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Research paper

An evaluation on SP surface property by means of combined FEM-DEM shot dynamics simulation

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ABSTRACT

The surface coverage induced by shot peening (SP) has substantial influence on the fatigue durability of components. The underlying motivation for this work was to predict coverage, compressive residual stress (CRS), and roughness of the alloy, Al 2024-T351. These characteristics were assessed by computational modelling that is based on a combined finite element method (FEM) and discrete element method (DEM). The advantage of this combined method is that we only need to combine a representative dimple with the impact locations obtained from different SP parameters in DEM. Especially in the parametric analysis was carried out to evaluate coverage regarding to SP parameters. Furthermore, the DEM simulation generates an input file for the FEM simulation, which is then used to analyse the CRS and the resulting roughness that corresponds to SP parameters. The numerical coverage study (based on the combined DEM-FEM method) exhibited the same trend as the experimental data, with respect to the percentage of full coverage time, t, and is more reliable than theoretical calculations. In a practical sense, the developed model has the ability to accurately achieve the desired surface with the ability to adjust the SP parameters efficiently.

1. Introduction

Studies have shown that in most cases, mechanical failures occur in the exterior layers of the samples used. Shot peening (SP) is a well-known cold-surface-strengthening and forming treatment that involves impinging the surface of a sample with multiple high velocity shots. This process leads to the formation of a layer with redistributed internal residual stress and microstructure fragmentation (nano-scale) near the treated surface [1]. Consequently, the process induces residual compressive stress near the surface, and induces work hardening in the near-surface material [2]. The reduction in friction and wear was attributed to the increase in hardness of the SP-treated specimen [3]. The residual stress and small grains close to the surface resulted in improved fatigue strength by restraining the extension of micro-crack propagation, fretting, and stress corrosion cracking, which can occur on the sample surface [4]. The SP intensity and coverage have a positive effect on fatigue performance [5]. Coverage is defined as the ratio of the impacted zone area to the total area of the sample surface. Nevertheless, most determinations of surface coverage, roughness, and peening intensity were made based on experimentation [6]. The experimental investigation of the mechanical properties of the material with regard to SP is complex and expensive. An efficient numerical method for the simulation of SP processes is needed to provide a faster procedure for the selection of the optimal parameters for a prescribed peening target to be achieved.

The numerical methods, such as FEM, were efficiently utilized to simulate the shot peening process. Single and multiple shot impacts have been analysed by Al-Hassani [7], Deslaef et al. [8] and Guagliano [9]. Al-Hassani et al. [7] studied the single indentation at different impact angles. Deslaef et al. [8] investigated the influence of deformable and rigid shot. Guagliano [9] related the plate deformation degree to CRS which were obtained from FEM simulation. In an attempt to analytically develop relationships between material properties, SP process parameters, single indentation area, and coverage, Nguyen et al. [10] introduced a new mathematical model for a single dimple area. This model incorporated the impact angle, shot diameter, shot weight, impact velocity, and hardness of the treated surface. Subsequently, the air-peen flow and airflow were individually simulated for coverage prediction in commercial Computational Fluid Dynamics (CFD) ANSYS-FLUENT software.

However, most of the numerical simulations were utilized to obtain the residual stress and strain profile [11–13]. At the same time, several relevant numerical simulations on how the coverage changes as the specific peening parameters change quantitatively, such as mass flow

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rate, feeding speed, and shot diameter, were rare. Recently, Majzoobi and Kim [14,15] conducted other FE simulations based on symmetrical cells to predict the SP coverage. Hassani-Gangaraj [16] attempted to utilize a symmetrical cell with variable dimensions to acquire full and realistic coverage and examined the existing three-dimensional (3D) finite element models. Compared to the symmetrical model from [14–16], embedding a subroutine in an FEM simulation has been proven to be a more realistic method for achieving random shot impingement [17]. Miao considered an impacted area where the von Mises equivalent plastic strain magnitude was above 0.027 at the edge of the SP impression. This was location was based on the result of an LS-DYNA explicit solver simulation [18]. The algorithm used for coverage calculation was approximately the ratio of the nodes with plastic equivalent strain (PEEQ) larger than 0.027 to all of nodes after SP processing. The sequence by which the shots impact the surface in a random way is realized by the Matlab program. Similarly, the coverage caused by severe SP is examined by utilizing the FEM code, Abaqus, to assess the PEEQ value [19]. The model defined severe SP coverage by illustrating the percentage of plastic deformation on the treated surface. It is to be highlighted random impact sequence and arrangement was generated by a Python subroutine. Bagherifard et al. [19] developed a procedure by applying the equation suggested by Kirk in which coverage is linked with the impact number. An algorithm that considers the target points on which the shot impacts hit at least once was proposed by Bagherifard et al. [19]. The algorithm could obtain 200% coverage, and avoided excessively repeated impacts at identical points by using 134 shots.

Aside from the aforementioned method for assessing the coverage percentage by observing the distribution of PEEQ, there is another area computation method available. This method assesses the coverage by counting the sample points included in the set of indentations [20]. The boundary of the indentation can be defined as the contour line with null Uz displacement in FEM. We selected this area computation method in this study. The coverage has a direct influence on the fatigue life of the treated component. Indeed, the previous study revealed that a coverage level of as little as 20% (0.2T) provided fatigue performance equivalent to 100%. This finding was in contrast to those of other investigators who have reported that fatigue life decreases dramatically with coverage less than 100% [21]. The reason for the above phenomenon was attributed to the fact that the residual stress zone was much greater than the deformed layer.

Until now, most effective multi-shot 3D multiple impinging simulations were based on FEM. Research on the influence of SP process parameters on coverage effect is rare. The projection of shots at high mass flow rate and impact velocity produces abundant impacts at every second on treated material, and results in increased surface roughness. The simulation of multiple impacts by FEM requires significant computational resources and seems to be impossible. Therefore, a large number of SP studies have been performed by utilizing the combination of FEM and DEM. Murugaratnam et al. [22] proposed a new algorithm to dynamically adapt the coefficient of restitution (CoR) for repeated impacts of shots on the same spot. This process was implemented in the DEM code to take into account the effect of material hardening. The build-up of coverage was also considered based on the visualization of accumulated impact locations in their work. A model that predicts shot dynamics within the ultrasonic SP chamber was proposed by Badreddine et al. [23]. Then, it was used to capture predictive values for the impact density and the spatial distribution of the velocity of the spheres before the impacts. It is then eventually possible to relate impact density to the coverage itself, using a relation between the size of the impact dent and the velocity. Bhuvaraghan et al. [24] attempted to address this issue by using DEM in combination with FEM to obtain reasonably accurate predictions of the plastic strains of SP and to obtain 100% coverage. Rousseau et al. [25] studied the effect of the number of beads used in the process on the treated surface by DEM numerical analysis. After the experimental validation, the effects of bead quantities on CRS were quantified.

Using the computational numerical studies discussed above, it is possible to provide consultations to numerically predict SP coverage. The utilization of an FEM-DEM method in this study practically eliminates the need for modelling all impact processing in FEM in our current approach. We only need to apply the SP parameters to a single impact simulation to obtain the dimple dimension in FEM. Then, we can combine the dimple dimension with the impact locations obtained from the DEM simulation to assess the coverage regarding the specified SP parameter. This implementation not only reduces the solving time of the simulation by 99% (in comparison to the conventional finite element models using the proposed method), but it also provides a more practical enhancement for measuring coverage. A combined simulation is capable of simulating SP processing more realistically without reducing the impact number.

Regarding the simulations for two other configurations, the S390 single-shot impact model was first developed in the commercial nonlinear analysis dynamics software, Abaqus, to attain the dimple area on the 2024-T351 Aluminium alloy. Secondly, the shot peening flow movement was taken as a random and discrete phase governed by the DEM simulation, while the impact locations were recorded continuously and cumulatively by using the imbedded subroutine. This subroutine was developed using the C++ programming language. Then, the impact locations were imported into Origin 9.1 to obtain the coverage [26].

In order to capture the CRS and roughness with respect to the SP parameters, the input files of the FEM simulation were developed separately. The *Parts, *Materials, and *Boundary files were developed in Abaqus code, but the *Nset, *Step and *Loads files were generated in EDEM code based on rigid body dynamics.

In general, the conducted numerical simulations in this work is to allow for the understanding the most influential parameters of SP on surface integrity, such as residual stress, roughness, and topography [27]. In addition, this work offers a theoretical basis for obtaining properly applied parameters with regard to full or desired coverage on the surface of a sample.

2. Study method and materials

2.1. Theoretical formula and calculation flowchart for coverage

In order to compare the numerical results with the previous analytical results, we introduced a theoretical formula. Coverage is defined as the ratio of the impacted zone area to the total area of the sample surface. However, 100% coverage is difficult to identify when the non-impacted area decreases in size [28]. Therefore, the accepted degree of saturation coverage percentage is suggested to be 98% [29].

A simplified equation based on the application of the Avrami formula was first proposed by Kirk and Abyaneh [30]:

$$C(t) = [1 - \exp(-\pi\bar{r}^2 Rt)] \times 100\% \tag{2.1}$$

where $\bar{r}$, R, and t refer to the average radius of indentation, the number of shots that impact the target surface per unit area per unit time, and duration, respectively.

Karuppanan et al. [31] converted Eq. (2.1) to

$$C(t) = [1 - \exp(-3\dot{m}\bar{r}^2 t/4Sr^3\rho] \times 100\% \tag{2.2}$$

where $\dot{m}$ is the mass flow rate, S is the peening area of the treated surface, r is the shot radius, and ρ is the density of the shots.

If we only consider a certain type of shot with a constant radius, r, and mass flow rate, $\dot{m}$, the mass of a particle, m, is given by

$$m = 4/3\pi r^3\rho \tag{2.3}$$

The number of impinging shots per unit area per unit time R is given by