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Effect of initial surface treatment on shot peening residual stress field: Analytical approach with experimental verification

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ABSTRACT

Shot peening is the most common surface treatment employed to enhance the fatigue performance of structural metallic materials and often carried out after other surface treatments. This paper mainly focuses on the effects of initial conditions of surface such as initial stress filed and hardness profile on shot peening residual stress field. The residual stress distribution induced by shot peening is obtained using Hertzian contact theory and elastic–plastic evaluation after yielding occurred during impingement and rebound of shots. Elastic plastic calculations are performed using different hardening models considering Bauschinger effect. The present model is able to predict redistribution of residual stresses in shot peening process by considering the initial conditions of target surface. Initial stress distribution and yield stress variation produced by previous surface treatments are taken into account by measuring residual stresses and hardness profile at near surface layers. An analytical parametric study is performed to evaluate the influence of initial conditions induced by surface pretreatments on shot peening residual stress field. The results of analytical model are validated by experimental data obtained in the literature as well as by our own measurements. The analytical results generally agree with the experimental measurements.

1. Introduction

To improve the fatigue performance, surface nano-crystallization and stress corrosion resistance of metallic components, shot peening is widely used in many industries. During shot peening, a large number of small shots impinge on the target surface at velocities in the range of 30–100 m/s. Resulting from each impingement, near surface layers undergoes compressive plastic deformation and consequently, compressive residual stress field (CRSF) is created. These compressive residual stresses are balanced by tensile residual stresses which are located in beneath the compressive layers.

A great number of numerical and experimental studies have been dedicated to investigate the effect of shot peening parameters such as shot velocity [1–6], shot diameter [5–8], Almen intensity [1–3,6–8] and peening coverage [1–4,9] on the CRSF. Also, many researchers have examined the role of shot peening process and generated CRSF on the extended fatigue life over the past decades [7,10–12].

Nevertheless, only a few studies have been carried out to investigate the effect of the initial residual stress field (IRSF) produced by primary surface treatments on shot peening residual stresses [13–16]. One of the comprehensive studies on this topic has been conducted by Mahmoudi et al. [13] in which they have investigated the effects of the IRSF on residual stress distribution induced by shot peening both experimentally and numerically. In their work, IRSF was induced using a four-point bending rig and grinding. Numerical analyses and experimental measurements of these processes were performed to provide quantitative comparison of different combinations of residual stresses [13]. In addition to Mahmoudi's et al. work, the effect of the initial conditions of surface pretreatments on shot peening CRSF have been investigated experimentally by a few researchers such as Hatamle and DeWald [14], Molzen and Hornbach [15] and Sidhom et al. [16].

Several analytical researches have been made to better understand the effects of various shot peening parameters on CRSF. Guechichi [17] outlined an analytical model to determine shot peening CRSF based on Hertzian contact theory and using Zarka elasto–plastic calculation method. Thereafter, Guechichi 's model improved by Khabou et al. [18] and Fathallah et al. [19].

Li et al. [20] proposed a mechanical approach for estimating CRSF of shot peening using the Hertzian contact theory and Iliushins elastic–plastic theory. Shen and Atluri [21] proposed a theoretical relation for the plastic indentation instead of empirical one and also added shot velocity to Li's model. Later, Bhuvaraghan et al. [22] included in Li's model the strain rate effect. Franchim et al. [23] improved Li's approach by considering the Hertzian pressure as a dynamic load and using the Ramberg-Osgood and Ludwick hardening models to

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Nomenclature

Latin characters

a	indentation radius
D	shot diameter
E	elastic modulus
F	tensile force
h	thickness of target part
H_V	Vickers hardness
k	efficiency coefficient of energy dissipation
K_l	strength coefficient of linear hardening model
K_p	strength coefficient of power-law hardening model
m	strain hardening exponent
M	bending moment
P_0	maximum pressure of Hertzian contact
S_{ij}	components of the deviatoric stress tensor
V	shot velocity
z	depth variable

Greek characters

β	Bauschinger factor
ε_{ij}	components of the strain tensor
θ	angle of impingement
ν	Poisson ratio
ρ	mass density
σ_0	initial residual stress field
σ_{ij}	components of the stress tensor
ψ	plastic strain to elastic strain ratio

Subscripts

eq	equivalent
l	loading process
s	shot
t	target part
un	unloading process
Y	yield stress

Superscripts

e	elastic
p	plastic
rel	relaxed stress
res	final residual stress

describe plastic behavior of treated part. Furthermore, Miao et al. [24] analytically estimated CRSF and arc height in the Almen strip for different combinations of shot peening parameters. Also, the effects of friction between shots and target material, real unloading behavior and kinetic energy dissipation of shot impact on the resulting CRSF were investigated by Sherafatnia et al. [25].

In spite of the above mentioned studies, there has been no analytical study considering IRSF in the literature except one by Wang et al. [26]. Wang et al. [26] studied on the residual stress distribution induced by shot peening with considering the initial welding stresses. Using Hertzian elastic contact theory, the shot peening stresses superposed with initial welding stress field and after yielding occurred, the CRSF determined based on elastic plastic evaluations. Due to lack of enough data to calculate plastic strain deviators, these strains were obtained from elastic stress deviators. So, with this simplified assumption, the ratio of deviatoric stress components of elastic model and elastic-plastic model were considered similar, which needs to be modified. Also, the effect of the hardness change due to welding process at near surface layers is not considered in their work.

Reviewing the existing work mentioned above, nearly all the analytical works were done without considering the initial conditions such as near surface material properties and residual stress field. In the shot peening process, the IRSF interacts with shot peening one and can influence on the CRSF. Since creating the residual stresses in pretreatment processes is inevitable and experimental tests and FE simulations are expensive and time consuming, so a suitable analytical model for considering the IRSF is required.

In the current research, an analytical model is proposed to determine residual stress distribution induced by shot peening after primary surface treatments. This model is able to consider the initial equi-biaxial residual stress and near surface hardness distribution produced by primary surface treatment. Also, unlike previous analytical models the current model can estimate the tensile residual stresses which created beneath the compressive layer. In elastic plastic calculations, the Bauschinger effect in reserve yielding and different hardening parameters in loading and unloading phases are utilized. Moreover, shot peening experiments are done with and without IRSF induced by grinding. The results of proposed analytical model for shot peening residual stresses are verified with our own experiments on ground samples and experimental measurements from other studies on welded samples.

2. Analytical model

2.1. Primary state of stresses

In order to evaluate the effect of the shot peening process on initial stresses induced by other treatments, the IRSF is defined as a function of depth. In this article, we focus on the primary surface treatments which produce equi-biaxial residual stress distribution (e.g. grinding and turning). It is assumed that the IRSF only exist in X and Y principle directions. Accordingly, the IRSF can be defined as $\sigma_{0x} = \sigma_{0y} = \sigma_0(z)$. According to Hook's law, the elastic stress and strain field induced by shot peening with initial equi-biaxial stresses can be obtained as:

$$\begin{aligned} \sigma_x^e &= \sigma_y^e = \sigma_x^{es} + \sigma_0 = \sigma_y^{es} + \sigma_0 \\ \sigma_z^e &= \sigma_z^{es} \end{aligned} \tag{1}$$

$$\begin{aligned} \varepsilon_x^e &= \varepsilon_y^e = \frac{1}{E_t}(\sigma_x^{es}(1-\nu_t) - \nu_t\sigma_z^{es}) \\ \varepsilon_z^e &= \frac{1}{E_t}(\sigma_z^{es} - 2\nu_t\sigma_x^{es}) \end{aligned} \tag{2}$$

The equivalent Von-Mises stress and strain in elastic state are derived as given in Eqs. (3) and (4), respectively.

$$\sigma_{eq-l}^e = \left(\frac{1}{2}\left((\sigma_x^e - \sigma_y^e)^2 + (\sigma_x^e - \sigma_z^e)^2 + (\sigma_z^e - \sigma_y^e)^2\right)\right)^{1/2} = \left|\sigma_x^{es} - \sigma_z^e + \sigma_0\right| \tag{3}$$

$$\varepsilon_{eq-l}^e = \frac{\sigma_{eq-l}^e}{E_t} \tag{4}$$

It should be noted that in above equations, the superscript index "es" and subscript index "l" belong to the elastic stresses generated by shot peening in the absence of IRSF and loading process, respectively.

Most surface treatments cause to change the mechanical properties of metals by heating them to a high temperature and then cooling back to room temperature (e.g. welding and rough grinding). Different conditions including temperature and cooling rate usually affect the mechanical properties of metals such as yield strength [27]. So, the primary yield strength is not constant in depth and should be considered as a function of z. Temperature change of component surface lead to increase (or decrease) in hardness of near surface layers. Hence, primary yield stress modified as a function of z using the below empirical relation [28]:

$$\Delta\sigma_Y = K\,\Delta\,H_V \tag{5}$$

where $\Delta\sigma_Y$and $\Delta\,H_V$ are yield stress in MPa and Vickers hardness in Kg/mm^2. K is a constant which has different values for different materials and generally get values between 2 and 4 [29,30]. Therefore, based