Application of the FEM for the Prediction of the Micro-region Stress of TiB_2/Al Composite

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ABSTRACT: A model of shot peening on particle reinforced TiB2/Al composite material was built with ANSYS/LS-DYNA software. The simulated residual stress matched quit well with experiment data. Typical residual stress field which was caused by shot peening had been observed in the plastic deformation zone. Analysis showed that tensile stresses generated inside some reinforced particulates of the surface layer. Besides, in the plastic deformation zone, residual stresses in TiB2 particles were generally greater than that in Al matrix. The reason could be ascribed to the difference of mechanical properties of these two materials.
Keywords: TiB2/Al composite, shot peening simulation， micro-region stress

1. Introduction

Shot peening (SP) is a widely used method employed by numerous industries with the aim of introducing high compressive residual stress to suppress crack initiation and crack growth and improving their fatigue strength and fatigue life [1].

Metal matrix composites, MMCs, are found to exhibit excellent physical and mechanical properties such as specific high modulus, strength as well as thermostability etc. and have been widely concerned in the field of aerospace and automobile industries [2]. Shot peening treatment can greatly improve the surface property of MMCs component to expand its scope of application. However, as there are reinforced particles in MMCs, the micorstructure and residual stress distribution in MMCs after shot peening treatment is more complicated than traditional metal and the micro-region stresses around the reinforced particles are hardly obtained by experimental measurement. Until now, the majority researches about the mechanical behavior of particle reinforced metal matrix composites are focusing on building mesoscopic-mechanical models [3, 4]. As the reinforced particles in MMCs are very small (from 1 to 100μm), the shapes of reinforced particles are irregular and the distributions of reinforced particles are random, the popular method to investigate the mechanical properties is assuming the microstructure of MMCs as a periodic unit cell model [5-7]. Furthermore, in shot peening process, the different dimension between shots, MMCs and reinforced particles makes it more difficult to build a shot peening model for MMCs material. In order to investigate the residual stress in micro-region around reinforced particles after shot peening process, this paper proposed a 3D shot peening model to calculate micro-region stress in TiB_2/Al composite material via ANSYS/LS-DYNA software. The mechanism of reinforced particles in TiB_2/Al composite material was also discussed according to simulated results.

2. Experimental setup

The investigated material was TiB_2/6351Al composite (in situ, 10 vol.% TiB_2). The chemical composition of TiB2/6351Al composite was 1.0 Si, 0.6 Mg, 0.6 Mn, 6.7 B, 3.0 Ti and the rest Al (all in wt%). Samples were cut from the center of the rod along the extrusion direction with the dimensions of 15×15×2mm^3, the treated surface was 15×15mm^2. Before shot peening treatment, all specimens were heat-treated with the same conditions: solution treatment at 530°C for 110 min, the quenched in water, and finally aging at 170°C for 6h. SP treatments were carried out according to the conditions: area pressure 0.5MPa, Al_2O_3 beads with average diameter 0.3mm, 0.2mmA Almen peening intensity, 100mm distance between nozzle and specimen. The measurements of the depth distribution of the residual stresses were performed by iterative electrolytical removal thin surface layers and subsequent X-ray measurements. For the measured values were nearly identical, the residual stress in every tested spot was tested three times and averaged.

3. Finite element model

3.1 Material model

In order to better describe the shot peening process of TiB_2/Al, two different material models were proposed to represent Al matrix and TiB_2/Al composite. In shot peening simulation, the material used in the area of possible collision was Al matrix + TiB_2 reinforcement particle and the material used in the non-collision area was TiB_2/6351Al composite. Cowper-Symbols model with Piecewise linear plasticity model was used to represent Al matrix and TiB_2/Al composite material. Considering the influence of strain rate, the real yield stress and the yield stress can be expressed by the following equation [8]:

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

Where $\dot{\varepsilon}$ is effective strain rate, C and P are the strain rate parameters and $\sigma_y(\varepsilon_{eff}^p)$ is the yield stress which does not consider strain rate. In Cowper-Symbols model, the input data in ANSYS/LS-DYNA software include material density, young's modulus, possion rate, yield stress, tangent modulus, the strain rate parameters and real stress-strain curves. The yield stress and tangent modulus can be neglected if stress-strain curves are given.

As piecewise linear plasticity models were used in Al matrix and TiB2/Al composite material, the real stress-strain curves were fitted via piecewise linear method. The experimentally measured stress-strain curves was engineering stress-strain curves, in order to obtain real stress-strain curves, engineering stress-strain curves from experimental measurement need to be transformed first according to the following equation:

$$\sigma_t = \sigma_\varepsilon(1+\varepsilon_\varepsilon) \quad \varepsilon_t = \ln(1+\varepsilon_\varepsilon) \quad (2)$$

Where σ_t is the real stress, σ_ε is the engineering stress, ε_t is the real strain and ε_ε is the engineering strain [9]. Fig. 1a and Fig. 1b show the real stress-strain curves and fitting points of 6351Al and TiB_2/Al composite. Additionally, the mechanical parameters of TiB_2 reinforcement and ceramic shots were also needed in this shot peening simulation. The

Young's modulus, the poisson’s ratio and the density of TiB_2 reinforcement were 500GPa, 0.25, 4.5g/cm^3. The Young’s modulus, the poisson’s ratio and the density of ceramic shots were 350GPa, 0.26 and 2.95 g/cm^3.

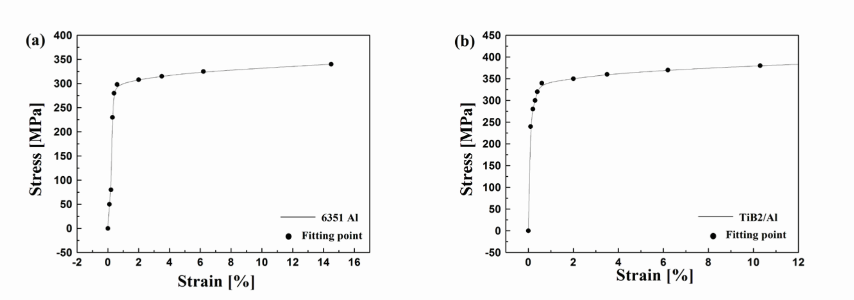

Fig.1 (a) Stress-strain curve and fitting points of 6351 Al, (b) Stress-strain curve and fitting points of TiB_2/Al composite

3.2 Model Geometry and Boundary Conditions

ANSYS/LS-DYNA was used to build dynamic model of the shot impacts on the surface taking into account inertia effects. The mesh of 3D model was set up by 646560 elements with Explicit 3-D Structural Solid (Solid164) provided by ANSYS-LS software. As the sample was symmetric, the model geometry of could be reduced to 1/4 of its real size. The material of shots was ceramic and all shots were set to rigid body. Fig. 2a shows the shot peening model of TiB_2/Al composite. The mean diameter of shots was 0.3mm and the mean velocity of shots was 80m/s. As the shot was symmetric, the shot was 1/8 of its real size in order to minimize the number of elements used. The dimension of 1/8 target component was 0.3mm ×0.3mm×0.3mm. The possible collision region was just below the shot and the material of this region consisted Al matrix and TiB_2 reinforcement. The dimension of the possible collision region was 0.1mm×0.1mm×0.1mm. In the possible collision region, the content of TiB_2 reinforcement was 8.3% (wt), which was the same as experimental specimen. Fig. 2b shows the contact region between the shot and plastic deformation zone. The TiB_2 reinforcement particles were evenly distributed within plastic deformation zone and the dimension of TiB_2 reinforcement particle was 4μm×4μm×4μm. In terms of non-collision area, the material was TiB_2/Al composite and the mechanical property of this area was the same as that of TiB_2/Al composite material. Non-reflecting boundary conditions were carried out on he bottom face and lateral face of target component. The planes of x = 0 and y = 0 planes were assumed to be the symmetry planes and the bottom face of target component was fixed in Z direction.

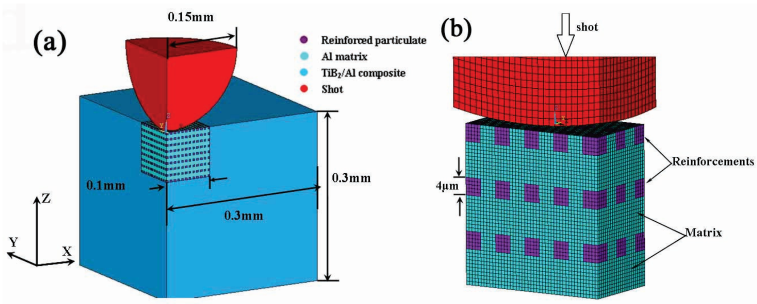

Fig.2(a) Shot peening model of TiB2/Al composite, (b) The contact region between the shot and plastic deformation zone

4. Results and discussion

Fig.3a shows the residual stress distribution of target component after one shot impact in X direction. It can be seen that in plastic deformation zone, the maximum compressive residual stress was less than -400MPa. In the center of dimple area, the residual stresses of all elements were compressive. However, in the edge of the dimple, the residual stress distributions were different. In the area near the X axis, the residual stresses of all elements were compressive but in the area near the Y axis, the residual stresses of some elements were tensile. In terms of residual stress in Y direction, the residual stress distribution was similar in the center of dimple area but the value of residual stress in the edge of the dimple was reversed, where were compressive residual stress in X direction were tensile residual stress in Y direction and where were tensile residual stress in X direction were compressive residual stress in Y direction. This phenomenon was due to the equilibrium of internal stress of the material after shot impact. When one shot impacted on the surface of target component, the stress states of edge of the dimple were totally different in X and Y directions. The surface material extended when the one shot impacted on target component, if there were compressive residual stresses in X (Y) direction in the edge of the dimple, there were tensile residual stresses in the Y (X) direction in the same area of the edge of the dimple. This was only the phenomenon about one shot impact on target component surface, when the shot coverage was nearly 100%, which meant all the surface material were not on the edge of certain dimple, the tensile stresses on the edge of dimple in certain direction disappeared. This was the reason why the coverage of shot peening treatment was at least 100% to generate the quality of target component.

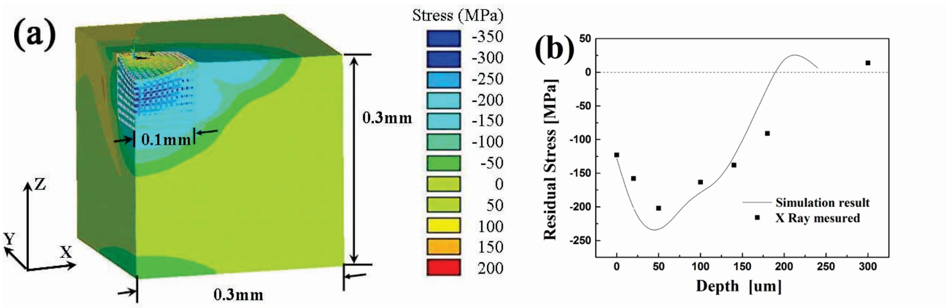

Fig.3 (a) Residual stress distribution in shot peened TiB2/Al model, (b) Depth distribution of experimental and simulated residual stresses in TiB_2/Al composite

As the measured value of X-ray residual stress is a statistical value of certain area, the simulated residual stress was calculated by averaging residual stress values of all elements in each depth layer of plastic deformation zone. According to this calculated method, simulated residual stress profile could be obtained. Fig. 3b shows the comparison of experimental and simulated residual stress profiles. It can be seen that experimental residual stress qualitatively agreed well with simulated results. No matter in experimental value or simulated value, the maximum compressive stress was located in the depth of 50μm and the depth of compressive residual zone was about 200μm. On basis of this observation it can be concluded that this simulation model is a reliable tool in the prediction of the residual stress state of TiB_2/Al composite material after shot peening.

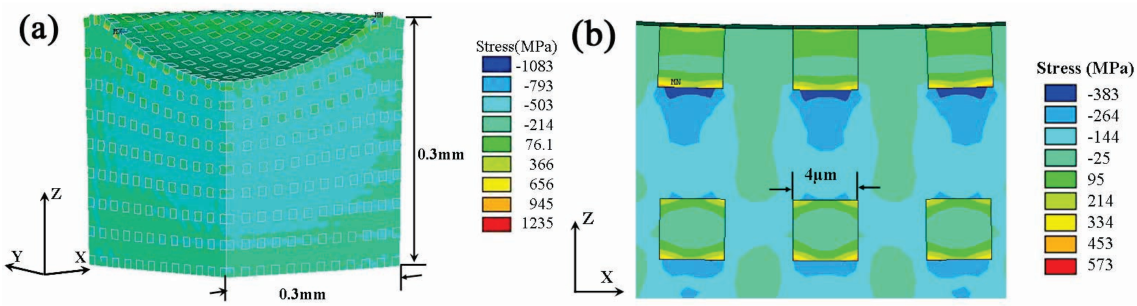

Fig.4 (a) Residual stress distribution in plastic deformation zone, (b) Micro-region stress distribution around the TiB_2 reinforcements in shot peening model.

Fig. 4a shows the residual stress distribution state of the whole plastic deformation zone. Fig. 4b shows the micro-region stress distribution in cross section of TiB_2/Al composite in near surface region of target component. From Fig. 4a and Fig. 4b, it can be seen that the treated surface deformed from plane to a curved surface. The maximum tensile stress and maximum compressive stress appeared in the reinforced particles which were located in the edge of dimple. As the maximum tensile/compressive residual stresses in TiB_2/Al reinforced particle were far much lower than its breaking strength, the residual stresses in TiB_2/Al reinforced particle did not make any adverse effects of overall performance of TiB_2/Al composite. In plastic deformation zone, the residual stresses of Al matrix in all plastic deformation zone were compressive but the residual stress state of TiB_2/Al reinforced particle were different. In some region inside TiB2/Al reinforced particle there were tensile stresses but in other region there were compressive stresses. In the whole target component, the averaged residual stress value inside TiB2/Al reinforced particle was larger than the averaged residual stress value in Al matrix, which was due to the big difference between TiB_2/Al reinforcement mechanical property and Al matrix property.

During the shot peening processing, the elastic-plastic deformation occurred in target component. After the shot impact, plastic deformation preserved and elastic deformation began to recovery. The recovery of elastic deformation in matrix was lager than that in reinforcement, which led to compressive residual stresses around reinforcement. The value of compressive residual stress was related to the different elastic recovery between matrix and reinforcement. In the contact region just below the shot impact, there was a big different elastic recovery between matrix and reinforcement. Therefore, relative larger compressive residual stresses appeared on the top and bottom of reinforcement. Furthermore, the macro compressive residual stress induced by the constraint of internal material further increased the value of compressive residual stress around the reinforcement.

In Metal matrix composites, the strength of Al matrix was relatively smaller, so the enhancement of shot peening treatment was mainly for Al matrix. The compressive residual stresses in Al matrix can improve the fatigue strength and fatigue life of TiB2/Al composite. Even though there were some tensile stresses in TiB_2 reinforcement, the values of these tensile stresses were far much smaller than breaking strength and they did not cause the adverse effects in the overall performance of TiB2/Al composite. R. S. Lee et al investigated the influence of surface treatment on residual stress state of composite and found that compressive residual stress state appeared in both matrix and reinforcement in the surface of composite after mechanical work of grinding [10]. Therefore, it was reasonable to speculate with the increasing the shot peening time, the tensile stress state of reinforcement in near surface region would gradually become compressive residual stress state.

Conclusion

In this paper a predictive model for calculating micro-region residual stress of TiB_2/Al composite material after shot peening treatment has been build via ANSYS/LS-DYNA software. The simulated results showed that simulated residual stress state qualitatively agreed well with experimental results. According to investigation of micro-region residual stress in TiB2/Al composite, it could be found that due to the difference between TiB_2/Al reinforcement and Al matrix mechanical property, there were elastic and plastic deformations in Al matrix but only elastic deformation in reinforced particle and the residual stress states in matrix and reinforcement were different. There were some tensile residual stresses in reinforced particle but the values of these tensile residual stresses were smaller than the breaking strength of reinforcement. Therefore, the tensile stress in reinforcement did not influence the overall performance of TiB2/Al composite. The averaged residual stress inside TiB2/Al reinforced particle was larger than the averaged residual stress value in Al matrix.

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