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Prediction of shot peen forming effects with single and repeated impacts

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ABSTRACT

Peen forming processing is widely used for shaping a large thin-walled component by introducing compressive stresses in surface layer. To predict the peening stress, expensive and time-consuming analyses were needed in experiments and numerical simulations. This paper is aimed to calculate the random peening effects based on the results of single and repeated impacts. Three kinds of finite element simulation models are adopted, including repeated impacts and two shots apart impacts as well as random peening models. With the repeatedly impacting simulations, the stress fields under different repeated numbers are obtained. With the two shots apart impacting simulations, the interactions of adjacent impacts are revealed and a size of isoeffect region of one impact obtained. Comparing the results of the repeated impacts and of random peening simulations, an expression is proposed to calculate random peening stresses with peening coverage less than 90% from the stresses of single and twice repeated impacts. Comparisons of the calculated and simulated stresses of random peening shows the same tendency and depth of compressive stress as well as the close magnitude of maximum compressive stress. The equivalent stretching force and bending moment of the calculated stress are in good agreement with the values of random peening simulation. The simulated results are verified with experimentally measured dimple sizes and resultant curvatures of peened plates.

1. Introduction

Shot peen forming is an ideal process in developing aerodynamic contours of large panels that with reasonable small curvatures and without abrupt changes in the contours [1]. In the forming process, numerous shots puffed from peening nozzle with a high speed to randomly impact a component within reachable area. The impacts produce local plastic deformations resulting in residual compressive stress, which causes convex curvatures on the peened surface. The compressive stress also improves the resistance to fatigue of components. To obtain desired contours in peen forming process, it is essential to generate reasonable peening stresses by controlling peening parameters.

Many experimental and analytical as well as numerical researches have focused on establishing the relationships between peening parameters and stresses. Experimental measurements on peening stress involve destructive, semi destructive and non destructive methods [2], such as semi destructive hole-drilling method and non destructive X-ray diffraction method are usually used to directly measuring the stresses of saturation peening [3,4]. The measuring methods also can be combined with theoretical analysis to obtain complete peening stress field [5]. Owing to the peen forming treatments with relatively low peening coverage, the directly measuring methods are not recommended since the serious variations between impacting indentations. The resultant shapes of peen formed plates are usually used to reflect the relationships of peening parameters and peening effects [6].

Analytical calculation is an another approach to obtain peening stresses under specific peening parameters. Al-Hassani [7] expressed the induce stress profile with a cosine function, and determined with Hertz contact theory. Li et al. [8] proposed a simplified model based on elastic-plastic analyses to calculate the peening stresses of saturation peening. Several researches developed Li's model on considering more peening parameters and material properties of target [9–11]. Guechichi et al. [12] developed an analytical model based on the elastic-plastic spherical indentation model [13] to calculate the residual stress profile under certain shot velocity. In the application of previous analytical models, there are common assumptions that saturation peening, steady and continuous induced plastic deformations. However, the peening coverage of shot peen forming is usually selected at a low value [14], varying in a relatively large range, called general peening coverage.

Numerical simulation technologies are extensively adopted to reveal the peening mechanism and predict peening effects with general peening coverage. Miao et al. [15] summarized several different types of numerical simulation models for shot peening process. In order to reduce consuming computational resources, symmetry boundaries are

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Nomenclature

r_c	Radius of isoeffect region of one impact
$\bar{a}$	Average radius of shot dimples
v	Poisson's ratio of material
σ^{ind}	Induced stress
σ^{peen}	Peening stress
σ_s	Yield strength of material
a	Indentation radius
C	Peening coverage
E	Elastic modulus of material
F_i^{ind}	Equivalent stretching force of induced stress in i direction
M_i^{ind}	Equivalent bending moment of induced stress in i direction
m_{shot}	Mass of a shot
N_s	Total indentations
n_s	Indentation density
N_{unit}	Impacting density

employed on those numerical models. Bagherifard et al. [16] reviewed different multiple impact patterns and proposed a method to obtain high coverage percentages in random peening simulation. Owing to the present computer technology, it is hard to simulate the practical shot peening process involving millions of shot impacts. Han et al. [17] simulated the resultant shape of a peened component with a proposed two-stage strategy: obtaining peening residual stress profile on a small scale sample problem, then applying the stress profile to the entire component to obtain the resultant shape. Gariépy et al. [18] developed and applied Han's strategy to the peen forming operation of an aircraft wing panel. Although the sample scale selected as small as possible, considerable consumptions of computational resources on simulating a peening process involving dozens of shots are still needed. Jebahi et al. [19] developed a 3D random DEM-FEM coupling model to simulate a real shot peening process, where a sufficiently representative elementary volume is selected to reduce computation cost and obtain representative peening stresses. Kim et al. [20] estimate peening stresses with a 3D multi-impact symmetry-cell finite element (FE) model to minimize the simulation cost.

From above reviews, the multiply impacting results can represent the peening effects involving numerous impacts within reasonable ranges. This paper is aimed to reveal the relationships between random peen forming and multiple impacts, and establish a model to calculated the random peening stresses, under general peening coverage, from the results of single and repeated impacts. Section 2 introduces the estimation of random peening and evolution of peening stress. Based on FE technologies, a simulation model with 200 shots impacting a cubic target is proposed in Section 3, to obtain peening stresses of different peening stages. Multiply repeated impacting and two shots apart impacting models are also proposed to investigate peening mechanism. The simulation models are verified with peen forming experiments introduced in Section 4. Section 5 presents and discusses the simulated and experimental results in order of repeated impacting, two shots apart impacting and random peening, and establishes a relationships between random peening and multiple impacting. Section 6 concludes this work and suggests topic for further researches.

2. Random peening process

2.1. Measuring peening process with peening coverage

Peening coverage, defined as the ratio of indented area at least once to target area [21], is usually used to estimate the peening effects. In theory the random peening coverage can be calculated with Avrami equation [22] as

$$C = 1 - \exp\left(-\pi a^2 \eta t\right) \tag{1}$$

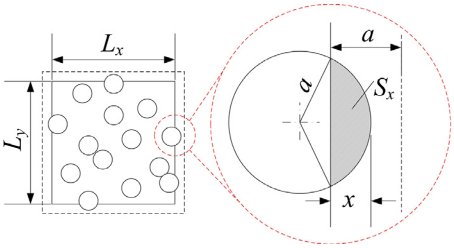

Fig. 1. Schematic diagram of shot dimple located on the boundary of representative peening region.

where, a is the projected radius of an indentation, η is the rate of indentation creation and t the peening time. The ηt indicates the current number of indentations within unit area, denoted as n_s, called indentation density. The average value of n_s can be determined by counting the indentations within a relatively larger region on a peened surface where indentations can be distinguished. With increasing peening coverage, it is hard to practically count the indentations, then the n_s can be derived from the previously determined values and the variations of the η and t.

In common FE simulation of shot peening, a finite region of target and a limited number of shots are involved for saving computational resources. Some shots may randomly locate on the boundaries of target surface as shown in Fig. 1. To precisely calculate the indentation density, the area of indentation out of the boundaries need be considered. The area S_x out of target region can be calculated with the indentation radius a and the intersecting depth x $(0 \le x \le a)$ as

$$S_x = a^2 \arccos\left(\frac{a-x}{a}\right) - (a-x)\sqrt{a^2 - (a-x)^2} \tag{2}$$

Then the intersected area within target region is $1 - S_x$. When the x approximates to 0, the whole indentation is almost included in the target region, and a tiny region is out of the boundary. The tiny width region xL should be added to the target region to calculate the indentation density by given the region xL a weight of about 1, where L denotes the total length of the boundaries. When the x is a, a half of area of an indentation is out of the target region, the weight given to the region xL should be 0.5. So $1 - S_x/\pi a^2$, which decreases from 1 to 0.5 with increasing x from 0 to a, is defined as a weight function to extend the target region. The extended area S_a can be calculated as

$$S_a = L \int_0^a \left(1 - S_x/\pi a^2\right) \mathrm{d}x \tag{3}$$

The indentation density n_c that considering the boundary effect in FE simulation can be expressed as

$$n_c = \frac{N_s}{S_T + S_a} \tag{4}$$

where, N_s is the total indentations on the target region S_T, $N_s = n_s S_T$.

To simplify above calculation, the S_x can be approximately represented by a linear expression $\pi ax/2$ with $0 \le x \le a$, then $S_a \approx 3aL/4$. The indentation density in a rectangular region with dimensions of $L_x \times L_y$ as shown in Fig. 1, where $L = 2(L_x + L_y)$, can be calculated as

$$n_c = \frac{2N_s}{2L_x L_y + 3a\left(L_x + L_y\right)} \tag{5}$$

Then the peening coverage can be calculated as

$$C = 1 - \exp\left(-\pi a^2 n_c\right) \tag{6}$$

2.2. Measuring peening process with impacting density

Impacting density N_{unit} also can be used to estimate the peening effects, defined as the number of shots impacted effectively on target