Numerical model of severe shot peening aimed to estimate surface nanocrystallization of Al material

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Abstract
Severe shot peening performed by particular combination of process parameters (mainly high impact energy and long exposure time) has been proved to be a promising method for obtaining a layer of nanocrystallized material on the surface of treated work pieces. In this paper a multiple impact finite element model of severe shot peening is developed to perform parametric study of the process and find a relation between surface characteristics and the treatment condition. The results are critically discussed in terms of induced residual stresses and surface work-hardening. An approach based on the results of the numerical simulation is developed to assess the formation of nanocrystallized layer of Al. Good correspondence of experimental data obtained from Al specimens, shot peened with similar set of peening parameters, and numerical results, affirms that the developed model is a useful tool to relate peening parameters to the treated surface layer characteristics in addition to assess the generation of nanocrystallized surface layer.

Key words: severe shot peening, finite element method, nanocrystallization, Al7075.

Introduction

Surface grain refinement is a relatively new process able to enhance mechanical properties such as fatigue behaviour, hardness, wear, corrosion and scratch resistance. The key point of the process that involves severe plastic deformation (SPD) is to introduce a large amount of defects and interfaces into the surface layer so that its microstructure is transformed into nano-sized crystallites. Shot peening (SP) is lately recognized as an SPD promising method that can be implemented in this field. Conventional SP is a popular mechanical surface treatment generally aimed at creating compressive residual stresses close to the surface and work-hardening of the same layer of material. These effects are very useful to totally prevent or greatly delay the failure of the part [1-3]. In the recent years particular SP processes different from conventional method that is air blast shot peening (ABSP), not only in the needed technological facilities but also for the mechanics of the treatment, have been aimed at achieving ultrafine grained materials on the surface of treated parts [4]. However setting-up SP processes aimed to the generation of nanocrystallized (NC) surface layer is quite expensive and requires several experimental analyses to achieve the proper combination of peening parameters that lead to the desired characteristics of the treated material. Accordingly, development of a numerical model of severe shot peening (SSP) with this aim can be of great help to correctly define the optimal parameters and reduce the number of needed experiments.

In this paper, a finite element model is developed to provide quantitative description of the effects of peening parameters in severe ABSP aimed at surface nanocrystallization. The model describes distribution and magnitude of residual stresses and also the thickness of the work-hardened layer. Furthermore a criterion based on the accumulated equivalent plastic strain (PEEQ) is applied to assess the formation of NC surface layer. This criterion is able to evaluate the favourable combination of treatment parameters to obtain NC layer of material.

In order to verify the numerical results, specimens peened with the same parameters used in numerical analysis have been experimentally studied using X-ray diffractometer (XRD) stress and grain size measurements, nanohardness tester and transmission electron microscopy (TEM); the detailed results of experimental characterization on Al specimens are available in authors' other publication [5]. Distribution and magnitude of residual stresses obtained from numerical simulation show good correspondence with those obtained from the numerical analysis.

Development of the numerical simulation

Geometry and material model. A Full 3D model is utilized to simulate the multiple impact SSP process. The target is modelled as a rectangular body (3x3x1.5 mm^3) at the centre of its top surface the impact area of (1x1 mm^2) is located. Target mesh is set up by 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 [6]. Target material is Al alloy 7075-T6 and the considered material model is the combined isotropic and kinematic material (Chaboche) constitutive model [7] the defining parameters of which for the mentioned Al alloy are taken from the literature [8].

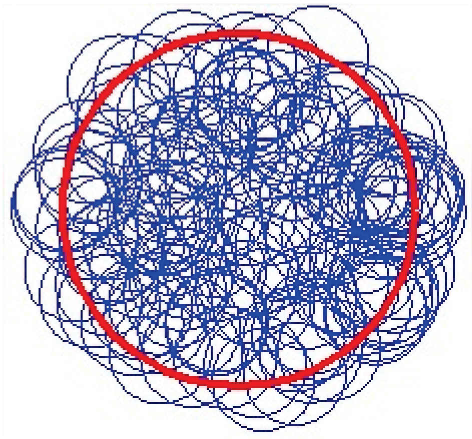
Steel shots with a diameter of 0.6 mm similar to the shots used in the experiment (commercial grade S230) are modelled as spherical bodies consisting of tetrahedral C3D4 elements with an isotropic elastic behaviour. Velocity in the z-direction is defined as initial condition to all the shots, regarding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

General contact is used as the criteria of contact with an isotropic Coulomb friction coefficient equal to μ= 0.2 [9]. It is to be underlined that thermal effects have been neglected in the developed simulation. More details on this numerical model are available in [10].

Mesh convergence analysis. In all numerical simulations of SP available in the literature, fine mesh has been used in the impact area and coarser elements in the area far from impact region in order to increase the accuracy of results and optimize duration of analysis in the meantime. All the few mesh convergence studies have focused on obtaining a good resolution of the residual stress distribution under impact area [11-13].

In this study, however, the effects of element size has been studied on both residual stress state and the strains particularly in terms of equivalent plastic strain (PEEQ), since PEEQ is recognized to have a key role in NC layer generation [14, 15]. For mesh convergence studies first a single impact was simulated in order to estimate the dimensions of the plastic indentation generated on target surface. Then convergence evaluation was performed changing element size in impact zone of the target as ratios of this dimple diameter. The results indicate that with very fine mesh in the impact zone, convergence can be reached earlier for residual stresses compared to PEEQ. Even with very minute size of elements it is not possible to find absolute convergent results in terms 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 for PEEQ in spite of decreasing element size even in the order of $1/30^{th}$ of dimple diameter.

The results of different analysis revealed that variation of PEEQ values with respect to target element size demonstrated a linear trend. Thus "zero element size" method, an extrapolating approach used in similar situations in simulation of cold spray process [16, 17] was applied to work out the "real" maximum PEEQ value independent from element size. 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. [16, 17] concluded that the extrapolation of the results to a meshing size of zero could be used to stand for the real one when the output parameter seems not to converge by decreasing element size. It is possible to estimate the desired parameter at infinite mesh refinement (mesh size =0) when the convergence rate is known [18].



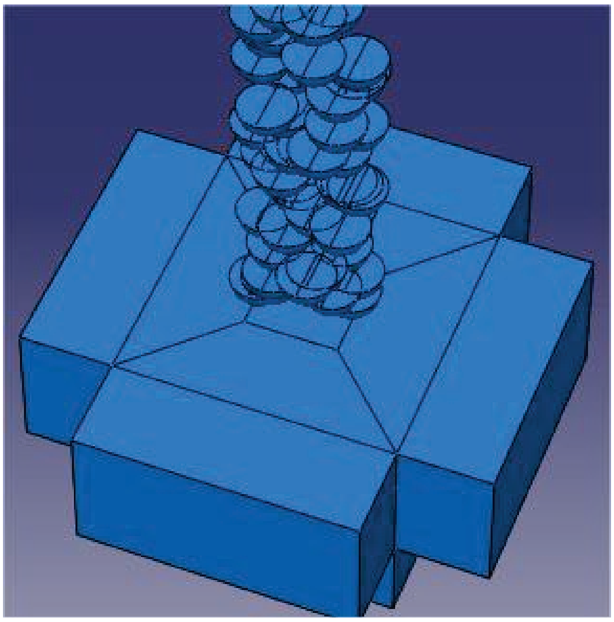


Fig.1. a. Random arrangement indentations b. Schematic of multiple impacts model

Surface coverage. The finite element model shall consist of a large number of identical shots impinging the target with an impact angle of 90º at random locations and in random sequences. Surface coverage is defined as the ratio of area covered by plastic indentation to the whole surface area treated by SP expressed in percentage. Theoretical and practical evidences point to an exponential approach to 100% coverage as the amount of peening is increased [19]. According to these evidences, the established relationship between coverage (Co%) and the ratio of total indent area to the target area (A_r) is given in Eq.1:

$$Co\% = 100\,[1 - e^{-Ar}] \tag{1}$$

SAE J2277 [20] sets a realistic target for coverage and defines full coverage as being equivalent to 98% actual coverage. Considering single indentation size and Eq.1, which requires A_r=4 to achieve 98% coverage, number of impacts needed for full coverage has been multiplied by three and consequently 140 impacts are needed to obtain 300% coverage in the considered impact area.
In order to obtain a realistic simulation, the impact sequence and arrangement of these 140 shots was generated by a Python subroutine developed to provide a uniform random sequence and arrangement for the multiple impacts. Fig.1.a represents the indentations generated by a random arrangement developed by the mentioned subroutine, which clearly cover all the points of the selected circular area. The highlighted circle in Fig. 1.a is considered as impact zone. Schematic of multiple impacts model is also presented in Fig. 1.b.

Results and discussion

Analysis of residual stress profile. Residual stress profile was measured on specimens shot peened with the same parameters used in the numerical simulation by using an AST X-Stress 3000 X-ray diffractometer (radiation CrKα, irradiated area 1 mm^2, $\sin^2\psi$ method, 11 diffraction angles (2θ) scanned between -45º and 45º). Measurements were carried out in depth removing a very thin layer of material using an electro-polishing device. X-ray diffraction measures an average value of stresses in the area covered by X-ray. Comparison of multiple impact simulation results with the XRD measurements was performed using a method suggested by Schwarzer et al. [6], in which mean of residual stresses in an area equal to the area affected by X-ray is calculated at each depth. The chosen area in the finite element model is a circle at the centre of impact zone shown in Fig.1.a. Comparison of numerical results with the XRD measurements in Fig.2 show a good correspondence thus validating the developed numerical model.

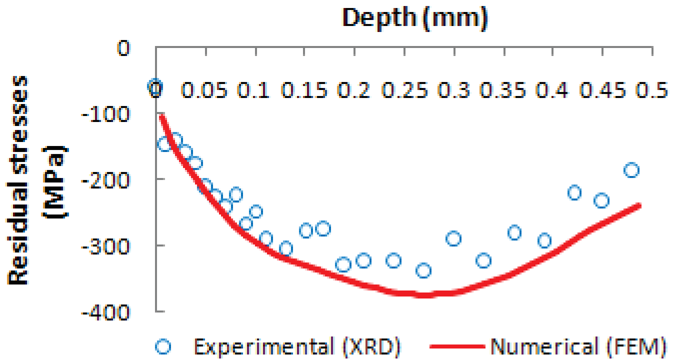


Fig.2. Comparison of experimental and numerical results in terms of residual stresses

Estimation of the work-hardened layer thickness. The depth of the layer characterized by FWHM *(*full width of the diffraction peak at half of the maximum Intensity) values considerably higher than that of core material is considered as an estimation of the thickness of work-hardened layer. This thickness obtained experimentally (~0.4 mm) is comparable to the depth of layer with non-zero PEEQ values obtained from the numerical simulation (~0.4mm). The profile of FWHM obtained form X-ray diffraction measurements and distribution of PEEQ values are presented respectively in Fig.3.a and Fig.3.b.

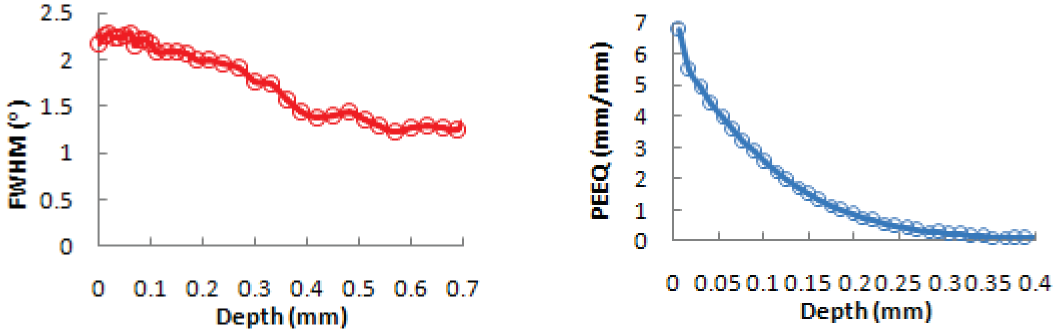


Fig. 3. a. FWHM profile obtained by XRD b. PEEQ profile obtained by FEM

Assessment of nanocrystalline structure formation and thickness of NC layer. The deformation conditions common to SPD processes that result in surface nanocrystallization are considered to be large strain and high strain rate. Reported amount of strain applied to obtain NC varies depending on the deformation technique and material. However, imposing large strains seems to be the most important condition favourable for production of NC [14]. Studying particle impact and ABSP, Umemoto et al. proposed the minimum necessary amount of PEEQ as the key parameter for formation of nanocrystalline structure, to be around 7~8 (mm/mm) [14]. Valiev (Valiev, 2004) also stated that formation of NC through different SPD methods is possible only at large accumulated strains ≥ 6-8 [15]. However Umemoto's experiments are devoted to steels while the criteria proposed by Valiev is more general considering the material type; thus it is regarded as the reference criteria for surface nanocrystallization of Al in this paper.

Having verified the linear trend of PEEQ by varying target element size, in order to obtain the final PEEQ value independent from mesh size, different simulations have been carried out using diverse target element sizes, keeping the shot element size constant. A linear extrapolation has been performed to obtain the fitted equation and accordingly the maximum PEEQ value corresponding to zero target element size. The corresponding max PEEQ value obtained through this method is 7.45 mm/mm which clearly satisfies the Valiev criterion for

formation of NC layer. Thickness of the nanocrystallized layer after 300% coverage was also estimated as the thickness of the layer with PEEQ value over 6. The thickness was measured to be 14 μm on the specimen surface.
It is to be recalled that due to computational costs, this PEEQ value (7.45 mm/mm), is calculated just after 140 impacts (i.e. 300% coverage according to the exponential approach). Coverage obtained in experiment according to optical measurements was reported to be 100% after 30 s treatment; consequently after 450 s, the obtained coverage can be decoded respectively as 1500% (multiplying by the treatment time needed for obtaining 100% coverage). In view of the fact that the coverage in experiment has been much more, and taking into account that the values of PEEQ rise by increasing the coverage percentage, the average values of PEEQ in the surface layer of the experimentally treated specimens would be even much more than the calculated value, accordingly also the thickness of NC layer would be more.

Conclusions
A detailed numerical model of severe ABSP aimed at surface nanocrystallization has been developed. The numerical model has been verified by experimental tests performed on specimens treated by similar peening parameters. In the light of the obtained results the following conclusions can be drawn.

- The numerical model of SSP is able to estimate the induced residual stresses and PEEQ, recognized as common favourable mechanism for generation of nanograins, and the depth of the surface layer affected by SSP: the experimental XRD measurements are in good agreement with the numerical results;

- A criterion based on the accumulated equivalent plastic strain (PEEQ), determined by using the so called “zero element size” linear extrapolation is applied to assess the formation of the nanostructured layer of material from numerical results.

- On the basis of the results, the proposed numerical model can be considered as a useful tool to assess the formation of nanostructured layer of material.

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