IOP Conf. Series: Materials Science and Engineering **409** (2018) 012017 doi:10.1088/1757-899X/409/1/012017

Analysis of Deformation and Texture Gradient in Shot Peened Pure Titanium

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Abstract. The plastic deformation of shot peened pure titanium and deformed texture along the depth were simulated by finite element method(FEM) and visco-plasticity self-consistent(VPSC) method respectively. The results show that the stress state is compressive stress in three principle directions from subsurface to the depth at 600μm. The strain state is a complicated strain state and exhibits strain gradient along the depth. Strain gradient results in texture gradient in shot peened pure titanium. The texture in pure titanium with initial typical recrystallized texture is strengthened after shot peening, with strongest texture at the depth where the maximum absolute values of strain components exist.

1. Introduction

Pure titanium and its alloys have been widely used in many key fields such as aerospace, chemical, energy and ocean industries due to their high specific strength and excellent corrosion resistance [1]. During the manufacturing process of titanium engineering parts, shot peening is usually employed to improve fatigue strength and other mechanical properties. It is well known that compressive residual stress and work hardening effects which are induced by shot peening contribute to the property improvement [2, 3]. In addition, it has been verified that distinct texture evolution occurs during the surface plastic deformation [4-6]. Chen et al. [4] investigated texture evolution in pure iron subjected to surface mechanical attrition treatment by using steel balls in diameter of 8 mm impacting target and found that the density of texture was strengthened and reached the maximum intensity in the micro-sized regime as increased the depth from the top surface. As for the shot peening deformation, Man and Zhai [5] have reported that texture was strengthened after shot peening in Ti-6Al-4V alloy and a basal fiber texture was formed in the surface layer, whereas Maawad et.al [6] have shown that the texture in hot rolled Ti-2.5Cu was weakened after shot peening and the texture intensity was weakest at the top surface. Extensive research has indicated that texture influence fatigue properties and other mechanical properties obviously [5, 7]. Therefore, in order to improve the performance of pure titanium and its alloy, further investigation should be conducted to clarify the texture evolution mechanism caused by shot peening.

In the present study, computer simulations by combining FEM and VPSC were carried out to investigate the deformation and texture evolution in shot peened pure titanium.

2. Model description

In this work, a 3D numerical simulation was carried out by using commercial finite element code ABAQUS/Explicit to calculate the stress and strain distribution in pure titanium after shot peening. A symmetry-cell model with single impacting ball was used to simulate shot peening process. The target with dimension of 2mm×2mm×4mm 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 modelled. A C3D4 4-node linear tetrahedron element was used for the ball. Additionally, the refinement mesh near the treated surface with 1 mm in depth has been adopted to improve the calculation accuracy. 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.

Plasticity deformation behavior of pure titanium was represented by Hollomon's equation as equation (1):

$$\sigma = K\varepsilon_p^{\ n} \qquad (1)$$

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 impact. The material parameters used in the simulation are summarized in Table 1.

Table 1. Material parameters used in FEM calculation.

Parameters / Objects	Density [kg/m^3]	Elastic modulus [GPa]	Poisson's ratio
Target	4510	114.8	0.32
Steel shot	7800	200.0	0.26

In the FEM simulation, an initial velocity of 80 m/s was imposed on the steel ball. The velocity was decreasing during impacting. When the velocity reached zero, it began to rebound. Strain along the depth at this moment calculated by FEM was treated as load for VPSC calculation.

The shot peened texture along the depth was simulated using VPSC code. The detailed VPSC model and the predominant twin reorientation scheme are described in the work of Tomé and Lebensohn et al. [8, 9]. The Voce law, shown by equation (2), is used to describe hardening behavior on different slip and twin systems.

$$\tau^s(\Gamma) = \tau_0 + (\tau_1 + \theta_1\Gamma)\left[1 - \exp\left(\frac{-\theta_0\Gamma}{\tau_1}\right)\right] \qquad (2)$$

$$\Gamma = \int_0^t \sum_s \left|\dot{\gamma}^s\right| dt \qquad (3)$$

where Γ in equation (3) is the accumulated shear within time t on all slip systems, and $\dot{\gamma}^s$ is the shear rate on slip system s. In the simulation, the prismatic <a> slip $\{10\bar{1}0\}\langle\bar{1}2\bar{1}0\rangle$, the basal <a> slip $\{0001\}\langle\bar{1}2\bar{1}0\rangle$, the first-order pyramidal <c+a> slip $\{10\bar{1}1\}\langle\bar{1}\bar{1}23\rangle$and two twinning modes, namely the tensile twinning $\{10\bar{1}2\}\langle\bar{1}011\rangle$ and compressive twinning $\{11\bar{2}2\}\langle\bar{1}\bar{1}23\rangle$, were taken into account. τ_0, τ_1, θ_0 and θ_1 are hardening parameters for each deformation system. The hardening behaviors representing the four parameters of the five deformation modes that lead to the best texture predictions are illustrated in Figure 1.

The texture evolution was characterized by the orientation distribution function (ODF) in the Euler space of (φ_1, ϕ, φ_2) following Bunge convention. When describing a specific orientation, the relationship between crystal and sample coordinate system is defined as $[\bar{1}010]$, $[\bar{1}2\bar{1}0]$ and [0001] corresponding to 1, 2 and 3 respectively. The texture was calculated using MTEX toolbox [10] by imposing the orthorhombic sample symmetry for shot peening process.

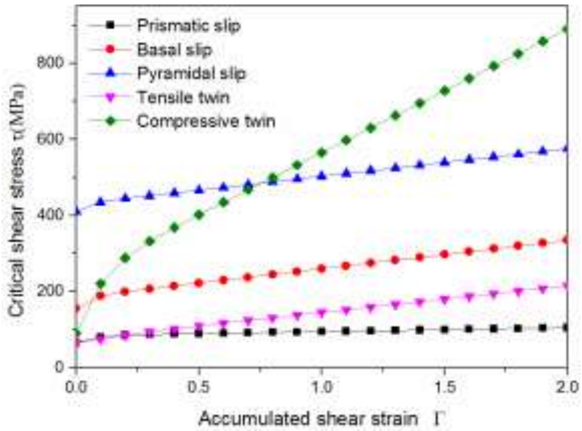

Figure 1. Hardening behaviors of the slip/twin systems.

3. Results and discussion

The schematic diagram of shot peening modeled by a single ball impacting and the calculated stress components by FEM are shown in figure 2(a) and figure 2(b) respectively. It is noted that three shear stress components can be negligible compared with the values of three normal stress components. That is to say, the stress state can be approximated three normal stress components as three principle stresses. At the top surface, the stress state can be described as compressive stress in two directions due to small value of σ_{33}. With the depth increased to about 600 μm, the stress state is compressive stress in three directions, as illustrated in figure 2(b). As the depth further increased towards interior, the stress state is changed from tensile stress in two directions and compressive stress in one direction to tensile stress in three directions, but the value of three normal stresses is relatively small.

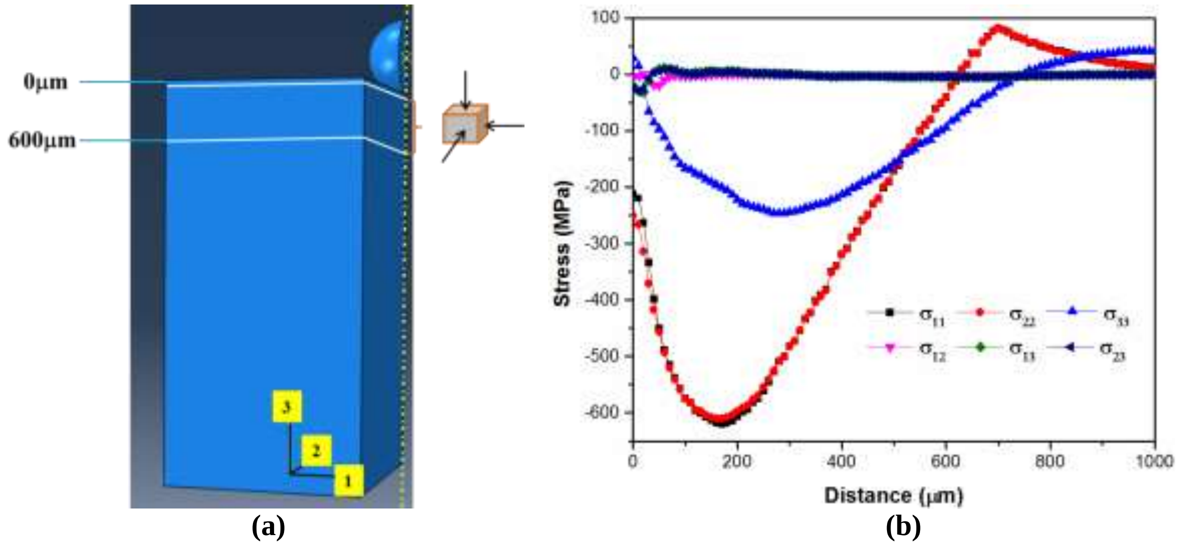

Figure 2. The schematic diagram of shot peening (a) and the calculated stress components (b).

The simulated equivalent plastic strain (PEEQ) and the strain components are given in figure 3. The PEEQ along the depth from the top surface after shot peening is increased firstly to maximum value and then decreased continuously to zero. The distribution of PEEQ is qualitatively good agreement with the work of Frija et al. [11]. The corresponding strain components are shown in figure 3(b). It can be seen that the strain state shows a gradient distribution along the depth and the strain affected range is between the top surface and the depth at 600μm. Among those strain components, the normal and shear strain components are nonzero except for shear strain ε_{12}, which means that shot peened deformation is a complicated strain state. And those nonzero strain components exhibit similar trend, i.e., with increasing the depth, the magnitude of strain is increased firstly to maximum value at depth around 60 μm and then decreased to zero at the depth near 600 μm.

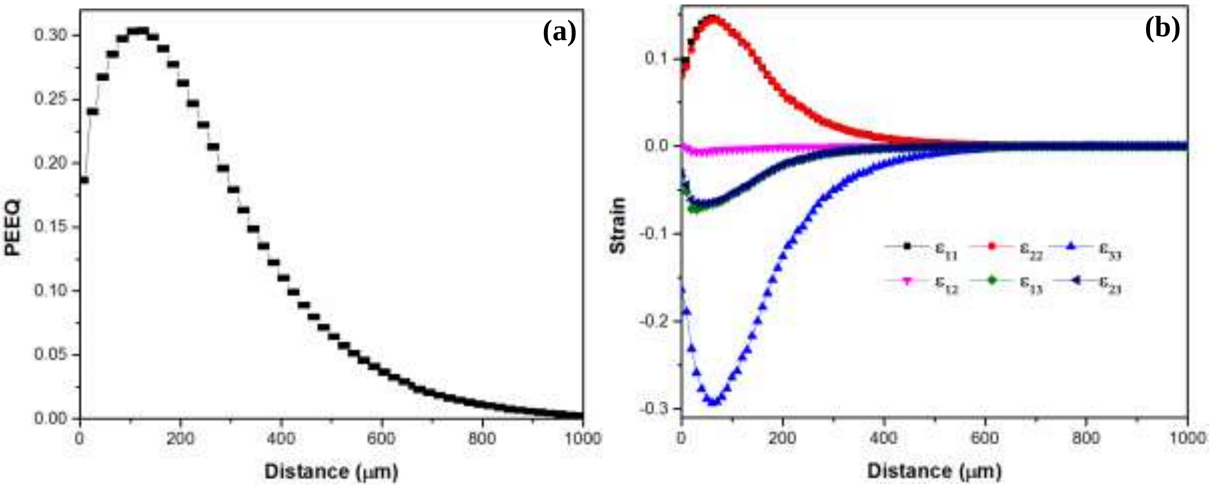

Figure 3. The distribution of PEEQ (a) and strain components (b).

The initial texture of pure titanium is illustrated by figure 4. It exhibits a tilt-model distribution of the basal poles and the $(\bar{2}110)$ pole is distributed along the rolling direction, which is typical texture commonly found in recrystallized pure titanium and can be characterized by basal poles tilted from the normal direction to transverse direction, i.e., two main components with Euler angles (0°, 40°, 30°) and (0°, 40°, 0°) [12]. Figure 5 shows the VPSC simulated texture at different depths after shot peening. From the (0001) pole figures, it can be seen that the deformed texture at different depths is all strengthened compared with initial texture. Moreover, it is noted that strongest texture is formed at the depth where the maximum absolute values of strain components exist, corresponding to the depth of 60 μm. The simulated results are contrary to the work of Maawad et.al [6], where the shot peened texture is weakened along the depth and the texture is weakest at the top surface, whereas they are agreement with the experimental result of Man et al. [5], who reported that texture was strengthened by shot peening.

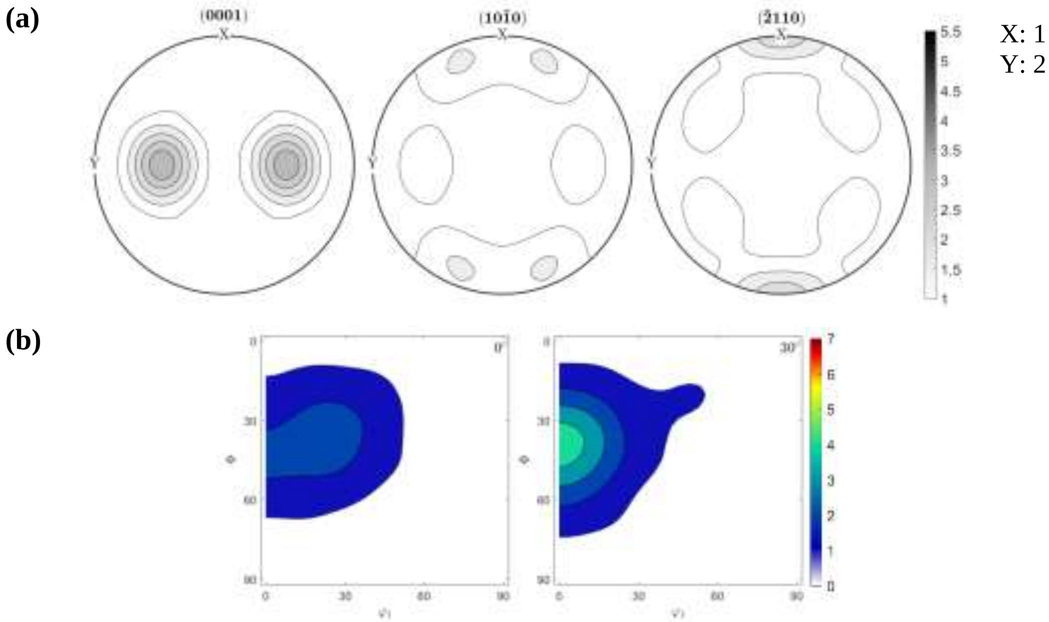

Figure 4. The pole figures of (0001), $(10\bar{1}0)$ and $(\bar{2}110)$ (a) and the ODF constant φ_2=0°and φ_2=30° (b) in initial pure titanium.

In order to investigate the variation of specific orientation, the ODF constant φ_2=0°and φ_2=30° at different depths is shown in figure 6. It can be seen that the deformed texture under complicated strain state caused by shot peening is quite different from plane strain rolled texture [12], the initial two main components (0°, 40°, 30°) and (0°, 40°, 0°) are strengthened simultaneously, and both are shifted towards little ϕ and it shifts much more at the depth of 60 μm with peak intensity at (0°, 25°, 30°) and (20°, 25°, 0°). Also, the ND//(01$\bar{1}$4) and ND//($\bar{1}2\bar{1}$7) fiber textures are formed at depth of 60 μm. And it can be seen the weak basal fiber texture or basal components are formed at different depths. At the depth of 300 μm, the deformed texture is nearly unchanged compared with the initial state.

As known, the deformed texture is determined by the activity of slip/twin system during plastic deformation. The simulated activity of slip/twin system is shown in figure 7. It is noted that prismatic slip, basal slip and both tensile twin and compressive twin are activated in shot peening. And it can be seen the activation of prismatic slip under complicated strain state is decreased compared to plane strain state [13]. However, further research is necessary to elucidate the specific mechanism.

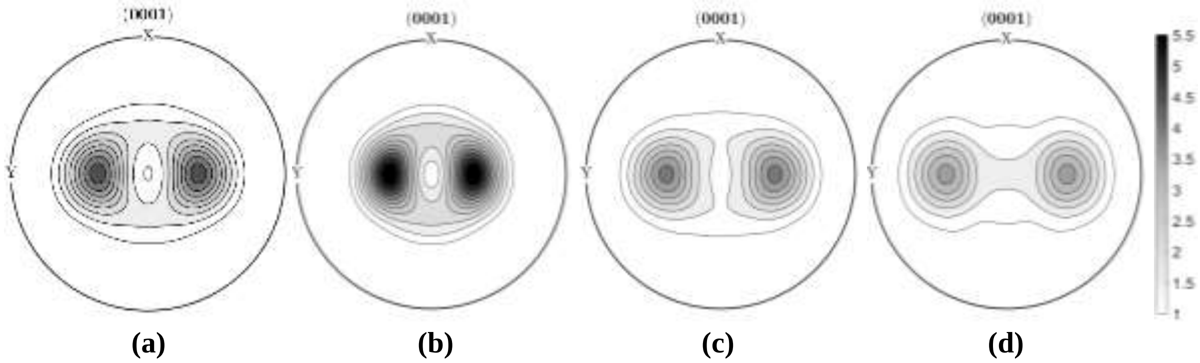

Figure 5. The simulated (0001) pole figure of shot peened pure titanium at depth of (a) 0 μm, (b) 60 μm, (c) 220 μm and (d) 300 μm from the top surface.

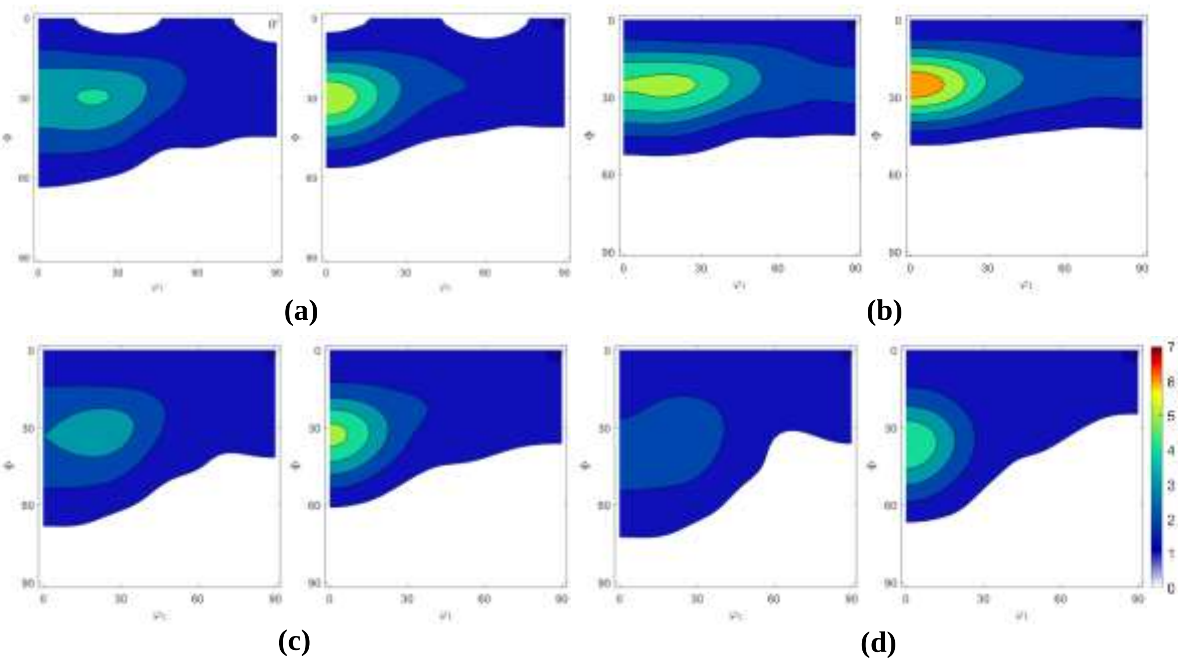

Figure 6. The simulated ODF constant φ_2=0°and φ_2=30° sections of shot peened pure titanium at depth of (a) 0 μm, (b) 60 μm, (c) 220 μm and (d) 300 μm from the top surface.

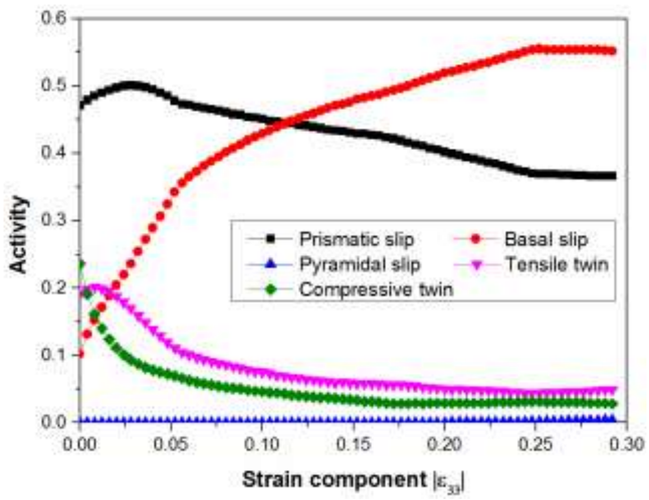

Figure 7. Slip activity for slip/twin systems at depth of 60μm in shot peened pure titanium.

4. Conclusions

The stress state in shot peened pure titanium can be described as compressive stress in three principle directions between subsurface and the depth at 600 μm. The strain state is a complicated strain state and the distribution of strain is in gradient along the depth.

The shot peened pure titanium with initial typical recrystallized texture is strengthened to different degrees at the depth between top surface and depth of 300μm. And the larger the magnitude of strain components, the stronger the deformed texture.

Acknowledgments

Financial support from Science and Technology Department of Shaanxi Province (2017GY-115) and Education Department of Shaanxi Province (16JK1466) are gratefully acknowledged.

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