From conventional to severe shot peening to generate nanostructured surface layer: A numerical study

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Abstract. Surface nanocrystallization (SNC) was shown to be an effective approach to bypass the challenges of synthesizing bulk nanocrystalline material (NC) and yet to harvest its potential advantages. In this study unusual coverage (high number of impacts) was simulated for air blast shot peening process to induce SNC. The process is called severe shot peening. While the body of knowledge is mainly experimental in similar processes such as ultrasonic shot peening or surface mechanical attrition, a multi-scale scheme was developed to discuss the possibility of refinement from micro to nano-regime. The numerical framework combines finite element simulation of peening process with the dislocation density model. The result affirms the possibility of adopting air blast shot peening to induce surface nanocrystallization using typical media size, typical impact velocity and high coverage. This is an attempt to move from conventional shot peening toward severe shot peening to obtain surface nanocrystallization.

1. Introduction

Shot peening is an approved, well-established type of mechanical surface treatment having the objective of enhancing the resistance of metallic components which are exposed to cyclic loading, wear and corrosion under applies stress [1]. During the process small spherical peening media (shots) are accelerated in various kinds of peening devices to hit the surface of work piece with energy able to cause plastic deformation, compressive residual stresses and work hardening in the surface layers [2,3]. Therefore, shot peening is able to totally prevent or considerably retard the failure of the mechanical component. Compressive residual stress induced by shot peening is usually introduced as the main advantageous effect of shot peening [4–8]. However, grain distortion, increased microstructural barrier [9] and also surface work hardening of the peened specimen [10] were also affirmed to be able to be introduced as the main advantage of the process. Shot peening is a highly industrialized technique. Therefore, two standard parameters (intensity and coverage) have been introduced in order to ensure its repeatability. Determining the impact energy level of a shot stream is one important means of ensuring process repeatability in a shot peening application. During 1940’s J. O. Almen [2] developed a standard process to measure the kinetic energy transferred by a shot stream. The measurement of peening intensity is accomplished by determining its effect on standard test strips. The test strip (Almen strip) and a gage (Almen gage) used to measure the strip’s curvature have been standardized and specified for the shot peening industries. The material used to produce the test strips is an SAE 1070 CRS (cold rolled spring steel) with a standard hardness of 44-50 HRC [1].

Beside intensity, the second standard parameter to characterize peening is coverage. Coverage is practically the most important measurable variable of the shot peening process. It is defined as the ratio of the area covered by hits and the complete surface treated by shot peening expressed as a percentage. Coverage of 98% is a degree of coverage, which can still be assessed visually. It is considered to be full coverage [11] or 100% coverage, in another word, the minimum coverage needed to get the improvement from the peening process. The correlation between the coverage and the ratio of the impacted area to the total area was proposed [12] to have an Avrami type [13] behavior. In the early stage impressions are likely to occur without overlap so that coverage increases linearly with time. As the surface
progressively becomes covered the probability of the overlap increases so that the rate of coverage must decrease. Finally when a large proportion of the area has been covered there remains a smaller and smaller proportion of the area to be covered. The probability of this very small area being covered by a new impression becomes smaller and smaller. Hence the approach to 100% coverage is exponential and 100% coverage is theoretically impossible [12]. Coverage higher than 100% can be obtained by multiplying the time needed to reach 98% coverage. For instance 200% coverage means the time of peening is set to be twice the time needed to attain 100%.

It has not been a long time that shot peening was recognized as a potential process to produce surface nano-crystallization. Ultrasonic shot peening (sometimes called surface mechanical attrition) was found to be a very successful treatment for surface nanocrystallization in iron [14], low carbon steel [15–17], stainless steel [18–21] copper [22] and Al alloys [23].

Because of its simplicity, low cost and applicability to variety of targets air blast shot peening is, as mentioned earlier, a popular process in industries. If one uses special combinations of peening parameters to multiply the kinetic energy of the shot impacts or increases the coverage it is possible to transform the target microstructure into ultra-fine grains or nano-structure [24–28]. The process in this case is called severe shot peening rather than shot peening to emphasize on micro-structural refinement [29–31].

The body of knowledge in surface nanocrystallization by severe shot peening is mostly experimental. In this work a numerical framework is proposed to assess the possibility of grain refinement to nano-regime by application of severe air blast shot peening. The model uses finite element simulation of shot peening and connects it to a dislocation density evolution. The effect of increasing coverage form 100% to 1000% on micro-structural refinement is discussed. This is an attempt to move from conventional shot peening toward severe shot peening to obtain surface nanocrystallization.

2. Numerical model

The deformation behavior of metals and alloys can be described in terms of dislocation density [32,33]. As plastic strain increase, dislocation density evolves as the sum of generation and annihilation terms by the following relation:

$$\frac{d\rho}{d\varepsilon} = \frac{k_0}{bL} - k_2\rho$$

This model was shown not to be able to capture stage four and five of hardening that occur in high strain regime. Estrin et al. [34] proposed 2D dislocation density model, based on Mughraibi's composite principle [35]. In the proposed model the evolution of dislocation density is expressed by two coupled differential equations separating cell and wall dislocation populations while taking their interaction into account. The model was then generalized for 3D cases [36] and became a useful framework to predict grain refinement. This model is adopted in the present work to predict the grain refinement during severe shot peening. For the sake of brevity the details of the refinement model is not explained here and readers are referred to the original papers. The necessary tunable parameters of the model were obtained such that the difference between the equivalent stress-strain curves at different rates simulated by this model and the ones predicted by Johnson-Cook constitutive equation for the present material is minimized [37]. Performing rolling or torsion experiments at different strain rates, however, could help to refine the tuning process.

In order to get the evolution of plastic strain during peening process and apply that as an input for the refinement model, finite element simulation of shot peening was developed. Two dimensional axisymmetric model was constructed using the commercial finite element
code Abaqus explicit 6.10-1 [38] to simulate single impact. Shot diameter was considered to be 0.6 mm. 4-node bilinear axisymmetric quadrilateral elements were used to discretize target and shot. Finer mesh was applied for the contact region where higher gradient is expected. To simulate shot and target interface contact elements were introduced using the penalty algorithm with no limit on shear stress, infinite elastic slip stiffness and isotropic coulomb friction coefficient of 0.2. Axisymmetric boundary condition was applied to the corresponding axis of shot and target. Target’s bottom was restrained against all degrees of freedom. Initial velocity of 65 m/s was applied on all finite element nodes of the shot. Elastic perfectly plastic behavior was considered to represent shot material. Mass density $\rho=7850$ kg/m$^3$, Elastic modulus $E=210$ GPa, Poisson’s ratio $\nu=0.3$ and yield stress $Y=1550$ MPa were applied for the shot. The target was assumed to be AISI 4340 steel that is a kind of steel often treated by shot peening. Because high strain rate deformation (up to $10^5$ 1/s) might occur in peening the constitutive equation used to represent the behavior of target material should be able to capture rate sensitivity. Therefore, Johnson-Cook constitutive equation was applied for the target. The five constants of this constitutive equation to simulate target material were considered to be $A = 792$, $B = 510$, $n = 0.26$, $C = 0.014$ and $m = 1.03$ [37].

The basic principles of 3D simulation, material behavior, initial and boundary condition and contact properties are similar to that of 2D simulation. The main difference is that a target area is going to be covered by large number of shots. Finite element model of 3D simulation of shot peening is shown in Figure 1.

![Figure 1. Finite element model of severe shot peening](image)

The most important challenge in 3D simulation of multiple impacts or in another word simulation of an actual shot peening is to represent a realistic and yet not computationally demanding evolution of coverage. It was discussed in detail [39] that the available models of shot peening often fail to simulate a full coverage condition. Finding a reasonable strategy for shot positioning is of great importance to address this challenge. Two strategies were examined in the present work: complete random and guided random positioning of shots. The correlation between the coverage and the ratio of the impacted area to the total area was proposed [12] to have and Avrami type [13] behavior. Coverage percent (C%) in this case is expressed as function of the ratio of the indented area to total ($A_i$) are by equation 2. $A_e$ can
be calculated by equation 3 where \( N \) is the number of impact, \( r \) is the radius of indentation by a single collision and \( R_{\text{target}} \) is the radius of the treated area that should be covered by shots.

\[
C\% = 100\left(1 - e^{-A_c}\right) \tag{2}
\]

\[
A_c = \frac{N\pi r^2}{\pi R_{\text{target}}^2} \tag{3}
\]

By adopting a complete random positioning of shots and varying the radius of treated area one can find how big the treated area should be in order to reflect a realistic evolution of coverage. Coverage evolution for three different radius of target area was compared with the Avrami type evolution in some trial runs. The error between predicted number of impact for full coverage by Avrami equation and the one obtained by FE simulation was 66% for \( R_{\text{target}} = R_{\text{shot}} \), 31% for \( R_{\text{target}} = 2R_{\text{shot}} \) and 16% for \( R_{\text{target}} = 3R_{\text{shot}} \) [39]. This suggests the amount of error would be less than 10% if the radius of \( R_{\text{target}} = 4R_{\text{shot}} \) is considered for the treated area. Expressing the finding in terms of indentation radius would be the radius of treated area should be at least 10 times larger than the radius of a single indentation in order to have a realistic evolution of coverage in the simulation. Referring to equations 2 and 3, this means the number of impact needed to reach full coverage would be around 400. The cost of computation will be very high, bearing in mind that this number of impact is needed only for full coverage. Therefore, in order to simulate high coverage peening which is the aim of this study, let’s say for 1000% coverage, 4000 number of impact is needed. The bottom line is complete random positioning of shot might come up with a realistic evolution of coverage but computational cost would be extremely high.

In the second strategy random positioning of shot is applied but somewhat in a steered manner. A constraint was added to the positioning such that the impact center of subsequent hit is not allowed to occur in the area that had been treated by the previous impacts. That does not mean there is no overlap as for instance if the impact center of the incoming shot is randomly located close to the border of previously treated area, there would be some area that is treated more than one before obtaining full coverage. However, the numerical effort needed to simulate decreases considerably. Yet, a reasonably realistic evolution of coverage is captured in the simulation. The issue that should be addressed in this approach is finding an appropriate size of the treated area. In order to do that the size of treated area was enlarged step by step and the semi-random positioning of shots was applied for peening simulation. It was found that residual stress distribution is converged for \( R_{\text{target}} = 5r_{\text{single indentation}} \). Full coverage in this approach was obtained by smaller treated area with respect to the complete random positioning of shots and with considerably lower number of impacts (90% reduction).

### 4. Result and discussion

Distribution of total dislocation density after single impact is shown in Figure 2. The initial dislocation density was assumed to be in the order of \( 10^{13} \) m\(^{-2}\). Dislocation density increased by 2 orders of magnitude after single impact in the most critical point. Maximum accumulation of dislocations occurs at the immediate subsurface layers located at the edge of the crater that is formed during impact. Therefore, this point is the location of minimum cell size after single impact, bearing in mind the inverse relation between dislocation density and dislocation cell size. Umemoto et al. [24] experimentally observed that nanocrystalline layer is formed along the edge of the crater after 8 times of particle impact at the same point. This experimental observation can be explained by the present simulation that introduces the same point as the point of critical refinement after single impact.
Figure 3 shows the variation of surface plastic strain as the coverage increases during shot peening. Conventional peening processes are considered done when the coverage of 100% or 200% is attained. Uniform distribution of residual stress and sufficient work hardening can be obtained by 100% or 200% coverage. However, the amount of plastic strain at this level of coverage, as can be seen from the Figure 3, is less than or around 1 m/m. This level of plastic strain is not sufficient to induce surface nanocrystallization. Umemoto [25] showed that to produce nano-grained structure by deformation, the most important condition is to impose a large strain (larger than about 7). High strain rates, low temperature deformation, multidirectional deformation, hydrostatic pressure are considered to be favorable conditions to produce nano-grained structure. Figure 3 shows as the coverage increases to 1000% the plastic strain at the surface increases to around 6. The trend is linear suggesting that higher level of plastic strain can be obtained by increasing coverage more and more. This can be interpreted as the motivation to move from conventional to severe shot peening in order to produce grain refinement. By treating the surface layers by large number of shots, large number of defects, dislocations and interfaces (grain boundaries) are generated. The microstructure, accordingly transforms to ultra-fine grains or nano-structure. The process in this case is called severe shot peening rather than shot peening in order to put the emphasis on the fact that it is amide to generate ultra-fine grained or nano-structure surface layers.
The variation of surface dislocation density as coverage increases is shown in Figure 4. The initial dislocation density was assumed to be in the order of $10^{13}$ m$^{-2}$. The initial cell size based on the assumed initial dislocation density was calculated to be around 18 µm. Dislocation density sharply increases in the early stage of peening to the order of $10^{15}$ m$^{-2}$. Then the rate of increment decreases and, as suggested by the trend, dislocation density is going to be saturated at high levels of coverage. The limit of attainable dislocation density found by the aforementioned argument is compatible with the one suggested by [40] i.e. $10^{16}$ m$^{-2}$ for the case of severely deformed iron. High level of refinement occurs at the early stage of peening. However, after conventional shot peening the cell size is still in the micro regime. As the coverage increases the cell size becomes smaller and smaller. Based on the result of this simulation, dislocation cell was refined from 18 µm to 246 nm after sever shot peening with 1000% coverage.
5. Conclusion
Because of its simplicity, low cost and applicability to variety of targets air blast shot peening is a popular process in industries. It was demonstrated in this study that if one applies high coverage for this process it is possible to transform target microstructure into ultra-fine grains or nano-structure. A hybrid approach was developed to simulate refinement from micro to nano scale. The numerical framework combines finite element simulation of peening process with the dislocation density model. Random positioning of shots in steered manner was proposed to simulate coverage levels higher than full (100%) coverage. This is an essential step to simulate severe shot peening. Dislocation density model was linked to finite element simulation to model the refinement occurring during severe peening. It was shown that maximum accumulation of dislocations after single impact occurs at the immediate subsurface layers located at the edge of the crater that is formed during impact. The level of plastic strain after conventional peening (peening with 100% or 200% coverage) was found insufficient to induce surface nanocrystallization. However, the linear increment of plastic strain with increasing coverage suggests that the minimum required level of plastic strain is attainable at high coverage. This can interpreted as the motivation to move from conventional to severe peening to obtain micro-structural refinement. It was shown that sharp increase in dislocation density and high refinement of cell size is obtained at the early stage of peening, even in conventional peening with 100% coverage. However, these are not sufficient to pass the micro-regime to nano-regime. High level of coverage is needed to refine the structure into nano-regime. By increasing coverage as much as 10 time of the full coverage it is possible to refine cell size to 246 nm.
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