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Influence of mesh parameters on FE simulation of severe shot peening (SSP) aimed at generating nanocrystallized surface layer

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Abstract

This study has focused on numerical simulation of severe shot peening aimed at creating a fine grained layer of material on surface of the treated part. Mesh size effects have been particularly studied and analyzed not only on residual stress trend which has been commonly dealt with but also by considering the accumulated equivalent plastic strain, recognized as a key parameter in development of grain refinement process. In the end, a practical method is suggested to estimate the equivalent plastic strain value independent from element size to be employed for assessing the generation of refined grains.

Keywords: severe shot peening; finite element method; mesh convergence;

1. Introduction

During shot peening (SP) process, a large number of hard, usually spherical shots impact the surface of workpiece and cause local plasticity. The induced effects are very functional in order to totally prevent or greatly delay the failure of the part [1-3]. Alternative methods of SP which use a combination of peening parameters to multiply the kinetic energy of the impacts have recently been developed to produce engineering components with a surface nanocrystalline layer and coarse grained interior [4].

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Several approaches have been suggested for SP simulation in the literature but there are very few studies dealing with simulation of severe shot peening (SSP) which leads to surface nanocrystallization. In these simulations the influence of element 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 analysis since in explicit finite element simulation, the size of smallest element determines the total solution time.

A wide variety of elements’ size have been utilized in the SP simulations available in the literature and there are not so many references assigning justifications for these chosen element sizes. Moreover the few mesh convergence studies have focused on obtaining good resolution just in terms of residual stress distribution under impact area [5-8].

Frija et al. carried out a sensitivity study to optimize the dimensions of the elements in impact zone 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 stresses [7]. Klemenz et al. also used Hertz analytical solution and a purely elastic material behaviour to examine the accuracy of finite element mesh and chose the size elements equal to 1/10th of dimple size [8].

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) that is recognized as a crucial parameter in assessment of favorable conditions for formation of nanocrystals should be investigated.

Another interesting issue is the effect of shot element size on the simulation output. This is the subject that has not been regarded in any of the SP simulations available in the literature, since all the few studies have been performed on the basis of target element size. In most of the researchers have chosen rigid elements for numerical simulations [9, 10-12]. Size of shot element has often been regarded much coarser that the size of elements in the impact zone [6, 8, 13-17].

A detailed finite element model of SSP validated by a comparison with experimental tests has been developed in the authors’ previous work to predict surface nanocrystallization phenomenon [18]. In this numerical simulation due to computational cost a fixed size of element has been chosen for meshing the shots while mesh convergence studies are mainly focused on element size in the target model.

The present paper, on the other hand, is devoted to detailed study of target and shot element size effects, simulating a single impact that is performed based on the previously developed multiple impact numerical models [18]. Performing several analyses with different combinations of shot-target element size, the study is aimed to describe the effects of influence on residual stresses and also PEEQ trend in impact zone. The results will help to correctly define FE simulations aimed at predicting the formation of nanocrystallized layers.

2. Finite element model

A model using FE code Abaqus/Explicit 6.9 is developed to simulate the impact process. The target model has a rectangular body and the impact area is located in the centre of the upper face. All side faces in the target’s base are surrounded by half infinite elements that provide quiet boundaries to the model avoiding the reflection of elastic shear waves [14, 19]. Target mesh is set up by C3D8R 8-node linear brick elements with reduced integration and hourglass control. Since strain rate dependency of target material will have notable effects on stress profile and the extent of surface hardening [9], Johnson-cook [20, 21] is chosen as target material model in order to describe near surface high strain rate response due to the high energy impact.
Steel shots are modeled as spherical bodies consisting of tetrahedral C3D4 elements with isotropic elastic behavior. Velocity in the z-direction is defined for all the shots, regarding the typical impact angle=90° for ABSP. The scheme of full model is presented in Fig. 1. More details about FEM model are described in [18].

Figure 1. Schematic of the model used for finite element simulation

3. Mesh convergence assessment

3.1. Mesh size effect

A single shot impact has been simulated in order to assess the dimensions of the plastic indentation generated on target surface. This dimple size evaluation has been performed with different element sizes always regarding the same element size on shot and target. Results indicated that if the mesh is fine enough, the dimple size can be supposed to be almost independent from element size. Having measured the size of dimple, the convergence assessment has been performed changing element size in impact zone of the target and also in the shots (ratios of this dimple diameter).

The results have been extracted through different (1: on-surface, 3: in-depth) paths starting from impact centre. Residual stress values in directions 1 (RS1) and 3 (RS3) obtained on paths beginning from impact centre for diverse analyses using different element sizes are shown in Fig. 2. In this set of analyses equal size of elements has been used for the impact area and the shots, considered as ratios of dimple diameter (for instance 1/30 stands for 1/30th of dimple diameter). The results indicate that with the mesh, convergence can be clearly reached in terms of residual stresses in the impact zone. Indeed, as observed in Fig. 2, stopping the refinement of the mesh at 1/20th of the dimple diameter does not cause excessive variation of the results.

Results of the same set of analyses in case of PEEQ values through the two paths are presented in Fig. 3. As observed in Fig. 3, contrary to residual stress case, even with very minute size of elements it is not possible to find absolute convergent results in case of PEEQ. The maximum and the impact centre 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 1/30th of dimple diameter.
3.2. Target element size effect

Variation of PEEQ values with respect to target element size was studied. As an initial solution to describe element size influence, the "real" maximum PEEQ is worked out by linear extrapolation to “zero element size” method used in similar situations in simulation of cold spray process [22, 23]. Reviewing the studies performed on cold spraying reveals a relation between instability in PEEQ and element size reported in numerical simulation of the process. Cold spray finite element simulations indicate that as the mesh size is decreased, variations of instable parameter are almost linear [22]. Considering the fact that while the meshing is excessively fine, apart from the high probability of inducing numerical errors in the solution, it is also difficult to conduct the calculation owing to limited system capability and time, Assadi et al. and Li et al. concluded that the extrapolation of instable results to a meshing size of zero could be used to stand for the real one [22, 23].

In this study a similar extrapolation has been performed on values of PEEQ in order to assess the influence of mesh size. Variations of maximum on-surface PEEQ value with regard to target element size by keeping constant the size of shot element show an almost linear trend (see Fig. 4), consequently
keeping shot element size constant, maximum amount of PEEQ can be linearly extrapolated and estimated independent from target element size (that is to say for target element size of zero).

Figure 4. Variation of maximum PEEQ through the on-surface path by changing element size (impact area element size of 0.01 mm)

3.3. Shot element size effect

In order to study the effects of shot element size separately, another set of analysis has been performed, fixing the target element size and changing the size of elements in the shots. The results indicate that decreasing the shot element size and not varying impact area elements also influences the final results in its turn. Residual stress values showed a very good convergence; however, the results in terms of PEEQ as demonstrated in Fig. 5 for different shot and target element size combinations represent continuous alterations by decreasing element size. The changes noticed in maximum PEEQ values are more significant in direction 1 (from 13% to 1.2% in direction 1 compared to from 1.2% to 2% in direction 3), taking into account that the criterion of grain refinement focuses on the PEEQ values on the surface that is in direction 1.
3.4. Calculating the mesh size independent PEEQ value

Having validated the linear trend of PEEQ variations, in order to obtain the final PEEQ value independent from mesh size, either target or shot element size, 9 simulations have been performed using diverse shot-target element size combinations. A linear extrapolation has been performed to obtain the fitted plane equation and accordingly the maximum PEEQ value corresponding to zero shot-target element size. The fitted plane is shown in Fig. 6 in which the shot and target element size parameters have been made dimensionless scaling by the dimple diameter. The corresponding max PEEQ value obtained through this method is 0.6714 which is clearly different from the value obtained by considering only the effect of target element size (0.640 acc. to Fig. 4), drawing attention to the necessity of taking both element sizes into consideration.

Figure 5. Effect of shot element size on PEEQ trend in different directions a) Shot 1/10-Target 1/10 vs. Shot 1/30-Target 1/10 b) Shot 1/13-Target 1/13 vs. Shot 1/30-Target 1/13 c) Shot 1/20-Target 1/20 vs. Shot 1/30-Target 1/20
This method can be applied for estimation of PEEQ values in all cases where the simulation is aimed to determine the PEEQ value, such as SSP where PEEQ is needed to be measured precisely to assess formation of refined grains since it is recognized as an essential condition favourable for grain refinement in the surface of treated part [18, 24].

4. Conclusions

A comprehensive study has been performed on mesh size effects in severe shot peening numerical simulation based on a FE model developed in a previous study of the authors. The following conclusions can be extracted in the view of the obtained results:

1. By decreasing element size, acceptable convergence can be obtained in case of induced residual stresses while accumulated equivalent plastic strain (PEEQ) values still need more refinement in element size; further refinement 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 trend 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 numerical assessment of surface grain refinement obtained through severe shot peening.
References