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A numerical model of severe shot peening (SSP) to predict the generation of a nanostructured surface layer of material

S. Bagherifard, R. Ghelichi, M. Guagliano *

Politecnico di Milano, Department of Mechanical Engineering, Via La Masa, 34 20156 Milano, Italy

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A B S T R A C T

Generation of a surface layer of material characterized by grains with dimensions up to 100 nm by means of severe plastic deformation is one of the most interesting methods to improve the mechanical behaviour of materials and structural elements. Among the ways to obtain a surface layer with this characteristic, shot peening is one of the most promising processes, since it is applicable to very general geometries and to all metals and metal alloys without high-tech equipments. Notwithstanding the fact that the ability of shot peening to obtain nanostructured surfaces by using particular process parameters (mainly high impact energy and long exposure time) is proved, deep knowledge of the correct choice of quantitative values of process parameters and their relation to the grain size and the thickness and uniformity of the nanostructured layer is still lacking.

In this paper a finite element model of severe shot peening (SSP) is developed with the aim of predicting the treatment conditions that lead to surface nanocrystallization. After having assessed the accuracy of the model as regards mesh parameters and constitutive law of the material, the results are discussed and interpreted in terms of induced residual stresses and surface work hardening. A method to assess the formation of nanostructured layer of materials based on the value of the equivalent plastic strain is developed.

The comparison with experimental results allow to affirm that the model is a useful tool to predict the generation of a nanostructured surface layer by shot peening and to relate the peening parameters with the treated surface layer in terms of residual stresses, work hardening, and depth of the nanostructured layer.

1. Introduction

Shot peening (SP) is a well-known mechanical surface treatment generally applied to improve fatigue behaviour of metallic components. During the process small spherical peening media which are accelerated in peening devices of various kinds impact the surface of work piece with energy able to cause surface plastic deformation. The process is aimed to create compressive residual stresses and work harden the near surface layer of material. These effects are very useful in order to totally prevent or greatly delay failure of the part by fatigue [1–6].

In recent years special methods of SP have been recognized to be beneficial in creating fine grained layers of material on surface of treated components in order to improve service life time and global behaviour. This improvement is due to the fact that most cases of material failure such as fatigue fracture, fretting fatigue, wear and corrosion originate from the exterior layers of the work piece. These phenomena are all extremely sensitive to the structure and properties of the surface material. Since most of fatigue cracks initiate from the surface and propagate to the interior, a component with a nanostructured surface layer and coarse-grained interior is expected to have highly improved fatigue properties. Since both fatigue-crack initiation and propagation are inhibited by fine grains near the surface and coarse grains in the interior, respectively. Moreover, the residual compressive stresses introduced during the process can effectively stop or delay the initiation and propagation of fatigue cracks [7]. Among the alternative SP methods aimed at surface nanocrystallization, we can recall ultrasonic shot peening (USSP) [8], surface nanocrystallization and hardening (SNH) [8] and high-energy shot peening (HESP) [8]. The mentioned processes are somehow different from the conventional SP process both for the needed technological facilities and for the mechanics of the treatment. The common aspect is to use special combinations of peening parameters to multiply the kinetic energy of the shot impacts in order to generate a large number of defects, dislocations and interfaces (grain boundaries) on the surface layer of treated part and consequently transform its microstructure into nanograin size [8]. Some experimental research has been developed to find the relationship between the process mechanisms and the characteristics of the generated fine grained layer but there are still many aspects to be studied.

* Corresponding author. Tel.: +39 02 23998206; fax: +39 02 23998202.
E-mail address: mario.guagliano@polimi.it (M. Guagliano).

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It is well-known that numerical simulation can be considerably helpful to limit the costly and time consuming experiments. Their efficacy is more appreciable in cases of attempt to obtain nanocrystals with SP. Since these processes necessitate performing many experiments with different combinations of peening parameters in order to increase the kinetic energy of process for generation of nanocrystals.

In the present paper, SSP refers to an SP process applied by conventional air blast shot peening device but using severe parameters which include high shot velocity and long exposure time. These parameters are basically different from those generally applied in industry to shot peen the same material. The aim of intensifying the peening parameters is to increase the kinetic energy of the process and eventually obtain surface nanocrystallization.

Several approaches have been suggested in the literature for numerical simulations of SP but there are very few studies dealing with simulation of SSP that leads to surface nanocrystallization. Dai et al. performed impact simulation of surface nanocrystallization and hardening process (SNH) and compared the results in terms of roughness, residual stress and effective plastic strain [9,10]. Ma et al. developed a routine using finite element method to perform a molecular dynamic simulation and calculate the dislocation density generated by ultrasonic SP [11].

In this study, finite element simulation of air blast shot peening (ABSP) with unconventional and severe parameters is performed to provide quantitative description of effect of peening parameters in order to describe the distribution and magnitude of residual stresses and also the thickness of the work-hardened layer. After having described the development of the model in terms of geometry, mesh parameters and the material mechanical behaviour schematization, the attention is focused on the critical assessment of the mesh convergence and the way the number of impacts can be related to the real treatment time and consequently to the resulting coverage.

In the final part of the paper the results are critically discussed in terms of residual stresses and surface work hardening.

Studies performed to distinguish the essential parameters for structural evolution and generation of nanograins have acknowledged large strains as the most important condition favorable to produce nanocrystals [12,13]. There is also a criterion set on the accumulated equivalent plastic strain (PEEQ) value proposed to assess the formation of nanograins [12,13]. In this paper a method based on the mentioned criterion is proposed for the estimation of the treatment parameters needed to obtain nanostructured surface layer of material and to assess its depth.

The comparison of the obtained numerical results with experimental data regarding the favorable condition for formation of nanograins allows validating the presented SSP numerical model. Some guidelines for future works aimed to refine the model are finally drawn.

2. Finite element simulation development

2.1. FE model geometry

A 3D model developed using commercial finite element code Abaqus/Explicit 6.7 is utilized to investigate single and multiple impact effects. Due to symmetry only one quarter of the specimen is modelled for studying single impact while in case of multiple impacts the full model is analyzed to maintain the arbitrary aspect of the process.

The target is modelled as a rectangular body ($3*3*1.5\ mm^3$), sufficiently large to avoid the effects of boundary conditions on the residual stress state in the impact area. The impact area of ($1*1\ mm^2$) is located in the centre of the rectangular face. Target mesh is set up by 513604 C3D8R 8-node linear brick elements with reduced integration and hourglass control. All side faces including target's base are surrounded by so called half infinite elements that provide quiet boundaries by minimizing the reflection of dilatational and shear waves back in to the region of interest [14]. The shape and orientation of this element are similar to C3D8R element excluding that the element must be attached such that the infinite end faces away from the model. Infinite elements are allowed only with linear elastic behaviour, so they must be positioned sufficiently distant from the non-linear interaction region to ensure accuracy [15].

Steel shots with a diameter of 0.6 mm similar to the shots used in experiment (commercial grade S230) are modelled as spherical bodies consisting of tetrahedral C3D4 elements with an isotropic elastic behaviour. Velocity in the z-direction was defined as initial condition to all the shots, regarding an impact angle = 90° as it is typical for ABSP.

General contact was used as the criteria of contact with an isotropic Coulomb friction coefficient equal to $\mu = 0.2$ [16]. The scheme of full model is presented in Fig. 1.

It is to be underlined that thermal effects have been neglected in the developed simulation.

2.2. Material model

Since strain rate dependency of target material will have notable effects on stress profile and the extent of surface hardening, it is recommended to use a material model able to describe the near surface high strain rate response due to the high-energy successive impacts [17]. In this study non-linear kinematic Chaboche hardening model [18] and also Johnson–Cook equation [19], which are both constitutive models representing effect of strain rate on material hardening, were initially chosen to describe target material's behaviour. The results for both material models were compared with experimental results and finally combined isotropic kinematic model was chosen for the rest of analysis due to better consistency with experimental results. Johnson–Cook model highly overestimated surface residual stress and also the maximum residual stress below the surface.

The material used in this study is steel (39NiCrMo3, according to the Italian nomenclature) with the chemical composition presented in Table 1. Static tension tests were carried out according to ASTM E8M [20] in order to obtain monotonic properties of the material. The specimens were prepared following the instructions of ASTM A370-05 [21]. Obtained results are reported in Table 2. For characterization of plastic behaviour of material a set of cyclic tension compression experiments were performed to obtain the properties needed for the Chaboche hardening model. The adopted model consists of a combined isotropic kinematic hardening formulation firstly introduced by Armstrong and Fredrick [22], and subsequently modified by Chaboche [18,23–25]. The detailed description of its formulation is provided in [26].

Low-cycle fatigue tests up to the stabilized cycle were performed at different deformation intervals ($\Delta\varepsilon = 0.012$, $\Delta\varepsilon = 0.014$, $\Delta\varepsilon = 0.016$), all symmetric with respect to zero, using cylindrical specimens following instructions of ASTM E606 [27]. Fig. 2 shows the monotonic tension and stabilized cyclic tension compression curves obtained from tests. The results represent that the material is subjected to cyclic softening.

The results obtained for different deformation intervals were elaborated to define parameters of hardening model [18]. For simplification it was supposed that the isotropic component can be excluded from hardening model taking in to account that shot peening process provides small number of loading unloading cycles and consequently the influence of cycling softening of material after small number of cycles can be negligible in this case.

Determination of combined hardening parameters was performed by Abaqus/CAE which provides a special function for determination of hardening parameters based on experimental data of a stabilized