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A unifying approach in simulating the shot peening process using a 3D random representative volume finite element model

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Abstract Using a modified 3D random representative volume (RV) finite element model, the effects of model dimensions (impact region and interval between impact and representative regions), model shape (rectangular, square, or circular), and peening-induced thermal softening on resultant critical quantities (residual stress, Almen intensity, coverage, and arc height) after shot peening are systematically examined. A new quantity, i.e., the interval between impact and representative regions, is introduced and its optimal value is first determined to eliminate any boundary effect on shot peening results. Then, model dimensions are respectively assessed for all model shapes to reflect the actual shot peening process, based on which shape-independent critical shot peening quantities are obtained. Further, it is found that thermal softening of the target material due to shot peening leads to variances of the surface residual stress and arc height, demonstrating the necessity of considering the thermal effect in a constitutive material model of shot peing. Our study clarifies some of the finite element modeling aspects and lays the ground for accurate modeling of the SP process.

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1. Introduction

Shot peening (SP) is one effective cold-working surface treatment employed in numerous engineering applications[1] to improve fatigue strengths of metallic materials. In this process, numerous small round particles are blasted against the surface of a metallic component, where a particle is generally much stiffer than the component being treated and thus acts like a peen-hammer to create an impacting region of sizable localized plastic deformation. SP induces compressive residual stress (CRS) beneath the surface of the treated component[2] to resist crack nucleation and growth, thus enhancing the fatigue strength.[3] The resultant CRS field from SP can then be measured via experimental methods such as X-ray diffraction (XRD).[4] Besides the CRS field, in industries, the effectiveness of the SP process is often assessed by two other quantities, i.e., Almen intensity[5,6] and SP coverage.[7] For instance, Sabelkin et al.[8] found that the improvement of the fretting fatigue life of titanium alloy Ti-6Al-4V was directly correlated with the increase of Almen intensity. Barrie et al.[9] reported that surface inclusion cracking could be suppressed under the conditions of a high Almen intensity and a low SP coverage, therefore resulting in an improved fatigue life of superalloy Udimet 720. Numerical simulation using the finite-element (FE) method is frequently adopted to study the SP process.[10–13] FE modeling provides a predictive tool to quickly and quantitatively analyze the deformation states and CRS field in the SP process, without conducting expensive and time-consuming (sometimes even destructive or semi-destructive) experiments. It also allows quick assessment of the roles of different processing parameters involved in the inherently complex SP process.

In early FE efforts for modeling the SP process, only limited work has been reported to predict Almen intensity and SP coverage due to the inherent complexity of the SP process, which involves numerous factors and peening parameters. In addition, the incoming particles neither are uniformly distributed in space nor follow a predetermined shooting sequence.[14–17] Therefore, it is necessary to account for the randomness of impacting shots in order to realistically predict a resultant residual stress profile and its relation with the Almen intensity and SP coverage.[18–20] An actual SP process normally involves a substantial number of shots ($>10^5$) that land randomly on the targeted surface. To this end, recent FE studies[7,21–23] have utilized random 3D representative volume (RV) models. For instance, Miao et al.[21] proposed a rectangular prism RV model, in which all shots, randomly distributed, were directed toward a square impact region. The Almen intensity and SP coverage were then evaluated from the deformation states of an inner portion of the square region. Gariépy et al.[7] later employed an improved 3D random RV model based on the one proposed by Miao et al.[21], by involving the Rayleigh damping of the region surrounding the impact region to reduce stress oscillations, and considered samples of different thicknesses. In another study by Gangaraj et al.[22], a cylindrical random RV model with a circular impact region was constructed. In this work, the impact region was not differentiated from the representative region and the focus was on the development of a coverage profile instead of Almen intensity. Additionally, the thickness of such a cylindrical random RV model was set to be very large, e.g., equal to $6R$ (R being the radius of the shot), which failed to reflect the actual situation in industries where thinner samples, e.g., a 1.29 mm ($\approx 3.2R$ in their case) thick A-type Almen strip, have been more commonly used.[24]

To ensure reliable evaluation of peening factors such as residual stresses profile, Almen intensity, and SP coverage from multiple-shot 3D random RV FE simulations, it is important to properly partition the simulation cell (e.g., defining the impact and representative regions).[7,22] Nonetheless, so far the partition was done on an *ad-hoc* basis without a systematic criterion. Additionally, in previous works[22,25–27], the constitutive material model was prescribed by isotropic hardening laws without considering the temperature effect, to literally follow a ‘cold-working’ process. However, Iida and Tosha[28] investigated the work-softening effect on shot-peened steel, and observed that excessive shot peening resulted in softening of the surface layer.

Due to so many contradictions between present FE modeling methods and experiments, in the present study, we examined the influences of the dimension and shape of a 3D random RV model on FE simulation of the SP process, and clarified the criterion in partitioning the simulation cell. This paper is organized as follows: firstly, a random multiple-impact 3D RV FE model was constructed. Simulations were then performed to study the SP process with the Johnson-Cook plasticity model employed to prescribe the deformation response of the peened material. Secondly, the resultant peening parameters including residual stress, Almen intensity, and SP coverage, were evaluated, and their dependences on the dimension and shape of the 3D random RV model were systematically examined. Finally, the temperature effect and peening-induced softening were discussed.

2. Random multiple-impact 3D RV FE model

2.1. Model set-up and parameterization

In our study, 3D random RV FE simulations were performed to study the SP of an A-type Almen strip, which has been commonly used in industries[24] and has dimensions of 76 mm × 19 mm × 1.29 mm. The material is SAE 1070 spring steel in reference to SAE J442 standard.[29] The elastic response of the material is assumed to be isotropic while its plastic response is prescribed by the Johnson-Cook plasticity model[30] which considers the strain rate and temperature dependence of material behaviors as:

$$\sigma = [A + B(\varepsilon)^n]\left[1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right]\left[1 - \left(\frac{T - T_{\mathrm{r}}}{T_{\mathrm{m}} - T_{\mathrm{r}}}\right)^m\right] \qquad (1)$$

where σ is the flow stress, ε is the equivalent plastic strain (PEEQ) and $\varepsilon = \int_0^t \sqrt{\frac{2}{3}\dot{\varepsilon}^{\mathrm{pl}} : \dot{\varepsilon}^{\mathrm{pl}}}\,\mathrm{d}t$, in which $\dot{\varepsilon}^{\mathrm{pl}}$ is the plastic strain rate and t is the loading time, $\dot{\varepsilon}_0$ is the reference strain rate, T is the applied temperature, T_{r} is the reference temperature, and T_{m} is the melting temperature. A, B, C, n, and m are material constants. The Johnson-Cook parameters[27] and material constants such as elasticity modulus E, Poisson’s ratio υ, and density ρ corresponding to SAE 1070 steel are listed in Table 1. Rigid spherical shots are assumed given their high yield and hardness values compared to those of the target

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