

2.1. Symmetry cell#1 (Meguid & Kim)

Kim et al. [11] applied the idea of area average solution on a symmetry cell to obtained 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 et. al is re-simulated in this work. However, on behalf of a great contribution of Meguid in developing the concept of this symmetry cell [8, 9], it is named Meguid&Kim symmetry cell in this paper. Fig. 1 (a,b) shows the finite element model used by Kim and that of the present work in order to assess his model. A brief material characteristics and shot peening parameters applied in the simulation are given in table 1. For detailed information about material behavior and modeling one can refer 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. [10] is re-simulated in this work. Fig. 1 (c,d) shows the finite element model used by Majzoobi and that of the present work in order to assess his model. Although he did not use the word “symmetry cell” for his model, the symmetry boundary condition were applied on all lateral sides. Therefore, the mode is recalled Majzoobi’s symmetry cell in this paper. A brief material characteristics and shot peening parameters applied in the simulation are given in table1. For a detailed information about material behavior and modeling one can refer 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.

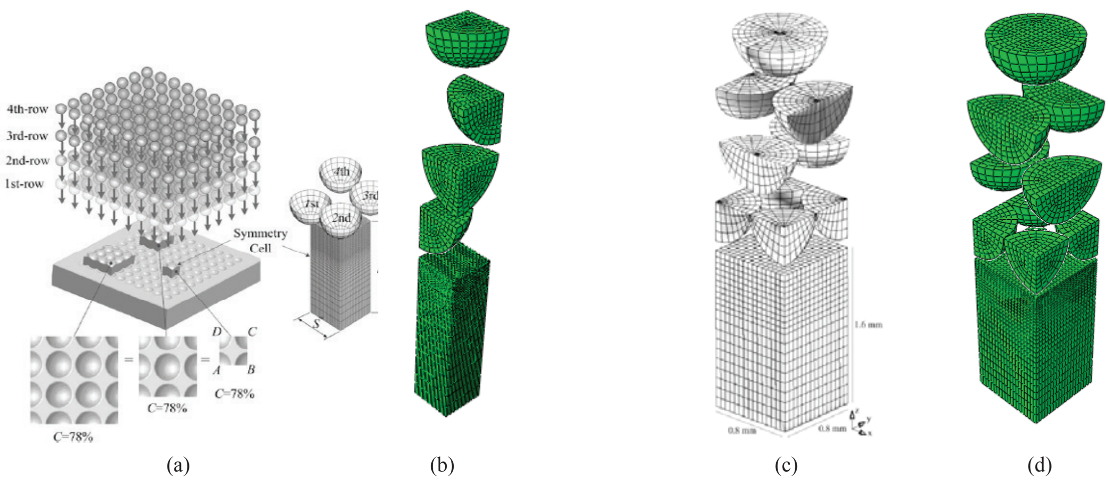

Fig. 1. (a) Symmetry Cell (Kim&Meguid); (b) Finite Element Mesh; (c) Symmetry Cell (Majzoobi); (d) Finite Element Mesh.

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	0.8×0.8×1.6	Cowper-Symonds	-
Shot (Kim)	7850	210	0.3	-	-	-	0.4 Radius		55
Target (Kim)	7850	205	0.25	1510	1860	-	0.4×0.4×1.5	-	-

2.3. Symmetry cell with variable dimensions

Taking all other process parameters as the same, the shot/workpiece material and also the velocity of stream can highly affect the obtained coverage. 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 cannot 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 parameters. Based on the idea of the larger impacts, the greater coverage, the first parameter that may come into mind is the number of shots. More recently, it was used in a randomly manner by Bagherifard et al. [14] to obtain a full coverage of 100%. Despite the good ability of this model to assess the residual stress field, very high computational cost restricts its application. Another alternative that can be considered as an index to coverage is the cross section of examined surface. The present finite element model examine if a symmetry cell with a variable dimensions has the ability of realistic simulation of coverage as well as residual stress field or not.

A two steps finite element simulation of shot peening is presented in order to acquire full coverage. First an impingement of a single shot on a target surface is examined. The output of the first analysis is the indentation radius introduced by each separate shot. Knowing the amount of treated parts by each shot, the problem is now to arrange the shot configuration and set the length of symmetry cell in such a way that a reasonable interaction between residual stress and also 100% coverage meet. 9 impacts (four impacts at each corner, four impacts at the middle of each side and one impact at the center) can produce a reasonable interaction of residual stress field. The length of the symmetry cell is proposed to be calculated by equating the area of surface target with the total area of produced impacts. This is shown by equation 1 in which r is the indentation radius by a single impingement and C is the length of the symmetry cell as an examined target surface. After calculation of the length of the desired cross section, a C×C×3C symmetry cell along with 9 sequential impacts is built to take the effect of multiplicity and full coverage.

$$4(1/4)(\pi r^2)+4(1/2)(\pi r^2)+(\pi r^2)=C^2 \tag{1}$$

Both single and multiple impacts have been simulated using finite element code Abaqus/Explicit 6.9. For the single impingement steel, R×R×3R symmetry cell were considered as the target. The model mesh is shown in Fig.2 .only a quarter of shot and target needed in this model due to their double symmetry with respect to X-Y and Y-Z planes. C3D8R eight node linear brick elements with reduced integration and hourglass control were used to discretize the model. In addition to the boundary constraints along the planes of symmetry, the bottom surface of the target was fixed in all degrees of freedom.

Since the introduced model is particularly aimed to simulate severe shot peening by remarkable coverage, a severe shot peening treatment investigated by bagherifard et al. [14] has been simulated. 0.6 *mm* diameter 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 (39NiCrMo3, according to the Italian nomenclature) which its plastic behavior and strain rate sensitivity have been applied by combined isotropic kinematic model. The monotonic mechanical characteristics, kinematic parameters along with cyclic behavior are reported in table 2. The initial velocity of 90 m/s has been exerted on all nodes of shot. The contact between shot and surface target were simulated using the penalty algorithm and isotropic coulomb friction coefficient of 0.2. After obtaining the radius of plastic indentation formed by one shot, the dimensions of symmetry cell have been calculated. The multiple impacts model was simulated like single impact except as described earlier; there were and new dimensions for target and aslo 9 shots such that a full coverage is acquired.

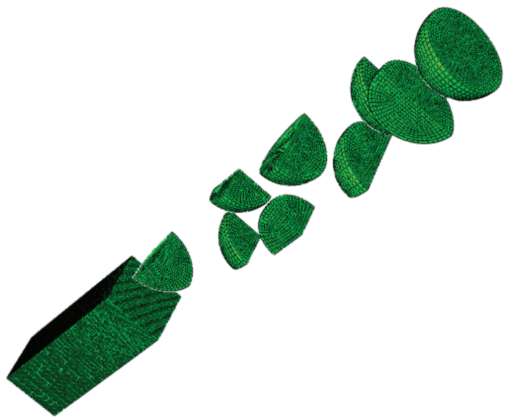

Fig. 2. Finite element mesh of variable dimension symmetry cell.

Table 2. Monotonic and cyclic behavior of the target used in variable symmetry cell model.

Monotonic Characteristis				Cyclic Characteristic and Kinematic Parameters				
σ_y	E	σ^u	A%	σ_{y0}	E	ν	C	γ
734 MPa	210 GPa	908 MPa	14.8	359 MPa	190 GPa	0.3	169823	501.87

3. Results and discussion

3.1. Coverage assessment

Coverage is well defined as the ratio of the area covered by indentations and the complete surface treated by shot peening expressed as percentage. Numerically, it has been proposed to approximate the coverage as the ratio of the number of nodes with plastic equivalent strain (PEEQ) larger than the PEEQ at the boundary of the indentation to the total number of nodes in the treated surface [13]. 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. Fig. 2 shows the displacement perpendicular to the surface cross section along with PEEQ around the impingement center. The indentation radius formed after shot peening were 0.11 *mm* and 0.134 *mm* for Majzoobi and Meguid-Kim symmetry cell respectively. The amounts of PEEQ at the boundary of indentation were 0.039 and 0.04 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 symmeyry cell have just simulated 16% and 38% 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 equation which correlated Almen height, shot velocity and coverage. Application of these relation is went under question by the result presented in this paper. With the same method the coverage of introduced variable dimension symmetry cell has been assessed and as expected, the amount of PEEQ at surface nodes was obtained to be greater than the critical amount of PEEQ at the boundary of single indentation.

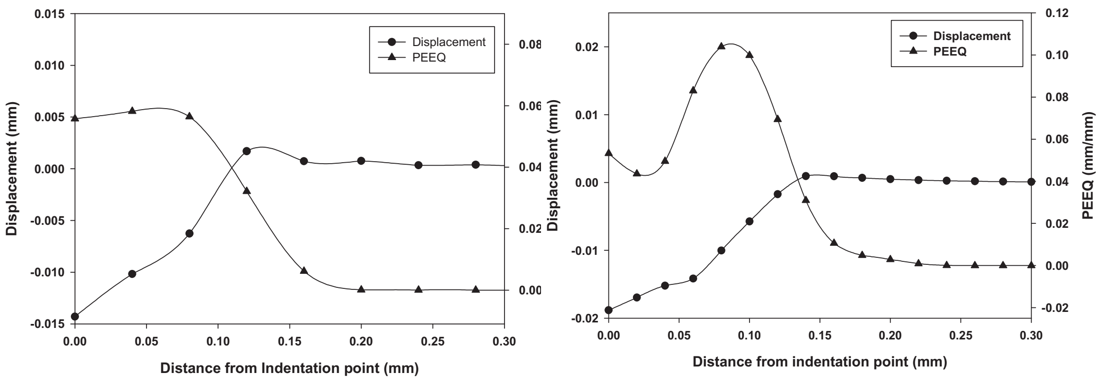

Fig. 3. Indentation profile and plastic equivalent strain for Majzoobi (left) and Kim&Meguid (right) symmetry cell.

3.2. Assessment of variable symmetry cell model

It has been shown in the previous section that variable symmetry cell model can successfully simulate the condition of full coverage. Here, its applicability to correctly simulate a real process is discussed. One of the advantages of variable symmetry cell model is its low computational cost to acquire full coverage. It will be very meaningful when very high coverage in the shot peening process is of interest. This is the situation that takes place in severe shot peening to obtain nano-crystalline surface. This is why a severe shot peening process with 1500% coverage conducted by Bagherifard et al. has been selected to be simulated in this paper. Bagherifard also developed a random finite element in which 67 and 134 impacts were needed to obtain 100% and 200% coverage respectively. Although comprehensive, the model was too costly and time consuming to simulate 1500% coverage. In contrast, since the variable symmetry cell model uses 9 impacts to reach 100% coverage, 135 (=9×15) is considered to be enough to simulate 1500% coverage. The variation of PEEQ with depth for both random and present finite element model is shown in Fig. 4. Notwithstanding the fact that the minimum amount of PEEQ for formation of nano-crystalline structure is around 7-8 (mm/mm) [16], it is evident from the results that only a simulation of real coverage can predict nanocrystallization. None of the simulations of 100% Coverage are able to predict what exactly happens in high coverage. The simulation of 200% coverage conducted by Bagherifard predicts a very shallow layer (about 1 μm) of nano-grains formation while simulation 1500% coverage by variable dimension symmetry cell estimates a 15 μm thick layer to be nano-crystallized during the process. Experimental observation revealed that a 10 μm thick nano-crystallized layer has been formed during the process [5]. Although a precise estimation of nano-crystallized layer in severe shot peening is still lacking, the variable symmetry cell with some modification has made a strong potential for severe shot peening simulation where coverage is a key parameter to take care.

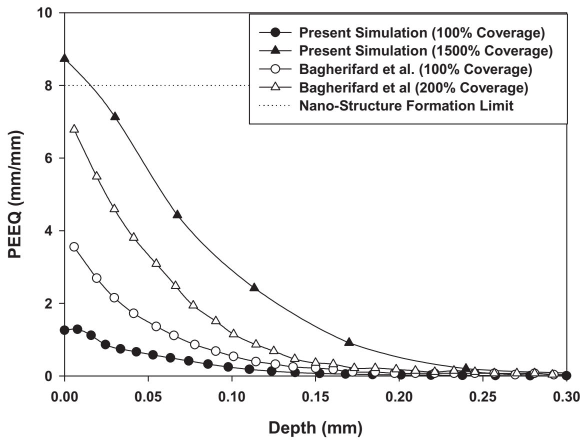

Fig.4. Variation of plastic equivalent strain with depth.

4. Conclusion

Existing finite element simulation of shot peening have been assessed in terms their resulted coverage which is practically the most important measurable variable of the shot peening process. Results of this study shows the existing models have the deficiency of either not capturing a realistic coverage or being very costly to simulate high coverage. A variable dimension symmetry cell has been introduced to cover both shortcomings. This model illustrated to have the ability of simulation of severe shot peening in which coverage is often more than 1000%.

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