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Numerical analysis and experimental validation on residual stress distribution of titanium matrix composite after shot peening treatment

Lechun Xie[a,*], Chengxi Wang[a], Liqiang Wang[a], Zhou Wang[b], Chuanhai Jiang[a], Weijie Lu[a], Vincent Ji[c]

[a] State Key Laboratory of Metal Matrix Composites, School of Materials Science and Engineering, Shanghai Jiao Tong University, No. 800 Dongchuan Road, Shanghai 200240, P.R. China
[b] School of Automotive Engineering, Wuhan University of Technology, 122 Luoshi Road, Wuhan, Hubei 430070, P.R. China
[c] LEMHE/ICMMO, UMR 8182, Université Paris-Sud 11, 91405 Orsay France

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ABSTRACT

The residual stress distribution introduced by shot peening (SP) in the deformed surface layer of titanium matrix composite (TiB+TiC)/Ti-6Al-4 V was investigated via three-dimensional (3D) finite element dynamic simulation and experimental validation. The program of ANSYS/LS-DYNA was utilized in the 3D finite element dynamic analysis of SP process, and the 3D homogeneous and inhomogeneous models were set up. The results showed that the compressive residual stresses (CRS) were introduced in the matrix, but the tensile residual stresses appeared in the reinforcements. The maximum CRS and tensile residual stress were -1511 and +1155 MPa respectively, which revealed the higher yield strength of reinforcements. This type of stress distribution revealed the effect of reinforcements, keeping the adverse tensile stresses in the reinforcements and retarding the damage to the matrix during deformation. In terms of experiments, after SP, the residual stresses along the depth from the surface were measured using X-ray diffraction (XRD) method. The experimental results indicated that the CRS formed in the surface layer and the maximum appeared on the subsurface. The range of residual stresses found in experiments supported the simulated results, which verified the validity of 3D finite element dynamic analysis.

1. Introduction

Shot peening (SP) can considerably improve fatigue strength and fatigue lives of cyclically loaded metallic components by inducing compressive residual stresses (CRS) and work hardening into the surface region (Schulze, 2003). Magnitude, distribution and depth of the CRS are mainly influenced by the material condition and the parameters of SP process. SP is a complex process and there are a significant number of parameters involved, which need to be controlled and regulated to produce an optimum CRS distribution. During the practical application of SP in industry, empirical knowledge should be accumulated for determining the appropriate processing parameters, which usually requires money and is time-consuming. In order to minimize these trials and obtain the suitable SP parameters as quickly and efficiently as possible, the simulation of the SP process is introduced, which can increase understanding of the SP process with the purposes of investigation, illuminating and predicting the relationship between the influencing factors and results.

Simulation of the SP process has been developed for more than four decades. Some research papers have shown that finite element methods for simulation is useful for predicting residual stress distribution after SP (Kim et al., 2011; Benedetti et al., 2010; Kim et al., 2010; Prasannavenkatesan et al., 2009). The simulation of SP process via finite element methods can be classified into two-dimensional (2D) and three-dimensional (3D) models. 2D SP models are usually utilized to simulate a single impact on a cylindrical or semi-infinite target body, and the verification of model accuracy is commonly realized by the comparison of the simulated residual stresses with the results measured by X-ray diffraction (XRD) and neutron diffraction (Ould et al., 2006; Baragetti et al., 2000; Boyce et al., 2001; Evans, 2002). However, direct comparison of the residual stress distribution along the symmetry axis of a 2D model with the experimental measurements on a peened component is questionable because the measurement area is different from the impact area in the 2D model. Stress measurement techniques like

* Corresponding author. Fax: +012246336062.
E-mail addresses: lechunxie@yahoo.com (L. Xie), wangzhou@whut.edu.cn (Z. Wang).

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XRD, neutron diffraction or hole drilling can provide macroscopic stress values, and the measurement area is larger than the diameter of the dimple used in 2D model. Furthermore, during multiple SP processes, the coverage rate, a very important parameter, can't be taken into account in 2D models, which led to the introduction and popular application of 3D models.

3D SP models are being used in practical work more and more because they can take into account the effect of coverage rate. Consequently, 3D SP models have become the main choice in recent years, especially 3D models with dynamic analysis. In the overview of SP simulation, some 3D models are proposed with different descriptions, numbers of shot balls, types of analysis, kinds of material models, and so on (Levers and Prior, 1998; Meguid et al., 1999; Majzoobi et al., 2005; Frija et al., 2006; Wang et al., 2008; Hong et al., 2008; Kim et al., 2012; Meo and Vignievic, 2003). Based on above 3D models, there are many studies on SP simulation regarding homogeneous materials, little investigation involves 3D inhomogeneous inclusions while setting up models. Even though some researchers have set up 3D inhomogeneous models of metal matrix composites by other methods (Bohm, et al., 2001; Bohm et al., 2002; Han et al., 2001; Duschlbauer et al., 2006; Borbely et al., 2001), there are few studies focusing on the SP process.

As an important metal matrix composite, titanium matrix composite has wide application prospects in the aerospace, automobile and other industries because of good properties such as high specific strength, good ductility, and excellent fatigue properties etc. (Tjong and Ma, 2000; Ranganath, 1997). Experimental investigation concerning the residual stress distribution of titanium matrix composite after SP has been carried out in previous works using the XRD method (Xie et al., 2011a,2011b). However, the tested residual stresses just show the average residual stresses of the matrix and reinforcements, since the irradiation area of X-ray is larger than the dimensions of the reinforcements. It is very hard to measure the residual stress distribution in and around the reinforcements directly via experimental methods, which can depend on the simulation. Thus, in this work, 3D finite element dynamic analysis of multiple shot impacting is carried out on titanium matrix composite (TiB+TiC)/Ti-6Al-4 V (TiB:TiC = 1:1 (vol%)), and the SP target component involves the matrix Ti-6Al-4 V and the inhomogeneous reinforcements TiB and TiC. The program of ANSYS/LS-DYNA (ANSYS Company, 2010) is utilized to simulate the SP process. A parametric study is conducted using this 3D dynamic model to investigate the influences of shot velocity and coverage rate on the residual stress distribution after SP. The residual stresses in and around reinforcements can be obtained and discussed in detail. Moreover, the experimental results using XRD method are compared with the simulated results.

2. Models and Experiments

2.1. Homogeneous SP model

ANSYS/LS-DYNA is utilized for the 3D finite element dynamic analysis of the shot impacting on the surface. The process of SP causes a plastic deformation on the matrix, so Cowper-Symonds model (Symonds, 1965; Johnson and Cook, 1983; Jones, 1997; Hallquist, 2006) in ANSYS is chosen to use in the 3D finite element dynamic analysis. Cowper-Symonds model is a piecewise linear plasticity model, and the yield stress can be obtained via the strain rate, which is shown in Eq. (1) (He et al., 2013).

$$\sigma_y\left(\varepsilon_{eff}^p, \dot{\varepsilon}_{eff}^p\right) = \sigma_y\left(\varepsilon_{eff}^p\right)\left[1 + \left(\frac{\dot{\varepsilon}_{eff}^p}{C}\right)^{\frac{1}{p}}\right] \tag{1}$$

Where $\dot{\varepsilon}$ represents the effective strain rate, P and C are the parameters for strain rate, and $\sigma_y(\varepsilon_{eff}^p)$ is the original yield stress.

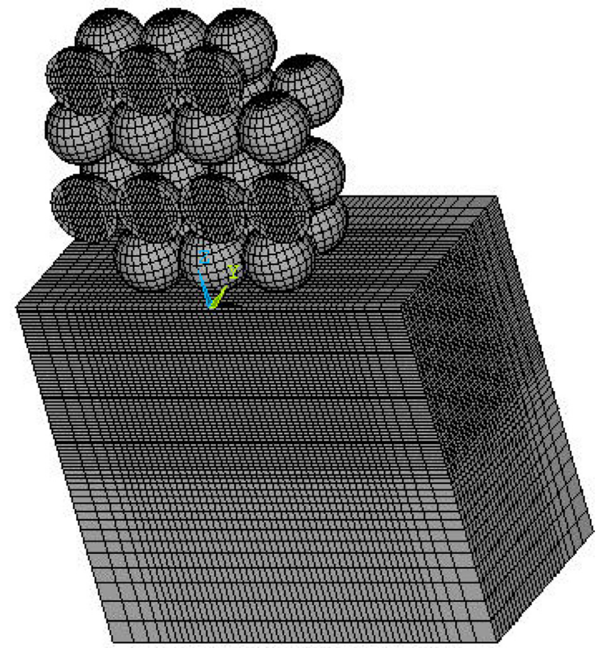

Fig. 1. 3D SP model for homogeneous materials.

Because of the existence of reinforcements and in order to mainly analyze the influences of reinforcements on the residual stress distribution of the matrix, the strain-stress curves with a single strain rate (10^{-3} s^{-1}) of the matrix and composite are adopted in the simulation process. It was pointed out that dynamic stress-strain curves become flatter with an increase in strain-rate, with reduced material strain hardening (Symonds, 1965). Therefore, considering the variation of strain rates, according to Eq. (1) and the references (Jones, 1983; Aljawi, 2004), the parameters C and P are set as $C = 1300$ and $P = 5$.

Before analyzing the model of titanium matrix composite (TiB + TiC)/Ti-6Al-4 V, the 3D model of homogeneous matrix Ti-6Al-4 V should be set up, which is shown in Fig. 1. The dimensions of the peened target are $12R \times 6R \times 2.1$ mm^3, in which R is the average radius of shot balls. In the impact area, a mesh refinement at the near surface layer is used because of intensive impacting, and the depth of the mesh is 0.02 mm. The mesh number reaches 120,000 in total, and the SOLID164 dynamic analysis display unit is chosen for meshing unit. Because the impact process of SP shows symmetry, this 3D model is set up in symmetry and is half of the actual size. In order to avoid the influence of reflected stress wave within the target on the distribution of residual stress during the process of impacting, non-reflective boundary conditions are implemented on the bottom and flanks of the target.

During the simulation process, the shot media is the case steel ball, and to shorten the simulation time, all freedom degrees of shot balls are coupled to the rigid body center of mass, meanwhile, the corresponding mechanical parameters are given to the rigid body center to describe the dynamic characteristics. Because the hardness of the matrix is smaller than that of the case steel balls, the deformability of the shot balls is very weak, which hardly affects the results of residual stress distribution. Thus, the shot balls are assumed to be rigid. About the reinforcements of TiB and TiC particles, the Young's modulus is much greater than that of Ti-6Al-4 V, and the hardness of the reinforcements are comparative equal to or greater than the hard ceramic, thus, the reinforcements can be considered also as rigid bodies, and there is hardly having any plastic deformation during the process of SP. However, after SP treatments, because of the constraint of the matrix around the