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Analytical modeling of shot peen forming process using cross-sectional linear indentation coverage method

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ABSTRACT

Shot peen forming process is a complex process in practice, and there are few analytical models published to facilitate analysis and design of the process. An analytical model of shot peen forming process is established by using cross-sectional linear indentation coverage method in this paper. Deformation of narrow-strip shot peened samples is examined by considering single indentation effect together with its distribution along a cross sectional line. Mathematical expressions are formulated to describe the deformation behavior of samples undergoing simple bending and simple extension. It is proven that the depth and coverage of indentations are the two essential factors that affect the deformation behaviors of the shot peened components. Verification shows that theoretical calculation agrees well with experimental observation.

1. Introduction

Shot peen forming, in which workpieces are deformed by bombarding the surface with a large number of small rigid balls [1], is still an important cold metal working process for forming large thin components with small-curvature, particularly in aerospace industries. However, due to the complicated effect of compressive residual stresses of randomly distributed indentations, shot peening operation is still amongst the most complex processes in practice, and available works on studying the theoretical modeling of shot peening process on macroscopic scale are very limited. This paper presents an analytical model of shot peening process.

Literature review shows that experimental and numerical methods are the main means adopted to model shot peening process. Almen strip intensity method is almost the most commonly used experimental method for quantitatively describing shot peening conditions in industrial practice [2]. Harburn and Miller [3] utilized Almen intensity as a unique indirect parameter to define peening conditions in different peening regions. Cao et al. [4] investigated the progressive deformation behavior, and explained the non-uniform curvatures observed in the constrained and free Almen strips. Miao et al. [5,6] performed detailed experimental studies to statistically establish quantitative relationships between the deformation of strips, peening parameters and other conditions such as pre-bending moment in shot peening of Almen sized aluminum 2024-T3 strips and 2024-T351 thick plates.

Almen intensity, which is usually characterized by the deformation extent or arc height of the Almen strips, was also used by many researchers as a criterion for optimally selecting peening conditions, for instance, the optimal conditions for resisting the propagation of fatigue cracks [7], the optimal peening parameters for improving mechanical properties [8] and the optimal peening media for strengthening metal alloy [9]. It should be pointed out that different peening parameters may correspond to the same Almen intensity, or vice versa [6,10]. That is, there exists a many-to-one or one-to-many relationship between peening parameters and the Almen intensity, and this will cause mathematical difficulties in modeling shot peening process. Thus, it is required to directly establish the relationship between the deformations of shot peened components and peening parameters.

Numerical methods can be effectively used to predict the deformation of a component under the given shot peening conditions. This is usually performed by treating the deforming action in the shot peened region as a series of equivalent loading layers, such as the squeezed layer model proposed by Grasty and Andrew [11], the equivalent thermal loading model presented by Levers and Prior [12] and Wang et al. [13], and the stress/strain profile loading method given by Han et al. [14]. However, the biggest problem of numerical approaches lies in that it cannot quantitatively reveal the relationship between deformation and peening parameters, and explicit means is still desired to detect the underlying mechanism of shot peening processes.

The motivation of this paper is to present an analytical model to relate the component deformation to shot peening parameters for better understanding the deformation behavior of shot peened components. A linear indentation coverage, i.e. average of indentations over a prescribed length, is utilized to derive explicit analytical relationships be-

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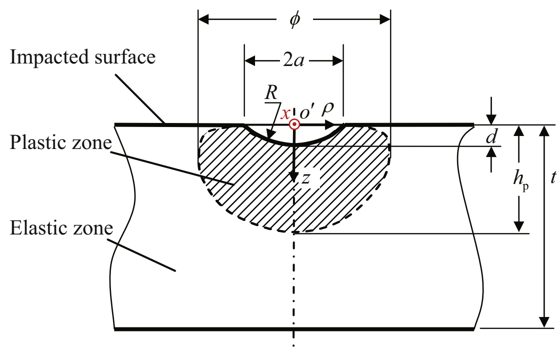

Fig. 1. Schematic diagram of plastic zone (shaded area) and adjacent elastic zone (blank area) of an indentation [14].

tween the deformation and detailed peening parameters. The deforming action of indentations is examined by considering individual indentation together with its distribution along a cross-sectional line. Deformations predicted by the proposed model are compared with experimental measurements to verify the validity of the new model. Finally, it should be mentioned that this work attempts to promote the understanding of the basic mechanical behaviors of shot peen forming, and thus, relatively simple cases of shot peen forming (e.g. simple bending or extending deformation) are first included in the model formulation. Process with pre-imposed strain or complex peening conditions, such as varying peening trajectories [15] and orientation of sheet rolling direction [16], remains as an open problem to be studied in the future.

2. Theoretical modeling

The deformation extent of shot peened components not only depends upon the local deformation induced by individual indentation but also the distribution of indentations. Any change of shots parameters, such as velocity, size or mass density, will result in a change of deformation extent. At the same time, any change of the distribution of indentations, for instance, coverage of indentations, will give rise to a change in the final shape of the peened component. Therefore, it is necessary to express the deformation of the shot peened components as a function of both the local deformation induced by individual indentation and the indentation's distribution.

2.1. Indentation geometry and compressive residual stresses

An indentation (see Fig. 1) produced by the elastic-plastic impact of a rigid ball is considered. The depth d, contact radius a and spherical radius R of the indentation are the significant parameters used to characterize the impact severity, and they meet the following geometrical relationship.

$$a^2 = 2Rd - d^2 \tag{1}$$

Previous work reported in Refs. [17,18] shows that

$$\frac{d}{R} = \left(\frac{2}{3}\right)^{1/2}\left(\frac{\rho_s V_0^2}{\bar{p}}\right)^{1/2} \tag{2}$$

and

$$h_p/R = 3(d/R)^{1/2} \tag{3}$$

where ρ_s and V_0 are the mass density and incident speed of the shot, respectively. $\bar{p}$ is the average contact pressure, and h_p is the depth of the plastic zone (see Fig. 1).

Eqs. (1) and (2) show that the effect of peening parameters on an indentation is characterized by d/R or h_p/R. By recreating Al-Obaid's data presented in Ref. [18], a better fitting of the experimental data (see

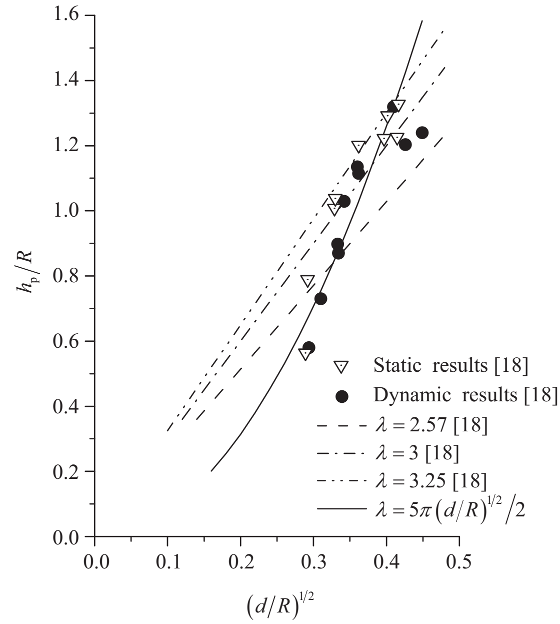

Fig. 2. Variation of h_p/R with d/R for dynamic and quasi-static loading by recreation of Al-Obaid's data [18].

Fig. 2) can be obtained as follows by introducing a varying coefficient, λ, into Eq. (2).

$$h_p/R = \lambda(d/R)^{1/2} \tag{4}$$

with

$$\lambda = \frac{5}{2}\pi(d/R)^{1/2} \tag{5}$$

As shown in Fig. 2, the coefficient (also the slope) λ increases with $(d/R)^{1/2}$.

Approximately, the radial diameter of the plastic zone ϕ shown in Fig. 1 is proportional to the depth of the plastic zone h_p.

$$\phi = \eta h_p \tag{6}$$

where η is a coefficient to be determined by experiment.

Owing to the interaction of plastic zones with the adjacent elastic field, compressive residual stress is trapped in the plastic zones. A simplified form of residual stress profile, σ_R, given by Al-Obaid [18] is adopted to approximately describe the residual stress within the plastic zones underneath indentations.

$$\frac{\sigma_R(z)}{Y} \approx -1 + 2\ln\left(\frac{z+R}{h_p+R}\right), \text{ when } 0 \le z \le h_p; \tag{7a}$$

$$\sigma_R(z)/Y \approx 0, \text{ when } h_p \le z \le t. \tag{7b}$$

where z is the coordinate in the thickness direction, which is defined in coordinate system $o'\rho xz$, as shown in Fig. 1. Y is the yield strength of the material. t is the thickness of the component, and it is assumed that $t \gg h_p$.

2.2. Linear coverage of indentations

In a pneumatic shot peening process shown in Fig. 3(a), a shot flow, propelled by the air flow through nozzles, impinges upon the surface of workpiece at the incident speed V_0 while the workpiece, carried by fixture, moves in the lateral direction (point into or out of the page) at a feeding speed v relative to the nozzles. An indentation strip of width L_s will then be produced on the workpiece surface with a random distribution of indentations. Neglecting the overlapping of indentations, the