

Numerical Study of Mechanical Response of Pure Titanium during Shot Peening

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Abstract. Mechanical response of pure titanium impacted by a steel ball was simulated using finite element method to investigate stress and strain evolution during shot peening. It is indicated that biaxial residual stress was obtained in the surface layer while in the interior triaxial residual stress existed because the S33 was comparable to S11 and S22. With decreasing the depth from the top surface, the stress was higher during impacting, but the stress relief extent became more significant when the ball rebounded. Therefore the maximum residual stress was formed in the subsurface layer with depth of 130 μm . As for the residual strain, it is shown that the maximum residual strain LE33 was obtained at the depth of 60 μm corresponding to the maximum shear stress during impacting.

1. Introduction

Shot peening is a cold working process used to obtain compressive residual stress and strain hardening. Mechanical properties, such as fatigue and wear resistance, can be enhanced by shot peening [1, 2]. Recently research showed that a nanocrystalline surface layer which is beneficial to mechanical properties could be produced by shot peening [3]. Extensive numerical simulations have been conducted to elaborate the creation of residual stress [4] and the formation of nanoscale microstructure during shot peening [5, 6]. Stress and strain of the target varied significantly with time during shot peening. The evolution led to the residual stress and plastic deformation which correlates with microstructure refinement. Therefore, variations of stress and strain with time are of importance to understand the underlying mechanism of shot peening. However, investigations on the time history of stress and strain are limited [6, 7]. In this study, finite element method (FEM) simulation was carried out to analysis the mechanical response during shot peening in pure titanium which is widely used in many key fields due to their high specific strength and excellent corrosion resistance [8]. Variations of the six components of the stress and strain as the function of time were investigated. Characters of residual stress and residual strain were discussed based on the simulation.

2. Model description

A 3D numerical simulation was carried out by using commercial finite element code ABAQUS/Explicit. A symmetry-cell model with single impacting ball was used to simulate shot peening process [9]. Figure 1 shows the model for single shot impacting. The target with dimension of 2 mm $\times$ 2 mm $\times$ 4 mm was used. A C3D8R 8-node linear brick element with reduced integral and hourglass control was used for the target. A quarter of the steel ball with a diameter of 0.8 mm was modeled. A C3D4 4-node linear tetrahedron element was used for the ball.



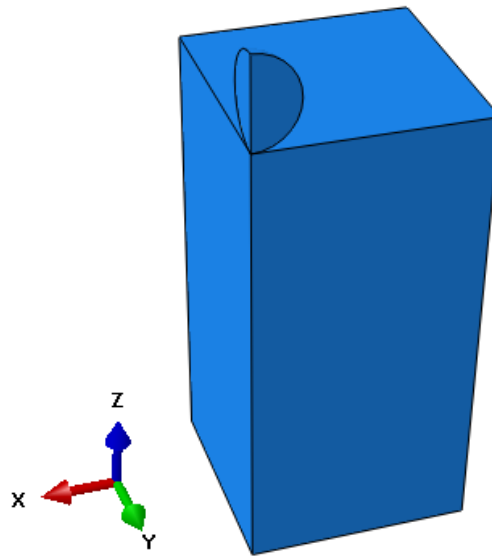


Figure 1. FE model for single shot impacting.

As for boundary conditions, the bottom and two side faces were fixed, and symmetry displacement conditions were applied on the two faces which were in the impacted area. A general contact with an isotropic friction coefficient of 0.1 was used [10].

Plastic deformation behavior of pure titanium was represented by Hollomon's equation as:

$$\sigma = K\varepsilon_p^n \quad (1)$$

where, σ is true stress, ε_p is plastic strain, K is a material constant and n is strain hardening exponent. In this study, $K=780.95$ MPa and $n=0.159$ were used. Steel shot was assumed to be elastic during the impacting. The material parameters used in the simulation are summarized in Table 1.

In the simulation, an initial velocity of 80 m/s which is typical for shot peening [11] was imposed on the steel ball. And shot impinging angle 90° was used.

Table 1. Material parameters used in FEM calculation.

	Density (kg/m ³)	Elastic modulus (GPa)	Poisson's ratio
Target	4510	114.8	0.32
Steel shot	7800	200.0	0.26

3. Results and discussion

Figure 2(a) shows the variation of kinetic energy of the system composed of steel ball and target. It can be seen that the energy decreased to the minimum within 1.17×10^{-6} s. Velocity of the ball reached zero at the moment as shown by figure 2(b). After that, the ball began to move inversely and got a stable velocity of 18.1 m/s at 1.53×10^{-6} s. The kinetic energy was about 1.07×10^{-4} J which was only 6.4% of the initial energy. Fluctuation of the energy shown in figure 2(a) was resulted by the stress wave in the target.

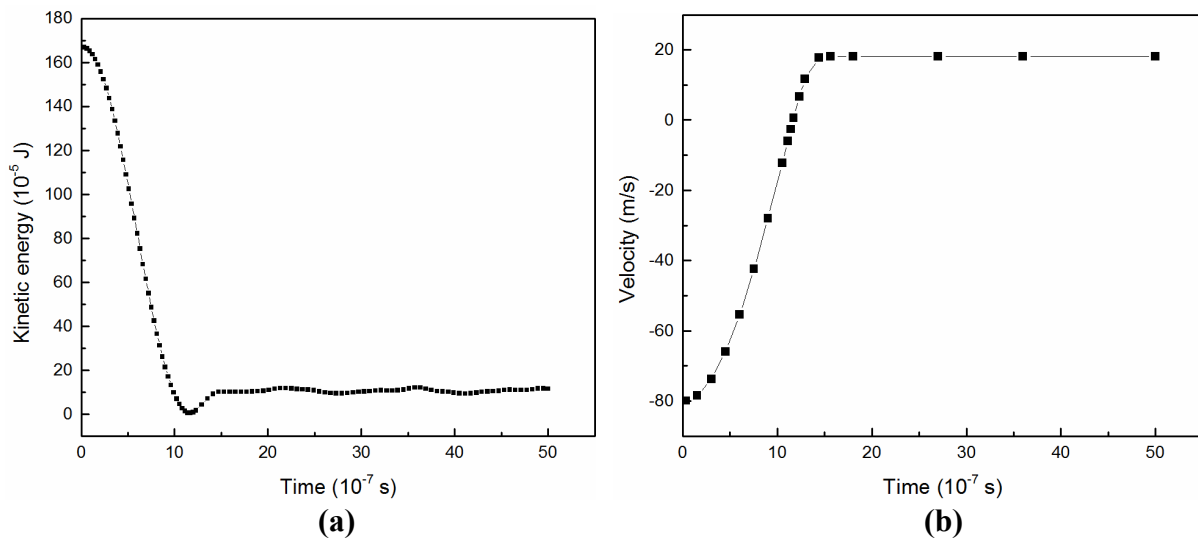


Figure 2. Time history of (a) the total kinetic energy and (b) the velocity of the ball.

Von Mises equivalent stress and plastic equivalent strain (PEEQ) variations with depth from the top surface of the pure titanium at different moments of the shot peening were illustrated by figure 3(a) and (b) respectively. It can be found that the stress level increased with time and reached the highest level at 1.17×10^{-6} s. After that the stress level decreased. At different moments, the maximum stresses occurred in the subsurface. At 1.17×10^{-6} s when the velocity reached zero, the depth at which the maximum stress occurred was about 60 μm . After the ball rebounded from the target, the depth was about 130 μm . The variation curves of the of Von Mises equivalent stress with time are not smooth at some depths because the change of stress sign. Similar to the Von Mises equivalent stress, the maximum of PEEQ also occurred in the subsurface. At the moment when the velocity was zero, the depth at which the maximum PEEQ 0.30 existed was about 60 μm . After that, the depth almost kept stable.

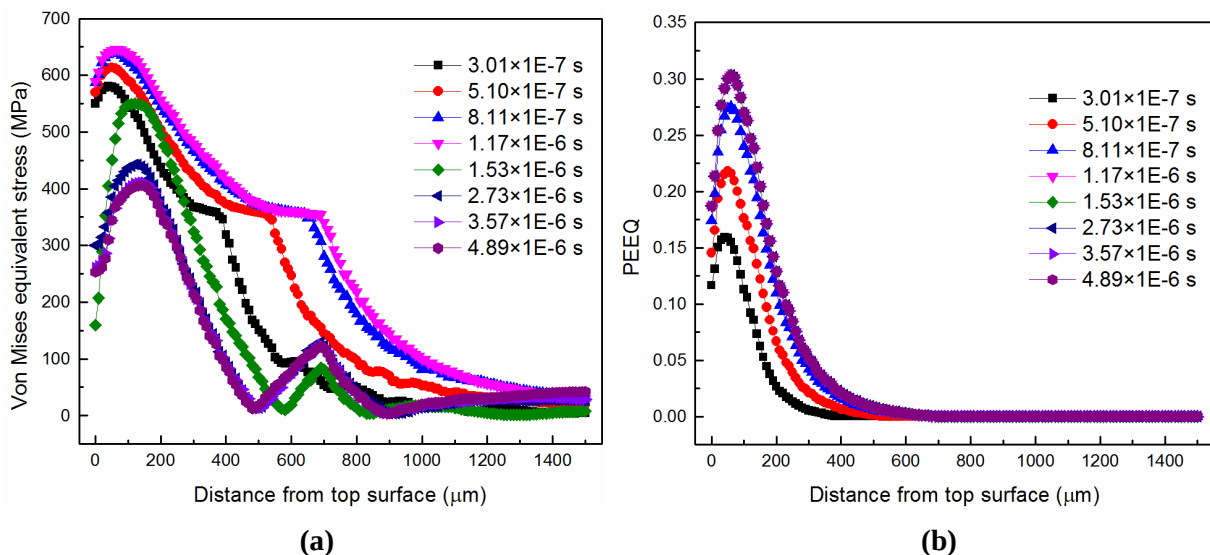


Figure 3. Distribution of (a) the Von Mises equivalent stress and (b) the PEEQ at different moments.

Variation of the stress components with time at different depths from the top surface of the pure titanium are shown in figure 4. Clearly, shear stresses were almost zero for the titanium at different depths and different moments. During impacting the normal stresses increased with time and the magnitudes of S33 were larger than S11 and S22 obviously. When the ball rebounded, the normal stresses decreased quickly especially the S33. At last, S33 nearly reached zero at the top surface.

Biaxial residual stress state was obtained in the surface layer. The residual S33 increased with the depth, which is shown by figure 4. It was found that at the depth of 400 μm , the residual S11 and S22 were about 309 MPa, while the S33 was about 222 MPa. Therefore, triaxial residual stress state was obtained in the interior because the S33 could not be neglected. Though the stress level was not high at the depth of 130 μm during impacting compared with the stress level in the top surface and at the depth of 60 μm , the residual stress was the highest because the stress relief was weakened with the increase of depth. In addition, fluctuation of the normal stresses can also be found because of the stress wave.

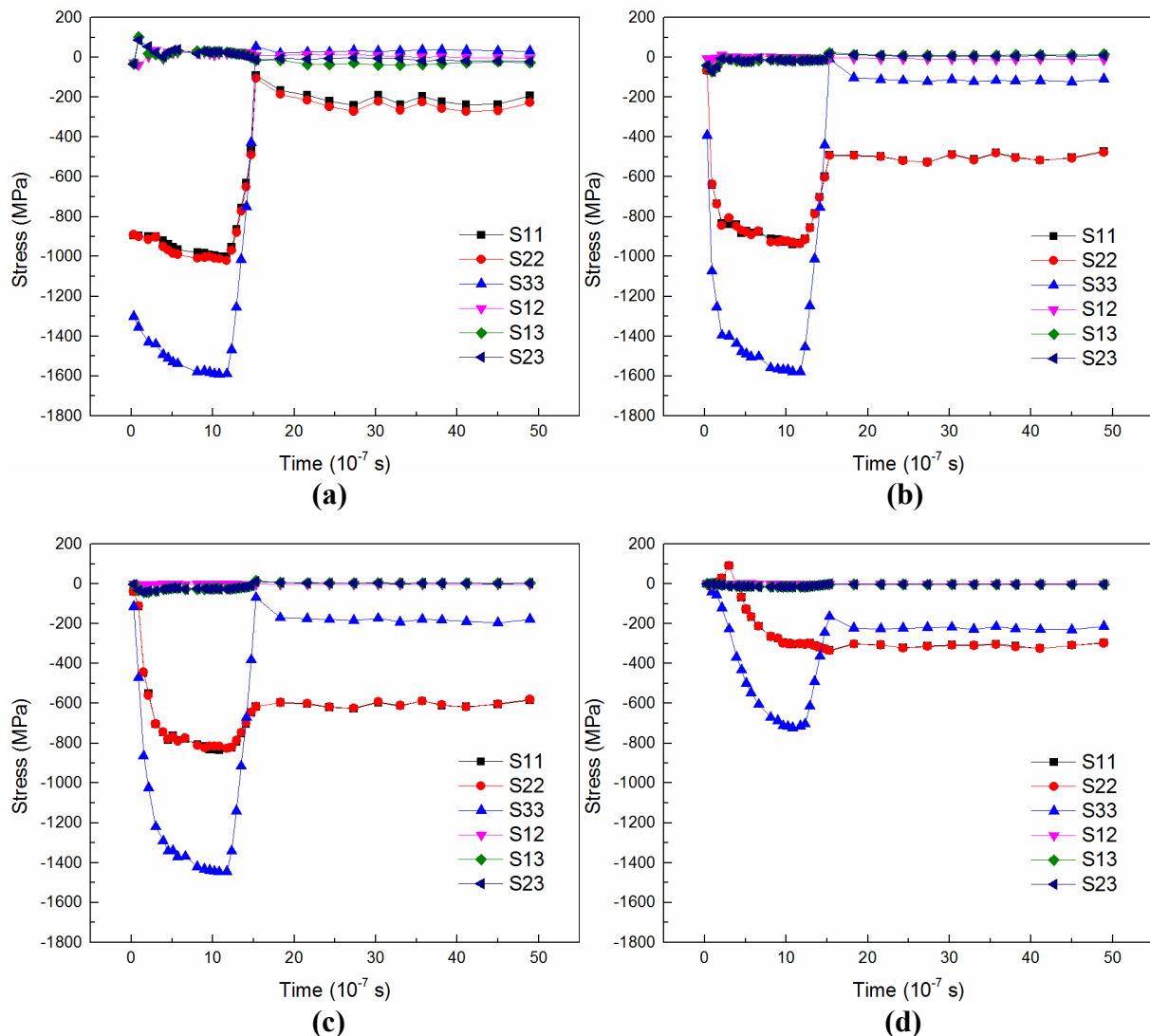


Figure 4. Time histories of stress components (a) in the top surface and at the depth of (b) 60 μm , (c) 130 μm and (d) 400 μm from the top surface.

Corresponding to the stress components in figure 4, variation of strain components were shown in figure 5. It is found that LE11 was equal to LE22, and the magnitude of LE11 or LE22 was half of LE33. LE12 was almost zero. LE13 and LE23 were equal. When the ball rebounded, strains relaxed slightly. It can be found the maximum strain occurred at the depth of 60 μm , which was agreement with the PEEQ distribution. Residual strain at depth of 130 μm where maximum residual stress occurred was obvious smaller compared with the residual strain at the depth of 60 μm . This means that the variation of residual strain with depth was different from the variation of residual stress with depth. If the shear stresses were not considered as shown in figure 4, the normal stress S33, S11 and S22 could be treated as principle stresses. In this case, it is easy to find that the maximum shear stress

existed at the depth of 60 μm . Because the plastic deformation was induced by shear stress, the maximum plastic deformation was reasonably obtained at the depth corresponding to the maximum shear stress.

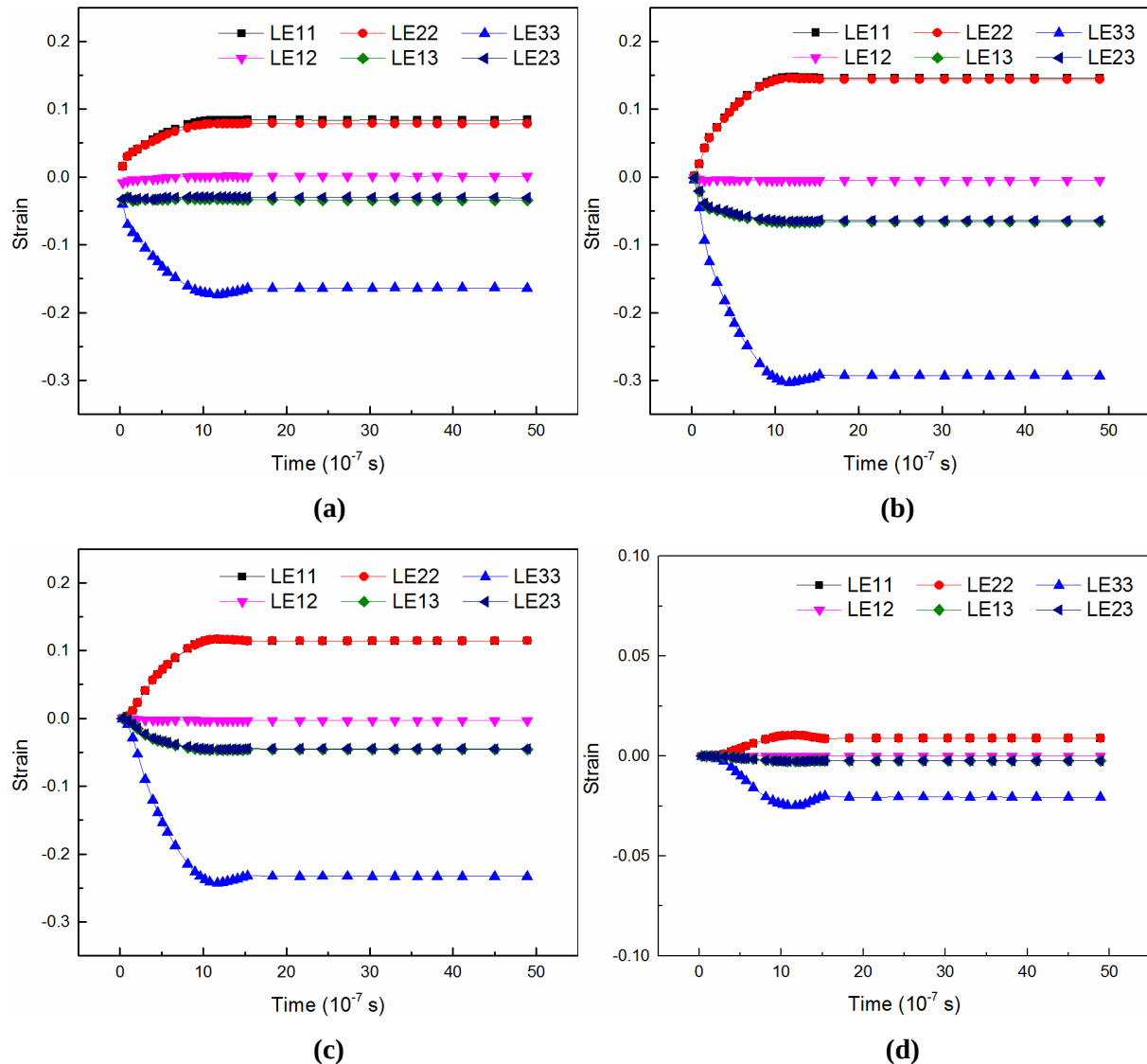


Figure 5. Time histories of strain components (a) in the top surface and at the depth of (b) 60 μm , (c) 130 μm and (d) 400 μm from the top surface.

4. Conclusions

In this study, shot peening was modeled by single shot impacting using FEM simulation. Based on the results and discussion, following conclusions can be drawn:

(1) Shear stress was nearly zero. The normal stress S_{33} along the impacting direction was the most significant during impacting. All the normal stress components especially S_{33} released quickly when the ball rebounded, therefore biaxial residual stress was obtained in the surface layer. In the interior triaxial residual stress existed because the S_{33} was comparable to S_{11} and S_{22} .

(2) The residual stress is influenced by the stress state during impacting and the stress relief when the ball rebounded. With decreasing the depth from the top surface, the stress was higher during impacting, but the stress relief extent became more significant. Therefore the maximum residual stress was formed in the subsurface layer.

(3) Strain component LE12 was nearly zero. LE13 and LE23 were equal and they were small compared with normal strain components. LE11 was equal to LE22, and the magnitude of them was half of LE33.

(4) The correlation between residual stress and depth is different from that between residual strain and depth. The maximum residual stress was obtained at the depth of 130 μm while the maximum residual strain was at the depth of 60 μm corresponding to the maximum shear stress.

Acknowledgments

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