Materials and Design 90 (2016) 478–487

Contents lists available at ScienceDirect

Materials and Design

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

A comprehensive experimental and numerical study on redistribution of residual stresses by shot peening

A.H. Mahmoudi [a,*], A. Ghasemi [a], G.H. Farrahi [b], K. Sherafatnia [b]

[a] Mechanical Engineering Department, Bu-Ali Sina University, Hamedan, Iran
[b] School of Mechanical Engineering, Sharif University of Technology, Tehran, Iran

ARTICLE INFO

Article history:
Received 8 September 2015
Received in revised form 18 October 2015
Accepted 31 October 2015
Available online 2 November 2015

Keywords:
Shot peening
Residual stresses
Redistribution
Grinding
Finite element

ABSTRACT

Shot peening is one of the most effective surface strengthening treatment technologies in which compressive residual stresses are induced beneath the specimen surface. Effects of various factors on the distribution of residual stress profile induced by shot peening have been investigated by many researchers. However, initial residual stresses are one of the important factors which affect the shot peening residual stress.

This study is aimed to present comprehensive numerical and experimental study on the effect of initial residual stresses on the shot peened specimen. Initial residual stresses were induced using a four-point bending rig and grinding. Incremental center hole drilling (ICHD) technique was employed to measure residual stresses on bent, ground, shot peened, bent plus shot peened and ground plus shot peened specimens. Numerical analyses of these processes were performed to provide quantitative comparison of different combinations of residual stresses. The comparison with experimental results helped to have a better understanding on how shot peening residual stresses were redistributed. Furthermore, the surface hardness was measured for all specimens.

1. Introduction

Shot peening is one of the most effective mechanical surface treatments generally applied to improve fatigue life of engineering components. Shot peening is carried out to postpone the crack initiation or reduce the propagation rate. In shot peening, a target is peppered using small spherical shots with a velocity of 20–100 m/s. The outcome is a compressive residual stress field beneath the surface of metallic components. Shot peening is widely used in automobile, power generation and aerospace industries [1–7].

Many studies have been carried out on the shot peening process. Al-Hassani [8], Hills et al. [9], and Al-Obaid [10] developed the analytical approaches to predict shot peening residual stresses. Al-Obaid [11] attempted to perform a simple numerical simulation of shot peening process. Mori et al. [12] considered the plastic deformation for both work piece and shots. In another study by Meguid et al. [13] a quarter symmetry model was presented in which both single and twin shot impacts on the target surface were considered. Boyce et al. [14] presented the quasi-static and dynamic finite element models to simulate a single shot impacting the surface. Guagliano [15] developed a finite element model with five subsequent shot impacts to relate effects of important parameters such as velocity and shot size on the residual stress and Almen intensity. Hong et al. [16,17] simulated single shot impact model and investigated the effect of parameters such as shot diameter, impact velocity, incident angle and component material properties on the residual stresses distributions in the target. Shivpuri et al. [18] created a 3D finite element model of shot peening to investigate the effect of process parameter and surface material response on distribution of residual stress. The single shot impact model [18] was validated by comparing the measured results to previously published experimental results presented by Kobayashi et al. [19].

Meguied and his co-workers created a symmetry cell to simulate shot peening process [20]. They considered parameters such as separation distances between adjacent shots, material damping and strain rate sensitivity for target and plastic properties on shots. Majzoobi et al. [21] performed a simulation on the shot peening process using a multi-impact symmetry cell model. Frija et al. [22] developed a model to study the effect of the friction coefficient. Kim and his co-workers [23] predicted residual stress profile based on area-average approach using a symmetry cell finite element model. Also, Kim et al. [24,25] presented a three dimension finite element model using several vertical shots impacting. The effects of material damping, dynamic friction, strain rate, impact patterns and impact sequence on the residual stress profiles were also investigated. In the modeling of shot peening process by other researchers parameters such as influence of impact angle and impact pattern [26], changes of material state in the treated area [27], using combined hardening for target material model [28] have been investigated. Others have examined the application of shot peening on aluminum [29] and steel [30] plates. The severe shot peening and its effect on creating nano-structured surface was studied by Bagherifard et al.

* Corresponding author.
E-mail addresses: a.h.mahmoudi@gmail.com, a.h.mahmoudi@basu.ac.ir (A.H. Mahmoudi).

http://dx.doi.org/10.1016/j.matdes.2015.10.162
0264-1275/

[31]. The surface roughness as a function of processing time and the impacting ball size was evaluated by Dai et al. [32] using the impact simulation of surface nanocrystallization and hardening process. Child et al. [33] investigated the depth of strain-hardening effects of shot-peening treatments applied to the Ni-based super alloy. The effect of shot peening on the microstructure, oxygen ingress and high-cycle fatigue properties of the titanium alloy was also examined by Thomas et al. [34].

The computational cost is also another aspect that has been considered by researchers [35]. A random positioning of shots to simulate shot peening was developed by Hassani-Gangaraj et al. [36]. Furthermore, shot peening has been used to interact with other residual stress fields such as welded samples [37], warm peened and pre-stressed rods by torsion [38], welded aluminum alloy samples [39] and combination of severe shot peening and nitriding on fatigue life [40].

Effects of various factors on the distribution of residual stress profile induced by shot peening have been investigated by many researchers. Initial residual stresses on the shot peened specimen are one of the important factors which affect the distribution of residual stresses. All mechanical processes can cause deformation that may lead to residual stresses within the engineering components. However, a comprehensive study in the literature on the effect of present initial residual stress on the shot peened specimen is still missing. This study is aimed to investigate effects of initial residual stress on the distribution of residual stress profile inducted by shot peening both experimentally and numerically. Initial residual stresses were generated using a four-point bending rig and rough grinding. Incremental center hole drilling (ICHD) measurement of residual stresses were carried out on bent, ground, shot peened, bent plus shot peened and ground plus shot peened specimens. Finite element simulations of these processes were also performed to provide a quantitative description of the effect of initial residual stresses on the redistribution and magnitude of residual stresses. The numerically predicted residual stresses were verified using experimental results. Furthermore, the surface hardness was measured for all samples.

2. Material, specimens and test procedures

The material used in this study was low-alloy steel DIN 34CrNiMo6 (1.6582) with the chemical composition presented in Table 1. In order to obtain monotonic properties of the material, tension tests were carried out according to ASTM E8M [41] as shown in Fig. 1(a). A set of cyclic tension compression tests were carried out to obtain the properties required for the nonlinear isotropic/kinematic hardening model. The evolution law of this model consists of two components: a nonlinear kinematic hardening component and an isotropic hardening component, as a function of plastic deformation. The kinematic hardening component was defined by specifying test data from a stabilized cycle. On the other hand, isotropic hardening component was defined by specifying the equivalent stress defining the size of the yield surface, as a function of the equivalent plastic strain. The simplest way to achieve these data was to conduct a symmetric strain-controlled cyclic experiment. Strain-controlled low-cycle fatigue tests were applied up to the stabilized cycle on cylindrical specimens at different strain intervals of ($\Delta\varepsilon = 0.012$, $\Delta\varepsilon = 0.06$). The specimens were prepared according to ASTM E606 [42]. Fig. 1(b) illustrates a picture of cyclic test sample. The stabilized cycle was obtained after 4 cycles which was used in order to make a more realistic model by simulating low number of cycles. Both monotonic tension and cyclic tension-compression test were carried out using an Instron servo-hydraulic testing machine.

Table 1
Chemical composition of steel grade 1.6582 used in this study (wt.%).

C	Si	Mn	Ni	P	S	Cr	Mo
0.34	0.272	0.743	1.341	0.025	0.017	1.58	0.18

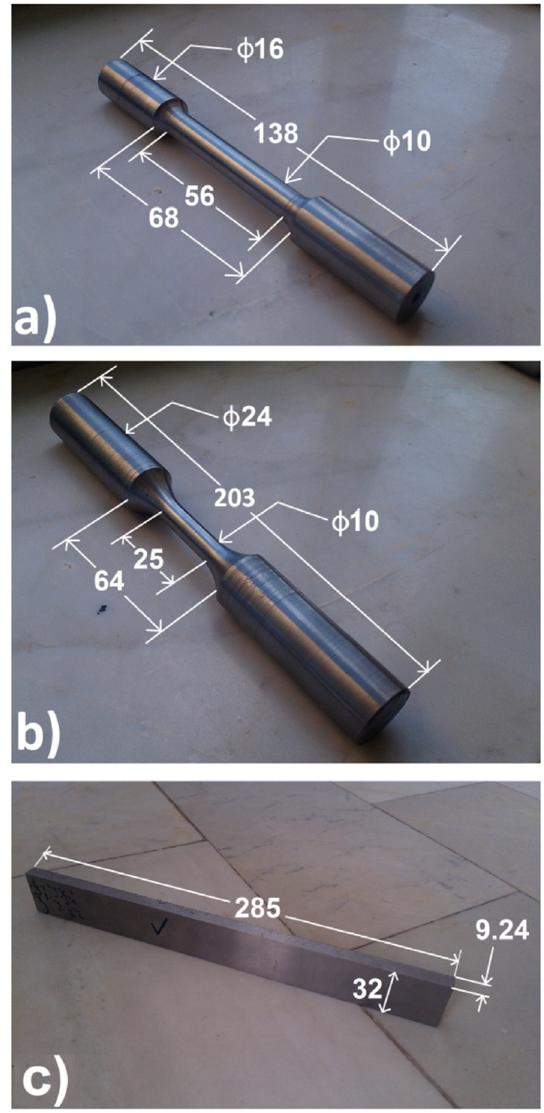

Fig. 1. Test samples, (a) tensile test specimen, (b) cyclic test specimen, (c) four-point bending test sample, all dimensions are in mm.

Elastic–plastic four-point bending can create a known stress field which is the best way to validate the finite element model. There are no transverse shear stresses on the cross-sections of the beam in the inner span of the bending sample due to the pure bending condition. To induce residual stresses, the beam must be loaded beyond the yield strength. Upon removal of applied moment, elastic unloading is occurred and the residual stresses formed. The tensile and compressive residual stresses are both produced on the opposite surfaces which are independent to sign of applied moment. The four-point bending process presents the following advantage over the three-point bending process: In a three-point bend, the maximum residual stress occurs only at the mid-section. However, the entire span length is subjected to a constant residual stress in the four-point bending sample [43,44]. Beam specimens were subjected to four-point bending to induce elastic–plastic deformation. Fig. 1(c) illustrates the sample that was manufactured for four-point bending test. In order to perform the experiment, a fixture was designed. The fixture consisted of fixed and movable fulcrums. The fixture with the specimen in position is shown in Fig. 2. The displacement was applied using a servo-hydraulic fatigue testing machines.

The second procedure that was employed to create residual stresses was grinding. Grinding is a commonly used finishing process to produce components with desired shape, size and dimensional accuracy. During