Materials and Design 31 (2010) 50–59

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

An area-average approach to peening residual stress under multi-impacts using a three-dimensional symmetry-cell finite element model with plastic shots

Taehyung Kim [a,*], Jin Haeng Lee [a,b], Hyungyil Lee [a], Seong-kyun Cheong [c]

[a] Department of Mechanical Engineering, Sogang University, Seoul 121-742, Republic of Korea
[b] Department of Materials Science and Engineering, The University of Tennessee, Knoxville, TN 37996, USA
[c] Department of Mechanical Engineering, Seoul National University of Technology, Seoul 139-743, Republic of Korea

ARTICLE INFO

Article history:
Received 3 June 2009
Accepted 13 July 2009
Available online 23 July 2009

Keywords:
Shot peening
Residual stress
Symmetry-cell
Area-averaged solution
Multi-impact
Finite element analysis

ABSTRACT

We estimate realistic peening residual stress based on area-averaged solution using a 3D multi-impact symmetry-cell finite element (FE) model. The analytical model includes elaborate factors reflecting actual peening phenomena and plastic shot effect. Area-averaged solution is much closer to X-ray diffraction (XRD) experimental solution than four-node-averaged solution in plastic shot FE model. The area-averaged solution, moreover, converges to the perfect equi-biaxial stress state. From this, based on the area-averaged solution, we obtained the FE Almen curve, and then derived related equations among FE arc height, FE coverage and shot velocity. The FE Almen curve corresponds well with experimentally obtained by Kim et al. [Kim T, Lee JH, Lee H. An Effective 2D FE model with plastic shot for evaluation of peening residual stress. J Mater Process Technol, submitted for publication; Kim T, Lee H, Lee JH. A 3D phenomenological FE model for unique solution of peening stress due to multi-impacts. Int J Numer Methods Eng, submitted for publication]. Using the FE Almen curve, we examine the FE area-averaged solution in major peening materials. The FE solutions of surface, maximum compressive residual stress and deformation depth quite reach experimental solutions. The FE Almen curve is thus confirmed to be useful for estimation of residual stress solution. Consequently, we validated that the concept of area-averaged solution is the systematical analytical method for evaluation of real peening residual stress.

1. Introduction

Shot peening has been widely used in automotive, power plant and aerospace industries to improve fatigue life of mechanical parts by generating useful compressive residual stress on the surface of metal. Peening residual stress is a main factor directly affecting the material behavior such as fatigue fracture, corrosion and wear. Therefore it is quite important to quantitatively evaluate residual stress for various peening conditions. An experimental Almen saturation curve used for prediction of the capacity of peening equipment and peening intensity is usually adopted in shot peening process. Using main parameters such as arc height, peening coverage and impact velocity which correspond to the curve, we can estimate peening residual stresses of various materials. Normally peening residual stress is measured by experimental method [3–7] using X-ray diffraction (XRD). However, the XRD measurement method is needed considerable cost, time and skillful technique. For this reason, the residual stress has been generally predicted by theoretical methods [8–10], and recently evaluated by lots of studies using finite element (FE) analysis.

In the early stage of FE analyses for peening, single impact and indentation FE models were largely used [11–16]. Recently, the single shot impact analytical model also was introduced by some researchers [17,18]. These FE analysis studies evaluated the residual stress field by assuming the single shot impact as 100% peening coverage on the surface of shot peened material. Multi-impact FE analyses closer to real shot peening phenomena have been performed in large numbers thereafter [19–22]. In these works, however, real peening phenomena including plastic deformation of shot were not sufficiently applied to the FE analyses, and examination of convergence to equi-biaxial stress and comparison between FE and experimental solutions were excluded. Kim et al. [1] have therefore proposed a 2D FE model including more realistic combined factors and plastic shot effect in a single shot impact, and extended it to a 3D FE model in multi-impacts [2]. Applying peening phenomena with FE coverage, impact sequence and cycle-repetition to the model additionally, they obtained an improved solution of equi-biaxial peening residual stress. However, previous FE analysis works merely gave single-node solutions on the surface of FE model. Namely, they did not consider concept of the area-averaged

* Corresponding author. Tel.: +82 2 705 8636; fax: +82 2 712 0799.
E-mail address: kthmax@sogang.ac.kr (T. Kim).

0261-3069/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.matdes.2009.07.032

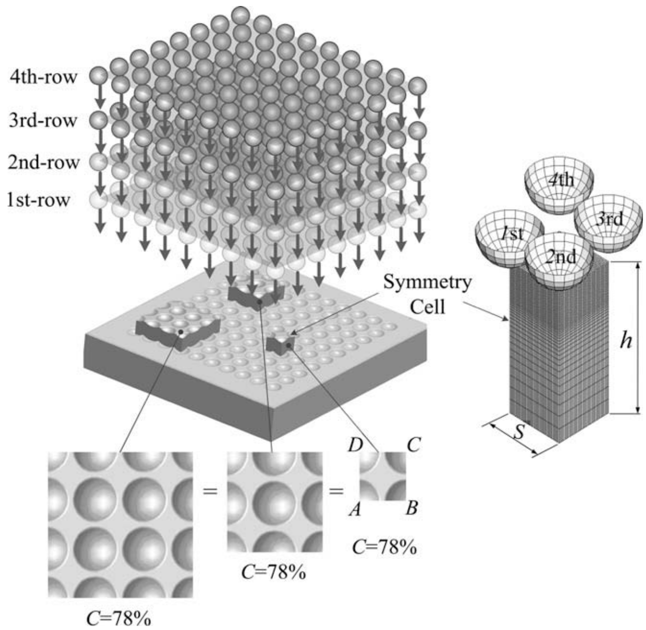

Fig. 1. FE symmetry-cell model for area-averaged residual stress of shot peening under multi-impacts.

solution. Consequently, it is clear that some amount of error between the FE solution and the experimental solution exists. Because generally experimental XRD residual stress is measured at area where is irradiated by X-ray. Boo et al. [23] experimentally measured residual stress solution at the ∅4 mm circular area irradiated by X-ray on the surface of WC–Co hardmetal. Hong et al. [24] evaluated the XRD residual stress at the 2 mm × 7 mm area. Recently Jakobsen et al. [25] estimated characteristic of strain at the 0.25 mm × 0.5 mm area irradiated on surface of material by 3D X-ray beam source. Especially, in the experimental peening studies, Prevey and Cammett [26] explained the relationship between area-averaged solution at the 5 mm × 5 mm area and peening coverage experimentally. Kirk and Hollyoak [27] obtained various area-averaged solutions of surface residual stress at the areas with 4 mm × 4 mm, 12 mm × 1 mm and 4 mm × 1 mm. For this reason, in this work, we evaluate the peening residual stress quantitatively using a new analytical approach based on concept of the area-averaged solution. Considering the experimental area-averaged solution, in this work, we first obtain the area-averaged FE solution from total nodes included at each cross-section of a 3D symmetry-cell model suggested by Kim et al. [2] in multi-impacts.

Moreover, prior studies did not considered Almen curve with arc height and peening coverage, which are essential to explain the real shot peening phenomenon. The Almen curve therefore has huge meaning in a numerical approach to quantitative evaluation of peening residual stress. Therefore, we predict the FE Almen curve using area-averaged solution, and derive the relationship among the FE arc height, FE peening coverage and impact velocity, and confirm usefulness of the FE Almen curve comparing the FE Almen curve with experimental curve. Substituting FE peening coverage and FE arc height into the derived equations, we obtain the impact velocity. Adopting the velocity to the FE model, we obtain four-node-averaged and area-averaged solutions of peening residual stresses after FE analysis, and we then compare these FE solutions with XRD experimental solution. Comparing FE solutions with XRD experimental solution, we examine closeness to experimental solution on the surface, maximum compressive residual stress and deformation depth. Ultimately, we propose the validation of the 3D multi-impact FE model integrated with FE Almen curve and plastic deformable shot based on area-averaged solution.

2. A 3D finite element model for area-averaged solution of peening residual stress

2.1. Finite element modeling and boundary conditions

Using the 3D symmetry-cell FE model proposed by Kim et al. [2] as shown in Fig. 1, we obtain area-averaged FE solution of peening residual stress in multi-impacts. We fixed S, which means a distance between shots (or a side of a cross-section of symmetry-cell), on the same shot radius R as $S = R = 0.4$ mm. This is because when

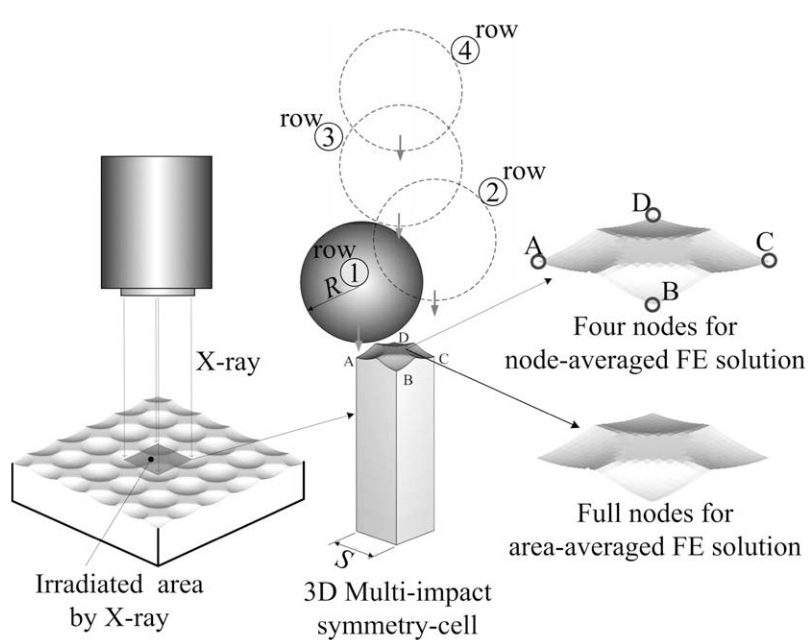

Fig. 2. Four and full nodes in symmetry-cell model for peening residual stresses.