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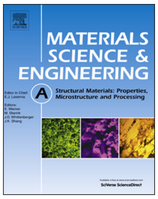

Experimental measurement and analytical determination of shot peening residual stresses considering friction and real unloading behavior

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ABSTRACT

This paper presents an analytical model to predict the residual stress distribution induced by Shot peening. The analytical approach is based on the work of Shen and Atluri (2006) [18] with some modifications. The modifications are related to the elasto-plastic unloading of shot impingements, friction coefficient effect and the fraction of kinetic energy transmitted to the treated material. In order to predict more realistic residual stresses, the elasto-plastic unloading phase of shot impacts is modeled using two nonlinear kinematic hardening models considering the Bauschinger effect. Moreover, the effect of the Coulomb friction between target surface and shots is evaluated. For this purpose, the interior stresses caused by tangential tractions of friction force are determined analytically. In this work, the effects of friction coefficient, hardening model in loading and unloading phases, the offset of determination of the yield points and the Bauschinger effect on the residual stress distribution are taken into account. Experiments are carried out on DIN 1.6582 medium carbon steel to validate the results obtained from the analytical model. The results of the comparison indicate that the analytical relations agree well with the experimental data.

1. Introduction

Shot peening is a cold-working process commonly used in industry to improve the fatigue performance, stress corrosion resistance and surface nano-crystallization of metallic parts. This process extends fatigue life via two mechanisms: (1) preventing the crack growth due to compressive residual stresses and (2) retarding the crack initiation because of increased material hardness. These beneficial effects are the results of the bombardment of the component's surface with small spherical particles. During impingement, a local plastic deformation is created below the indentations and a compressive residual stress (CRS) field is generated in the near surface layers of the structural component.

Numerous experimental studies [1–3] on the effect of shot peening parameters on compressive residual stress distribution and the extended fatigue life have been published over the past decades. Numerical simulations [4–8] of the shot peening process have also begun to predict the influence of shot peening parameters on the residual stress (RS) field.

Dynamic system and contact are two parameters which make the shot peening a considerably complex process. Despite the complicated behavior of the shot peening process, researchers attempt to calculate the CRS distribution using approximate methods. Several studies have been published on developing analytical and numerical models for estimating the shot peening RS. In previous works, the effect of changing different shot peening parameters such as shot velocity, shot diameter, Almen intensity and peening coverage have been investigated. A comprehensive review of the wide variety of analytical and numerical modeling of the shot peening process reveals that the complicated mechanism of shot peening is inadequately developed.

The earliest work on analytical solutions for contact of a spherical shot and a semi-infinite body can be found in Hertz works. Hertz was the first scientist to develop the stresses at the contact of two elastic solids. Hertz calculations in this field were lately used by the other researchers to determine the residual stress distribution induced by shot peening. The overall researches about the shot peening residual stresses can be generally categorized into two groups: the first group is based on Guechichi's [9] theoretical model while the second group is based on the Li et al. [10] work.

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The first theoretical attempts for determining the residual stress filed of shot peening were made by Flavenot and Nikulari [11]. They utilized the stress source technique which is defined for the target material in shot peening process, to estimate the mentioned CRS.

In order to determine CRS induced by shot peening, Al-Hassani [12] and Al-Obaid [3] used the Flavenot's [11] concept of a stress source in a spherical cavity model. In their research, the RS field induced by impingement of shots with target surface was modeled as a spherical cavity undergoing elastic plastic deformation. They considered the elastic-perfectly plastic model to describe the material behavior of target part. However, this model is not suitable for real world application. Moreover, Al-Hassani proposed several theoretical models to predict shot peening CRS by utilizing experimental findings [12,13].

Guechichi [14] proposed a fundamental analytical model to determine shot peening CRS. His model was based on Hertzian contact theory as well as an elasto-plastic calculation method presented by Zarka et al. [15]. By using Isotropic and linear Kinematic hardening model along with the Zarka et al.'s [15] elasto-plastic method, he obtained good results for RS filed. However, his method was complicated and computationally expensive. Using appropriate material behavior laws for target material, Khabou et al. [16] improved the Guechichi model. They investigated the effect of constitutive laws and different hardening models on RS distribution. Fathallah et al. [17] extended the Guechichi model by considering tangential friction, angle of impingement and hardness ratio and so studied the effect of these parameters on CRS profile.

Beside Guechichi's analytical model, Li et al. [10] outlined another basic approach for modeling CRS which has been referred by many researchers. Using the Hertzian contact theory and IIyushins elastic–plastic theory, they presented a simple mechanical approach to approximate the CRS induced by shot peening. The bilinear hardening model was used in their approach to estimate the residuals stresses. The main disadvantage of their model is the need for empirical measurement of the produced dents due to shot impingement. In addition, the hardening model used in their approach is very preliminary. Li et al. [10] mentioned that the lack of considering the Bauschinger's effect and the multiple shot impingements could be the sources of error in their results.

Shen and Alturi [18] improved the Li et al.'s model by analytical calculation of the plastic radius of the dents. They used the average pressure distribution presented by Al-Hassani [19] to determine an analytic relation for the dent's radius in perfectly plastic condition. They modeled the dynamic impact instead of static contact to make the model capable of considering the effect of shot velocity and shot diameter.

By adding the strain rate effect, Bhuvaraghan et al. [20] improved Li et al.'s approach. In his work, Johnson–Cook model was used in elastic–plastic calculations and the Nueber's relation was utilized instead of an elastic–plastic coefficient to calculate plastic strains. The CRS distributions obtained from Bhuvaraghan were not in good agreement with the experimental findings.

Franchim et al. [21] investigated the effect of the plastic behavior of the target material on the CRS profile using the Ramberg–Osgood and Ludwick constitutive models. They showed that the hardening model of target material play a major role in RS distribution. Compared to the Li et al.'s model, their results were considerably different due to applying different hardening models.

The effect of shot peening parameters on both Almen intensity and RS distribution in Almen strip was analytically investigated by Miao et al. [22]. In their study Li et al. and Shen and Alturi models were used to calculate CRS distribution and the method presented by Guagliano [23] was utilized to estimate the arc height in the Almen strip. The following two sources of error were mentioned in their research: (1) the model considered only one impact and did not take into account the repeated peening passes. (2) The experimental constraints allow small deflection of constrained strips while this deflection is not modeled in analytical calculations [22].

The previous studies reveal that the models describing the materials behavior have significant role in CRS determination. In shot peening process, however, due to accidental nature of shots impingement, it is probable to have more than one incident. In all previous researches, behavior law of target material in loading and unloading processes, were considered identical, while this assumption is not always true in practical situations. Additionally, researchers used the Iliushins plasticity theory which is only appropriate for monotonic loading. In most materials, specifically in high-strength steels the stress–strain curves of loading and unloading are significantly different. The main differences are found at the end of the elastic region and the shape of hardening constitutive law. Each of these differences can lead to considerable changes in the RS field induced by shot peening. Moreover, the effect of the friction on residual stresses induced by shot peening is not taken into account in previous analytical works. Among the analytical papers discussed in introduction, only Fathallah et al. [17] have considered the effect of friction on shot peening residual stresses for oblique shot peening. In Fathallah et al.'s work [17], the effect of the tangential friction between the shot and the treated material is investigated for the certain direction of nuzzle motion and by using the simple relation of tangential traction.

In the current research, a plasticity model appropriate for cyclic loading instead of Iliushins elastic–plastic model is used. Furthermore, in order to model the unloading process more realistically, the Bauschinger effect and cyclic hardening model are utilized to predict the RS distribution. Also in the present study, the effect of the friction between shots and target material in slip zone of the contact area is considered.

2. Analytical modeling of the residual stresses

2.1. elastic relations of the loading process

The elastic loading process of the shot peening is the same as the Li et al.'s [10] method developed by Shen and Atluri [18]. In this process, it is assumed that the spherical shots with the same dimensions are impinged to the target surface uniformly with a distinct angle. The target part is assumed to be semi-infinite and elastic.

According to the Hertzian contact theory, when the elastic compression reaches its maximum value, the radius of the elastic contact dent between the shot and the semi-infinite body, is obtained as:

$$a_e = \frac{\pi p_0 D}{2E_H} \tag{1}$$

where P_0 is the maximum pressure at the center of contact surface, D is the shot diameter and E_H is the equivalent elastic modulus which can be obtained in terms of E_s, shot's elastic modulus and E_t, target's elastic modulus as follows:

$$\frac{1}{E_H} = \frac{1-\nu_s^2}{E_s} + \frac{1-\nu_t^2}{E_t} \tag{2}$$

also, P_0 in Eq. (1) is obtained as:

$$p_0 = \frac{1}{\pi}\left(40\pi\rho k E_H^4 (V \sin\,\theta)^2\right)^{\frac{1}{5}} \tag{3}$$

In Eq. (3), V is the shot's velocity, θ is the angle of impingement, ρ is the shot's density and k is an efficiency coefficient related to