Mesh sensitivity assessment of shot peening finite element simulation aimed at surface grain refinement

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1. Introduction

During shot peening (SP) process, a large number of hard and almost spherical shots accelerated in peening device impact the surface of a work piece and cause local plasticity. The induced effects are very functional in order to totally prevent or greatly delay the failure of the part. Moreover in case of thin components, the effects lead to deformation of the structures to a desired shape namely peen forming [1–3].

Innovative methods of SP have recently been developed to produce engineering components with a surface nanocrystalline layer and coarse grained interior. These methods use a combination of peening parameters to substantially increase the kinetic energy of the impacts in order to generate a huge number of defects and dislocations on the surface layer of treated part. This has the effect of transforming its microstructure into nano grain size [4].

It is to be mentioned that the set-up of these processes is very time consuming and requires expensive experimental effort; thus the development of numerical methods can be considerably useful to assess the effect of process parameters and optimize the peening treatment with reduced experimental costs. Applying numerical models for parametric study of the process for example to simulate severe shot peening (SSP) aimed at surface nanocrystallization or grain refinement, is of great interest since knowledge of the correct choice of process parameters and their relation to the grain size and uniformity is still lacking.

Several approaches have been suggested for SP simulation in the literature, but there are very few studies dealing with the simulation of SSP. These simulations are challenging since they involve different severe sources of nonlinearity in contact, material constitutive law, etc. In these cases, the influence of elements dimension is well recognized as a key parameter affecting the validity of final results. Furthermore, properly setting the minimum element size would be of great importance in these set of analyses since in explicit finite element simulations, the size of the smallest element determines total solution time.

In all SP simulations available in the literature, a fine mesh is used in the impact area and a coarser far from the impact region [5–19]. The size of elements utilized in these simulations is different and there are not so many references assigning justifications about the chosen element size. Moreover all the few mesh convergence studies have focused on obtaining good resolution just in terms of residual stress distribution under the impact area [5–10]. Frija et al. carried out a sensitivity study to optimize dimensions of the elements in the refined zone, using simplifying assumptions and comparing stress results with the elastic Hertz contact problem [6].

Zimmerman et al. used an element size equal to 1/15th of the dimple diameter produced by a single shot impact for which convergence was obtained in terms of residual stresses [7].

Klemenz et al. also used Hertz analytical solution for a purely elastic material behavior to examine the accuracy of finite element mesh in the cases of single and double impact model and eventually chose the size of elements equal to 1/10th of dimple size for multiple impacts [8].

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Table 1
Mechanical characteristics of target material (elastic and Johnson–Cook properties).

E (MPa)	ν	σ_0 (MPa)	B	C	n	m	$\dot{\varepsilon}_0$
190,000	0.3	792	510	0.014	0.26	1.03	1

Studying surface nanocrystallization generated via SSP necessitates dealing with the induced strains' trend on the surface; therefore effects of element size not only on stress state but also on the strains particularly in terms of equivalent plastic strain (PEEQ) should be investigated; owing to the fact that strain is the crucial parameter to be studied in assessment of favorable conditions for formation of nanocrystals.

Indeed the deformation conditions common to almost all processes reported to be able to generate nanocrystals such as high-pressure torsion, ball milling, drilling, shot blasting and annealing, ultrasonic shot peening and air blast shot peening (ABSP) are considered to be large strain and high strain rate [20]. Reported amount of strain applied to obtain nanocrystals varies depending on the deformation technique and material. However, imposing large strains seems to be the most important condition favorable for production of nanocrystals [21]. Studying particle impact and ABSP, Umemoto et al. [21] proposed the minimum necessary amount of PEEQ as the key parameter for formation of nanocrystalline structure, to be around 7–8 (mm/mm). Valiev [22] also stated that formation of nanocrystals through different severe plastic deformation methods is possible only at large accumulated strains $\geq$ 6–8.

Since to best of the authors' knowledge no other quantitative criteria are available in the literature for the assessment of surface nanocrystallization, this study is based on the available experimental criteria that are dealing with PEEQ value.

Another interesting issue is the effect of shot elements size on the simulation output. This subject, to the best of the authors' knowledge, has not been regarded in any of the SP simulations available in the literature, since all the few mesh convergence studies, are performed on the basis of target element size. In fact most of researchers have chosen rigid elements for numerical simulations [11–14] and in those which regard deformable shots there is no evaluation of shot element size effect. Size of shot element in these simulations has often been regarded much coarser that the size of elements in the impact region [6,8,15–19].

A finite element model of SSP has been developed in the authors' previous works. This model predicted surface nanocrystallization phenomenon, in addition to provide quantitative description of effects of peening parameters in severe ABSP. It also described the distribution and magnitude of residual stresses and the thickness of the work-hardened layer [23]. This numerical simulation has been validated by comparing the distribution of residual stresses as well as

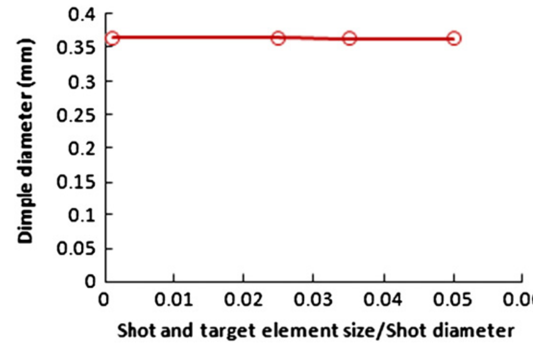

Fig. 2. Effect of element size on dimple diameter.

the depth of the work hardened layer with experimental tests and the results showed a good agreement [23]. In the aforementioned numerical simulation, due to computational costs, a fixed size of element has been chosen for meshing the shots, while mesh convergence studies were mainly focused on element size in the target model.

The present paper, is devoted to a detailed study of target and shot element size effects, simulating a single impact based on the previously developed multiple impact numerical approach [23]. The study is aimed to describe the mesh size influence on residual stresses and also PEEQ trend in the impact zone. The results will help to correctly define FE simulations aimed at predicting the formation of nanocrystallized layers.

2. Finite element model development

A 3D model using commercial finite element code Abaqus/Explicit 6.9 was developed to simulate the impact process. The target was modeled as a rectangular body ($3*3*1.5\ mm^3$) and the impact area ($1*1\ mm^2$) was located in the center of the upper face. All side faces, including target's base were surrounded by the so-called half infinite elements that prevent the reflection of elastic shear waves [16,24]. Infinite elements are allowed only with linear elastic behavior, so they must be positioned sufficiently distant from the non-linear interaction region to ensure accuracy [24]. Target mesh was made of 513604 C3D8R 8-node linear brick elements with reduced integration and hourglass control. Since strain rate dependency of target material has significant effects on stress profiles and the extent of surface hardening [9], Johnson–Cook [25,26] was chosen as the material model. Elastic and Johnson–Cook material parameters for the target model are presented in Table 1.

Steel shots of 0.6 mm similar to the shots used in experiment (commercial grade S230) were modeled as spherical bodies consisting of tetrahedral C3D4 elements with an isotropic elastic behavior

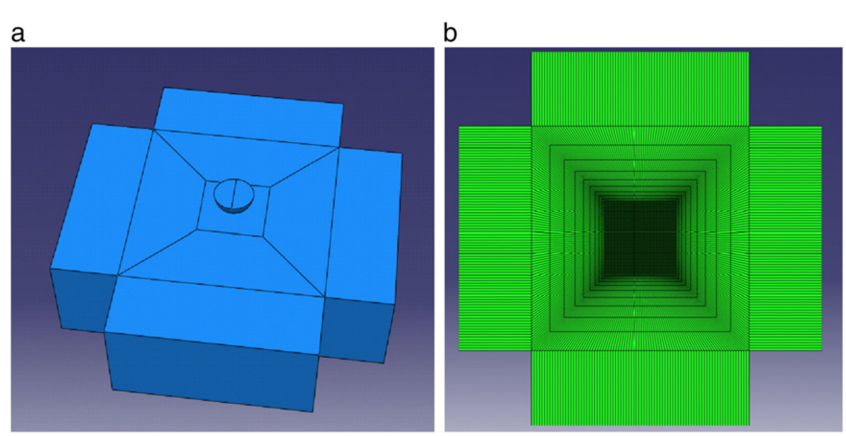

Fig. 1. a. Schematic of the model used for finite element simulation b. Top view of the target mesh.

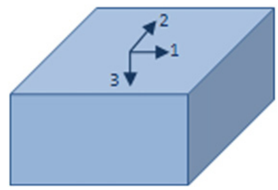

Fig. 3. Local coordinate system of the model.

using elastic properties of target, as presented in Table 1. Velocity in the vertical direction was defined as initial condition for all the shots. The impact angle was set to 90° as it is typical for ABSP. General contact was used as the criteria of contact with an isotropic Coulomb friction coefficient equal to $\mu = 0.2$. Fig. 1 shows the model and mesh used.

3. Mesh convergence assessment

3.1. Element size effect

Initially a single shot impact was simulated in order to assess the dimensions of plastic indentation generated on target surface. This dimple size estimation was performed with different element sizes (the element size of the shot and the target were always identical).

ALE (Arbitrary Lagrangian–Eulerian) adaptive meshing was also used to take benefit from adaptive meshing options due to strong deformation generated in the impact zone. ALE adaptive meshing can often maintain a high-quality mesh under severe material deformation by allowing the mesh to move independently of the underlying material. It can also be used as a continuous adaptive meshing tool for problems undergoing large deformations such as dynamic impact [24]. The choice ALE meshing was found to be of no significant effect on the resulting dimple diameter.

The results, as presented in Fig. 2, indicate that if the mesh is fine enough, the dimple size can be supposed to be almost independent of element size. Defining the parameter ρ for the ratio of mesh size to the obtained dimple diameter, different analyses have been performed. The convergence evaluation was performed by changing this mesh size ratio in the impact zone of the target and also in the shots. The results were then extracted through different paths starting from impact center. Figs. 3 and 4 respectively represent the coordinate system and the paths from which the results have been extracted.

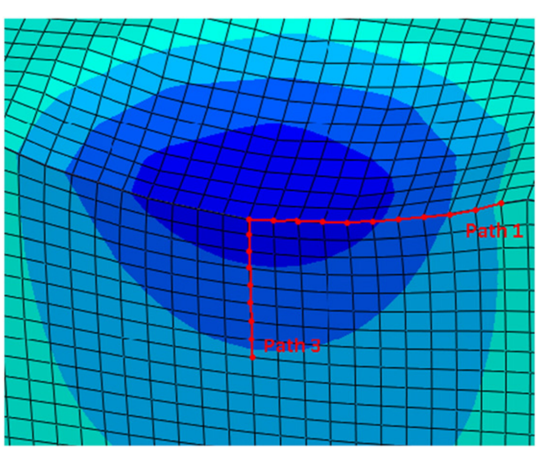

Fig. 4. Illustration of the on-surface (path 1) and in-depth (path 3) paths through which the numerical data have been extracted.

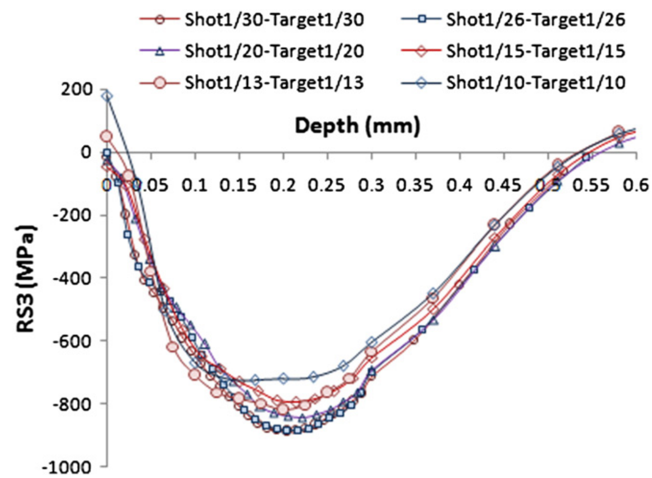

Fig. 5. Effect of element size on RS3 profile through an in-depth path starting from the impact center (identical shot and target element size).

Fig. 5. shows a typical plot of residual stress RS3 right below the impact center for different mesh sizes. It represents that residual stresses for $\rho = 1/26$ and $\rho = 1/30$ are almost identical; it can be inferred that stopping the refinement of the mesh at $\rho = 1/20$ does not cause excessive variation of the residual stress results.

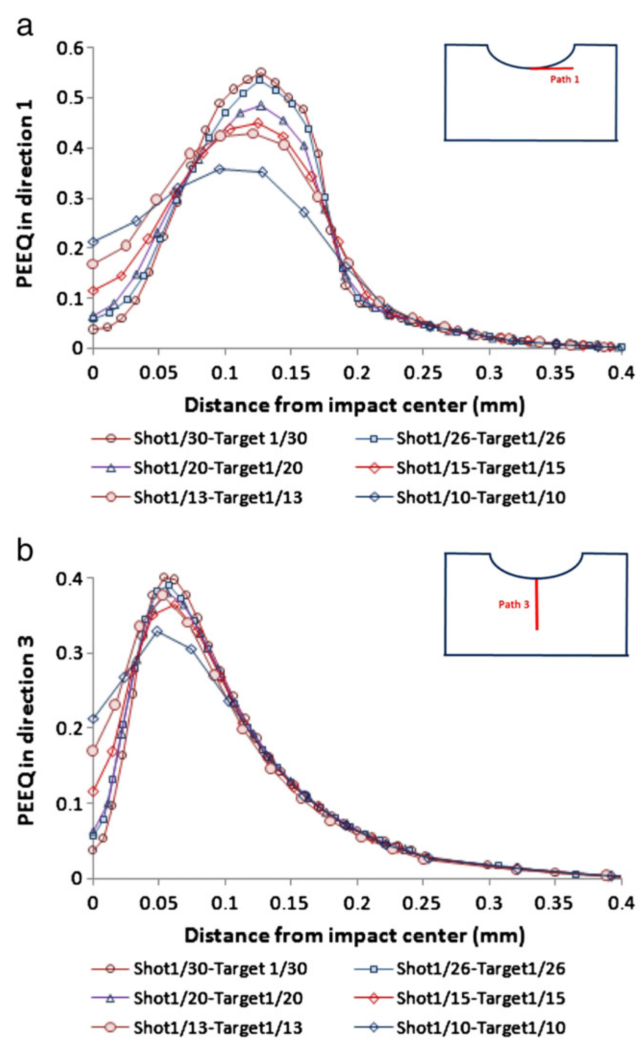

Fig. 6. Effect of element size on PEEQ profile a. on-surface path b. in-depth path (identical shot and target element size).

PEEQ in Abaqus is defined as

$$PEEQ = \bar{\varepsilon}^{pl}\big|_0 + \int_0^t \dot{\bar{\varepsilon}}^{pl} dt \tag{1}$$

where $\bar{\varepsilon}^{pl}|_0$ is the initial equivalent plastic strain. The definition of $\dot{\bar{\varepsilon}}^{pl}$ depends on the material model. For classical metals (Von–Mises) plasticity is used [24] and:

$$\dot{\bar{\varepsilon}}^{pl} = \sqrt{\frac{2}{3}\dot{\varepsilon}^{pl} : \dot{\varepsilon}^{pl}} \tag{2}$$

Since on-surface PEEQ shall be taken into account for assessment of surface nanocrystallization, PEEQ trend has been studied on two different paths: on-surface and in-depth. Results of the aforementioned sets of analyses in case of PEEQ values through the two mentioned paths are presented in Fig. 6. Fig. 6a represents the results through the on-surface path and Fig. 6b shows the results through the in-depth path, both starting from impact center. As observed in Fig. 6, contrary to residual stress case, it is not possible to find absolute convergent results for PEEQ parameter. The maximum and the impact center value of PEEQ are evidently changing by decreasing element size. Therefore it seems inconvenient to obtain entirely stabilized results in terms of PEEQ in spite of decreasing element size even in the order of $\rho = 1/30$.

Tables 2–4 report the on surface and maximum values of RS3 and PEEQ in direction 1 and direction 3 respectively.

3.2. Target element size effect

Variation of PEEQ values with respect to target element size was also studied. The study relied on the “real” maximum PEEQ obtained by linear extrapolation to “zero element size”, a method used in similar situations in the simulation of cold spray process [27–30]. The basis of finite element simulation of cold spraying is somehow similar to SP simulation and the two phenomena have many aspects in common. In both cases the aim is to simulate impacting behavior of solid

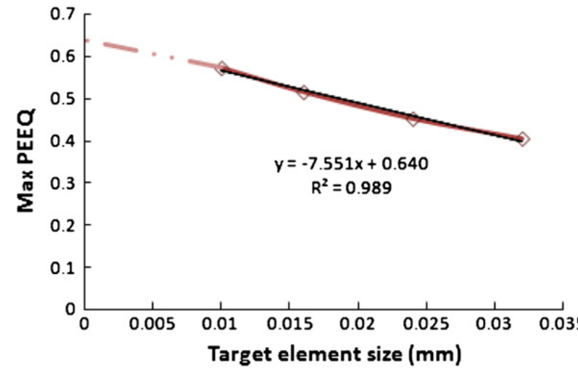

Fig. 7. Variation of maximum PEEQ through an on-surface path by changing element size in impact area (shot element size 0.01 mm).

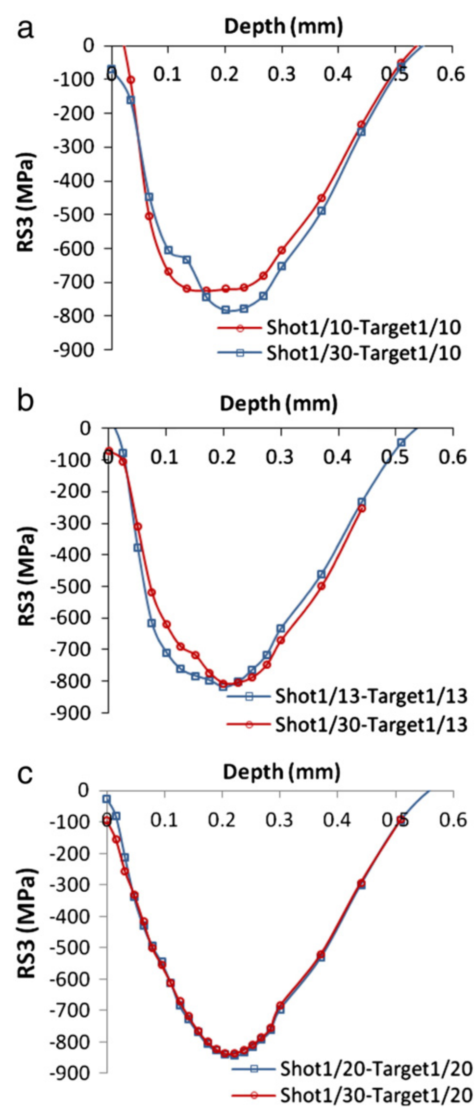

Fig. 8. Effect of shot element size on residual stress profile for an in-depth path starting from the impact center a. Shot $\rho = 1/10$–Target $\rho = 1/10$ vs. Shot $\rho = 1/30$–Target $\rho = 1/30$ b. Shot $\rho = 1/13$–Target $\rho = 1/13$ vs. Shot $\rho = 1/30$–Target $\rho = 1/30$ c. Shot $\rho = 1/20$–Target $\rho = 1/20$ vs. Shot $\rho = 1/30$–Target $\rho = 1/20$.

Table 2
RS3 parameters through an in-depth path starting from the impact center (Fig. 5).

Mesh density	Surface stress (MPa)	Peak stress (MPa)	Peak position (mm)
ρ = 1/10	176.438	−724.391	0.167
ρ = 1/13	46.244	−818.476	0.200
ρ = 1/15	−45.053	−793.755	0.214
ρ = 1/20	−25.710	−843.651	0.221
ρ = 1/26	−0.625	−884.309	0.204
ρ = 1/30	−17.928	−884.866	0.204

Table 3
PEEQ in direction 1 parameters (Fig. 6a).

Mesh density	Surface PEEQ	Max PEEQ	Peak position (mm)
ρ = 1/10	0.213	0.358	0.100
ρ = 1/13	0.169	0.429	0.121
ρ = 1/15	0.116	0.448	0.124
ρ = 1/20	0.063	0.483	0.127
ρ = 1/26	0.057	0.535	0.125
ρ = 1/30	0.037	0.483	0.127

Table 4
PEEQ in direction 3 parameters (Fig. 6b).

Mesh density	Surface PEEQ	Max PEEQ	Peak position (mm)
ρ = 1/10	0.213	0.329	0.049
ρ = 1/13	0.169	0.376	0.053
ρ = 1/15	0.116	0.365	0.062
ρ = 1/20	0.063	0.380	0.056
ρ = 1/26	0.057	0.389	0.057
ρ = 1/30	0.037	0.400	0.054

spherical particles on a substrate. However, in case of cold spraying, the particles adhere to the impacted surface and form a coating.

Numerical studies on cold spraying reveal that there is a relationship between instability in PEEQ and element size [27]. As the mesh size is decreased, variations of instable parameter were found to be almost linear [27]. Using excessively fine mesh induces a high probability of numerical errors in the solution. In such cases, it would be also difficult to conduct the calculation owing to limited system capability and time. Accordingly Assadi et al. and Li et al. concluded that extrapolation of instable results to a meshing size of zero could be used to stand for the real one [27,28].

Variation of maximum on-surface PEEQ value as a function of target element size is shown in Fig. 7 (size of shot element was kept constant). Thus, in this study, a similar extrapolation has been performed on values of PEEQ in order to assess the influence of mesh size.

As it is observed by decreasing the mesh size, variations show an almost linear trend; consequently keeping shot element size constant, maximum amount of PEEQ can be linearly extrapolated and estimated independently from target element size (that is to say for target element size of zero). The linear equation of trend line is also shown in Fig. 7. The effect of shot element size is discussed in the following section.

3.3. Shot element size effect

In order to study the effects of shot element size separately, another set of analyses have been performed, fixing the target element size and changing the size of elements in the shots. The results indicate that decreasing the size of elements on the shots and not varying impact area element size, also influences the final results in turn; that is the results are not only sensitive to element size in target area but also to the size of elements in the shots; this fact has generally been neglected in previous numerical studies performed on SP process.

The results in terms of residual stresses and PEEQ are demonstrated respectively in Figs. 8 and 9 for different shot and target element size combinations. It is again worthy to note that the size

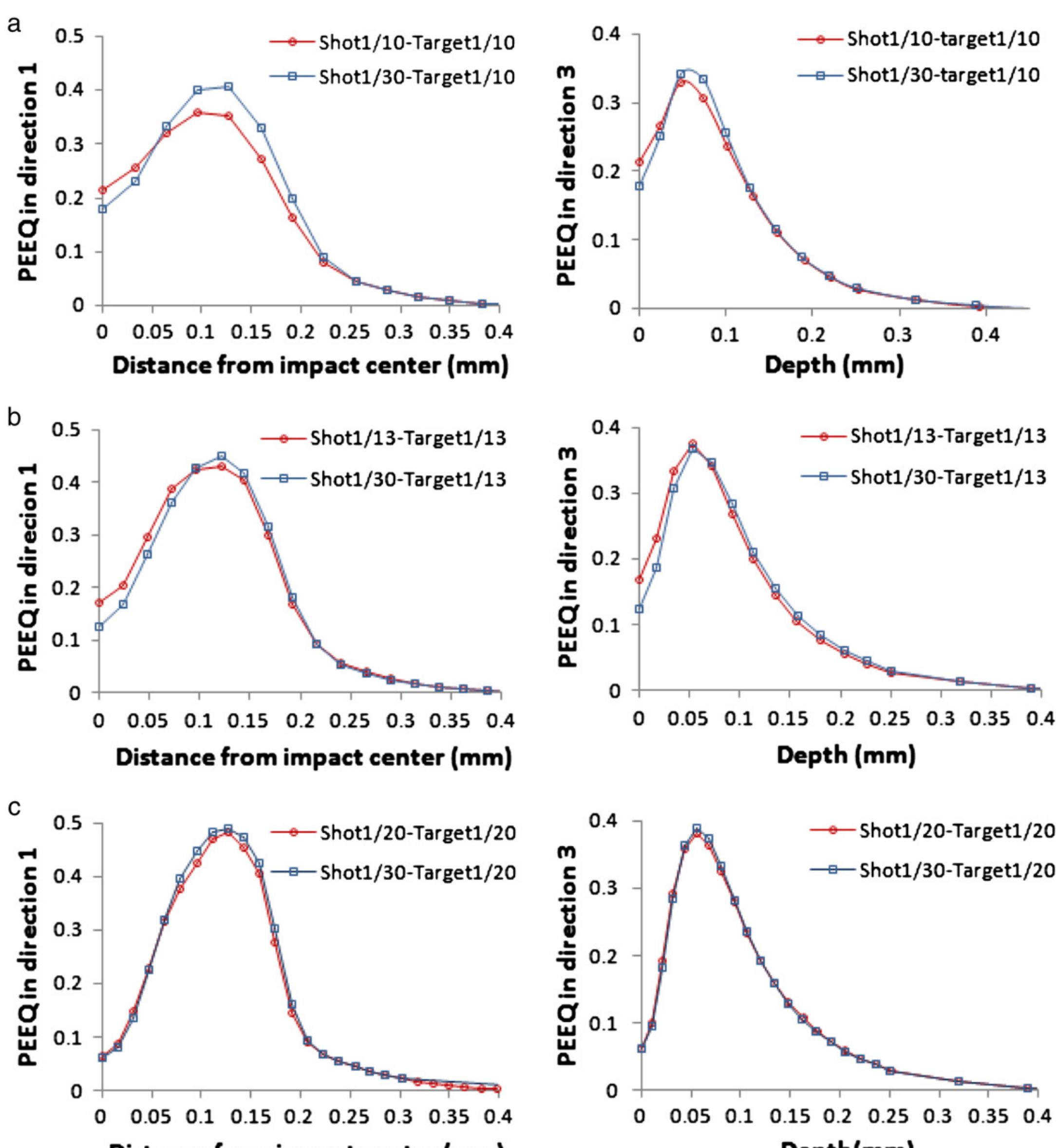

Fig. 9. Effect of shot element size on PEEQ profile in different directions a. Shot $\rho = 1/10$–Target $\rho = 1/10$ vs. Shot $\rho = 1/30$–Target $\rho = 1/10$ b. Shot $\rho = 1/13$–Target $\rho = 1/13$ vs. Shot $\rho = 1/30$–Target $\rho = 1/13$ c. Shot $\rho = 1/20$–Target $\rho = 1/20$ vs. Shot $\rho = 1/30$–Target $\rho = 1/20$.

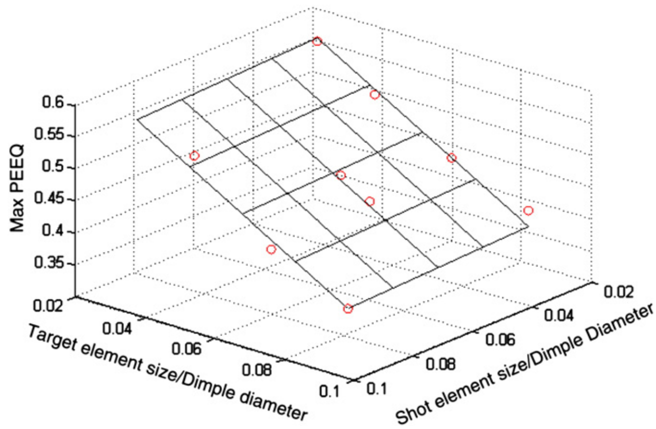

Fig. 10. 3D linear extrapolation of PEEQ results for different shot–target size combinations.

of elements in impact area and in the shots has been provided as ratios of dimple diameter

As can be observed in Fig. 9, decreasing shot element size induced variations of max PEEQ values (ranging from 13% (Fig. 9a) to 1.2% (Fig. 9c) in direction 1 and from 3.9% (Fig. 9a) to 2.5% (Fig. 9c) in direction 3). Considering that the criteria of grain refinement focus mainly on PEEQ values at the surface in direction 1, these variations could have significant impacts on the simulation results.

4. Calculating the mesh size independent PEEQ value

In order to obtain the final PEEQ value independent of either target or shot mesh density, 9 simulations have been performed using diverse shot–target element size combinations. A 3D linear extrapolation has been performed throughout the results in order to obtain maximum PEEQ value corresponding to zero shot–target element size. The fitted plane is shown in Fig. 10 in which the shot and target element size parameters have been normalized by the dimple diameter. The corresponding max PEEQ value obtained through this method is 0.6714 that is clearly different from the value obtained by considering only the effect of target element size (0.640 acc. to Fig. 7). This exemplifies the necessity of taking both element sizes into consideration.

Eq. (3) is for the plane fitted to the data obtained from different analyses

$$PEEQ = 0.597 - 0.201\, S/D - 2.015\, T/D \quad (3)$$

in which S stands for shot element size, T for target element size and D for dimple diameter.

The previous approach can be used in similar cases for PEEQ prediction for different shot–target element sizes. This method can be applied for estimation of PEEQ values, where it is needed to be measured precisely to assess formation of refined grains. Given that PEEQ is recognized to be an essential condition favorable for grain refinement in the surface of treated parts [21,23].

4.1. Practical shot–target element size choice

Based on the results obtained in this study, after performing analysis with a wide variety of shot–target element size combinations, the following procedure can be suggested for element size choice in SP simulation in order to decrease computational costs.

As the first step a regular mesh convergence study shall be performed on shot and element size in order to obtain the element sizes which provide convergent results in case of residual stresses.

According to the obtained results shot element size does not show to have a very significant effect on residual stress distribution, therefore in this step more attention should be paid to target element size.

In terms of PEEQ, on the other hand, it was indicated that an optimal accuracy can be achieved by performing zero element size extrapolating method. Thus decreasing the element sizes with respect to those recognized for residual stress convergence, two set of analyses should be performed, one with constant shot element size and the other with constant target element size, with the intention of obtaining the linear trend of PEEQ variations for each series. Once the required data is available, a plane can be fitted to them and accordingly the PEEQ value for 'zero shot–target element size' that is almost independent form mesh size can be achieved. Admittedly increasing the number of simulations, namely increasing the number of points lying on the plane will decrease the fitting error leading to a more accurate PEEQ assessment.

5. Conclusions

A comprehensive study has been performed on mesh size effects in shot peening numerical simulation based on a finite element model developed in a previous study by the authors. The following conclusions can be extracted according to the obtained results:

1. By decreasing element size, acceptable convergence can be obtained quite smoothly in case of induced residual stresses while accumulated equivalent plastic strain (PEEQ) values still need more refinement in grain size, which may be inconvenient to carry out due to computational costs (limited system capability and time).
2. It was demonstrated that the FEM results are sensitive to both shot and target mesh, giving emphasis to the fact that both element sizes shall be studied in order to obtain reliable numerical results.
3. Regarding the linear profile of PEEQ maximum value variations, PEEQ can be determined using the proposed "zero element size" 3D extrapolation. It would be a practical method to be used in simulations where PEEQ profile is of interest, as for numerical assessment of surface grain refinement obtained through severe shot peening.
4. A general equation along with a practical procedure has been suggested to find the proper combination of shot–target element size that maintains computational costs and accuracy at the same time. Following this procedure and implementing the proposed "zero element size" 3D fitting method, reliable results can be obtained not only in case of residual stresses but also in terms of PEEQ that is recognized as a key parameter in assessment of grain refinement process.
5. The developed process constitutes a systematic approach to improve the control and calibration of shot peening numerical simulation especially in the cases that are aimed to obtain grain refinement.

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