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ARTICLE

Numerical and Experimental Investigations on the Effect of Shot Peening Intensity on the Surface Integrity of TA15 Titanium Alloy Profiles

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Abstract: The effect of the shot peening intensity on the surface integrity of TA15 titanium alloy hot extruded profile was numerically and experimentally studied. The surface roughness and residual stress distribution obtained by the numerical simulation were compared with the shot peening experimental results, and the reliability of the established finite element model was verified. The effects of shot peening intensity on the microhardness and microstructure of the material surface were investigated. The experimental results show that the compressive residual stress layer with a maximum value of 558~764 MPa and a depth of 115~151 μm was introduced into the surface of TA15 titanium alloy profile after shot peening. The plastic deformation occurs on the material surface, the grain is refined, the dislocation density and the hardness of the material surface increase. The hardened layer with a depth of 100~150 μm forms, and the surface roughness increases. The increase of the shot peening intensity increases the maximum compressive residual stress, the depth of the compressive residual stress layer and the surface hardness. However, the increase is not obvious when the intensity exceeds 0.188 mmA, and the cracks might appear on the material surface. Moreover, at the intensity of 0.222 mmA, the residual stress relaxation occurs on the material surface due to the folding defect, which reduces the surface integrity of the material.

Key words: titanium alloy; profile; shot peening; numerical simulation; surface integrity

TA15 is a near-α titanium alloy with moderate strength at room and high temperature, good thermal stability and welding performance. It is widely used in aircraft structural parts and engine parts at high temperature[1,2]. However, due to the influence of the airflow and the engine vibration during flight, and the low fatigue strength and the high notch sensitivity of titanium alloy itself, the fatigue failure has become the main failure form of the aviation titanium alloy structural parts. The statistics show that 90% of the failure of the titanium alloy aircraft structural parts is related to the fatigue[3,4]. The shot peening is widely used to improve the surface integrity and the fatigue properties of the materials because of its advantages such as simplicity, low cost and remarkable strengthening effect[5,6].

The surface integrity and the fatigue properties of titanium alloy after shot peening were researched extensively. Xia et al[3] noted that the effect of the shot peening on the fatigue behavior of TC4 titanium alloy is attributed to the effect of the shot peening on its surface integrity. When the compressive residual stress and the microstructure strengthening factors are dominant, the fatigue resistance of titanium alloy can be significantly improved. Ji et al[7] found that TA15 titanium alloy can obtain the best fatigue property under the condition of the shot S280 and the intensity 0.15~0.2 mmA, and the relationship between the surface roughness and the fatigue life showed that better surface roughness corresponds to higher fatigue life. Sabelkin et al[8] reported that the residual stress and the improvement in fretting fatigue life of Ti-6Al-4V alloy are directly related to the shot peening intensity. The magnitude and depth of the compensatory tensile stress increase with increasing the intensity, which prevents the shift of the crack source from inside towards the contact surface

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and improves the fatigue life. All those researches on titanium alloy shot peening treatment are mainly aimed at non-profile.

Titanium alloy profile, as a special semi-finished product of near-net shape, has higher structural benefits and is widely used in aerospace field[9-11]. It is necessary to study the shot peening of titanium alloy profiles to improve the service performance and meet the requirements of the engineering application. The numerical analysis is an important means to study the mechanism of the shot peening, the effect of the shot peening and the optimization of the process parameters[12,13]. In the study, the TA15 titanium alloy hot-extruded profile is considered to investigate the effect of the shot peening intensity on the surface integrity by the method of numerical simulation and experiment.

1 Numerical Analysis of Shot Peening

1.1 Finite element model

The numerical analysis of the random multi-shots peening assumed that a single shot impacted the target only once, and the collision between shots was ignored. The finite element software ABAQUS was used to simulate the shot peening process. The dimension of the target was defined as 2 mm×2 mm×1 mm to ensure the calculation efficiency and the accuracy of the numerical results. The random function of MATLAB was used to generate the coordinates of the shot centers, and the distance between every two shot centers was greater than the diameter *d* of the shot, so as to establish a random shot stream model. The target's bottom and sides were constrained against all degrees of freedom, and the contact pair algorithm was used to define the contact between the shot and the target. The relative motion between them was described by Coulomb friction model with a friction coefficient of 0.1. The shot impacted the target with a certain initial velocity in the direction perpendicular to the sprayed surface. The C3D8R linear hexahedron element was used to discretize the target, the C3D8R linear hexahedron element and the C3D6 linear wedge element were used to discretize the shot. The meshing diagram of the target surface is shown in Fig. 1. The sprayed area of 1 mm×1 mm is the range of action between the shot and the target, the research area is 0.5 mm×0.5 mm. Considering the solution accuracy, the element size in the sprayed area should be no larger than 1/10 of the diameter of the shot[14], so the element size was set as 0.02 mm×0.02 mm×0.02 mm. The finite element model of the shot peening is shown in Fig.2.

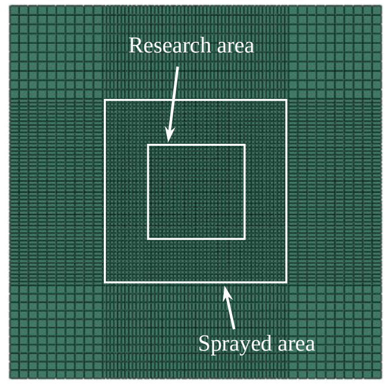

Fig.1 Diagram of target surface mesh division

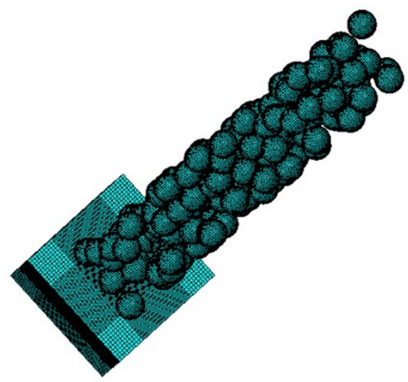

Fig.2 Random multi-shots peening finite element model

1.2 Material model

The shot was defined as rigid body. The main properties of TA15 titanium alloy are density of 4450 kg/m^3, elastic modulus of 118 GPa and Poisson's ratio of 0.34. The shot peening is a high-speed impact process, where the strain rate is high. Since the effect of the adiabatic temperature rise on the flow stress at room temperature and the non-linear effect of the strain rate are ignored, the Johnson-Cook model[15] cannot accurately describe the flow stress characteristics of TA15 titanium alloy at high strain rate. The model was modified here by introducing the adiabatic temperature rise ΔT and improving the strain rate hardening coefficient C. The relationship between ΔT and both the strain ε and the strain rate $\dot{\varepsilon}$ can be determined as follows:

$$\Delta T = (0.036\dot{\varepsilon} + 422)\varepsilon \quad (1)$$

The relationship between C and $\dot{\varepsilon}$ is as follows:

$$C = 0.018 + 2.84 \times 10^{-8}(\dot{\varepsilon})^{1.65} \quad (2)$$

Therefore, the modified Johnson-Cook model is as follows:

$$\sigma = (842 + 468\varepsilon^{0.48})\left\{1 + \left[0.018 + 2.48 \times 10^{-8} \cdot (\dot{\varepsilon})^{1.65}\right]\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right\}\left\{1 - \left[\frac{(0.036\dot{\varepsilon} + 422)\varepsilon}{1640}\right]^{2.07}\right\} \quad (3)$$

where σ is the flow stress, the $\dot{\varepsilon}$ is the reference strain rate.

1.3 Calculation of shot peening intensity

The material properties of the "A" Almen strip are density 7800 kg/m^3, elastic modulus 205 GPa, Poisson's ratio 0.29, and its Johnson-Cook constitutive parameters are A=1408 MPa, B=600.8 MPa, C=0.0134, n=0.234[16]. The residual stresses along the thickness of the Almen strip at different time after shot peening were obtained by the numerical simulation. The bending moments and bending heights of the strip at different time were calculated by Eq.(4) and Eq.(5), respectively[17]. The calculation results of the shot peening intensity under different process parameters are shown in Table 1.

Table 1 Shot peening intensity under different process parameters and the number of shots required to achieve full surface coverage

Shot diameter/mm	0.425			
Impact velocity/m·s^{-1}	30	40	50	60
Crater diameter/mm	0.113	0.136	0.146	0.152
Number of shots, N	220	160	130	115
Shot peening intensity/mmA	0.117	0.167	0.192	0.214

$$M = \int_S \sigma_x(z) z \mathrm{d}S \tag{4}$$

$$H = \frac{3ML^2}{2EBh^3} \tag{5}$$

where M is the bending moment, S is the cross-sectional area of the Almen strip, $\sigma_x(z)$ is the residual stress in the x-direction at the distance z from the surface of the strip after shot peening, H is the arc height value, E is the elastic modulus, L is half of the distance between the supporting points of the arc height measuring instrument, and B and h are the width and thickness of the Almen strip, respectively.

1.4 Calculation of surface coverage

Considering the model geometry and the symmetry of the boundary conditions, a quarter target model was established to improve calculation efficiency. The single shot peening finite element model is shown in Fig. 3. The displacement curves along the depth direction of the crater at different impact velocities are plotted in Fig.4.

The distance between two points with zero displacement along the depth direction of the crater was taken as the crater diameter. It was assumed that in the process of the random multi-shots peening, the crater diameter formed after each shot collided with the target was the same. The center coordinates (x_i, y_i, z_i) of the shot were generated by the random function in MATLAB, so the center coordinates of the crater were (x_i, y_i). Combined with the crater diameters obtained by the single-shot numerical analysis, the crater on the target surface under the process parameter can be plotted, as shown in Fig.5.

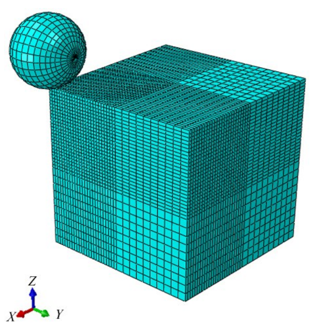

Fig.3 Single shot peening finite element model

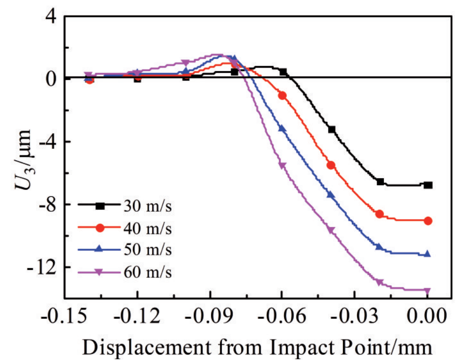

Fig.4 Displacement curves along the depth direction at different impact velocities

The overlaps and the parts outside the sprayed area have been removed, the black areas and white areas represent the crater and the untreated area on the target surface, respectively. The ratio of the shot peening area to the sprayed area is the coverage C_o. When C_o is more than 98%, it is considered that the full surface coverage is achieved[18]. The number N of the shots required to achieve the full surface coverage under different process parameters is shown in Table 1.

2 Experiment

The nominal composition of TA15 titanium alloy hot extruded T-profile is Ti-6.5Al-2Zr-1Mo-1V. The shot peening experiments were carried out on the MP4000 large-scale numerical control pneumatic shot peening equipment. The cleaned surfaces of samples were divided into different areas to perform the shot-peening experiments under different process parameters. Only one area was shot-peened in each experiment, and other areas were protected with protective tapes. The AZB425 ceramic shots with 0.425 mm in diameter

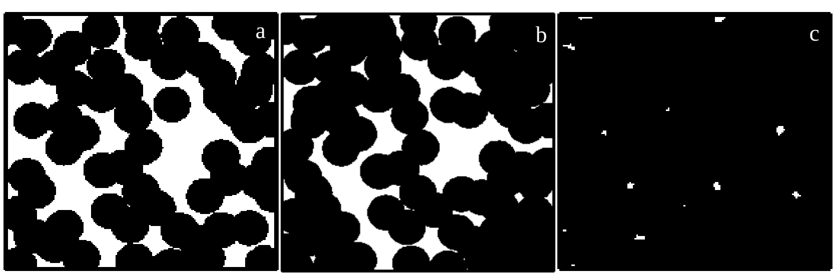

Fig.5 Surface coverage corresponding to different numbers of shots when impact velocity is 50 m/s: (a) N=60, C_o=68.11%; (b) N=80, C_o=79.17%; (c) N=130, C_o=98.10%

were used. The coverage, the shot flux and the shot peening angle were 100%, 8 kg/min and 90°, respectively. The shot peening intensity of 0.088~0.222 mmA and the shot peening pressure of 0.1~0.4 MPa were applied in the experiments.

The surface roughness was measured by Surftest SJ-410 surface roughness measuring instrument with 0.8 mm in sampling length, 5 sampling numbers, and 0.5 mm/s in probe moving speed. The maximum height of profile R_z was taken as the evaluation parameter of the surface roughness. The residual stresses were determined using LXRD-COMBO X-ray stress instrument and the $\sin^2(\psi)$ method and the cross correlation method for determining peak positions with Cu-Kα radiation on {213} plane at a voltage of 25 kV and current of 30 mA. The distributions of the residual stresses along the layer depth of the shot peening samples were measured by the electropolishing stripping method. The depth of stripping was 20 μm for each time. The microhardness were measured using HVS-1000A Vickers hardness with 1.96 N test load and 15 s holding time, and the measurements were carried out successively along the depth to the interior. The microstructures were observed by Jiangnan MR5000 inverted metallographic microscope.

3 Results and Discussion

3.1 Surface roughness

Fig. 6 shows the numerical and experimental results of the surface roughness of TA15 titanium alloy profile under different shot peening intensities. It can be seen that the surface roughness of the samples obtained by simulation and experiment increases with the increase of the shot peening intensity. The numerical results show that when the shot peening intensity increases from 0.117 mmA to 0.214 mmA, the sample surface roughness increases from 9.61 μm to 16.94 μm, with an increase of 76.3%. The experimental results show that the surface roughness value of TA15 titanium alloy profile is increased by 303.5% compared with the surface without shot peening (the shot peening intensity is 0.000 mmA) when the shot peening intensity is 0.222 mmA. It can be seen that the shot peening has a great effect on the surface roughness of TA15 titanium alloy profile. Table 2 lists the experiment and numerical results of the surface roughness when the shot peening intensities are similar. It can be seen that the numerical values of the roughness are smaller than the experimental values, and the differences are within 10%, suggesting a very good correspondence.

The cause for the difference is that the shot-peening pressures set in the experiments do not correspond to the shot-peening velocity defined in the simulations, as well as the error in the shot-peening intensity between the experiment and the simulation. The surface roughness of the targets before shot peening in the numerical simulations is zero, while in the experiments it is 4.62 μm before shot peening. In addition, it is assumed that a single shot impacts the target only once in the simulation. The shot will repeatedly impact the sample surface in the actual shot peening process. All those make the depths of the craters obtained by the simulation smaller, that is, the numerical results of the surface roughness are smaller.

3.2 Residual stress

The numerical results of the residual stress of TA15 titanium alloy profile under different shot peening intensities are shown in Fig. 7a. It can be seen that the depths of the compressive residual stress layer introduced under different shot peening process parameters are about 115~157 μm. With the increase of the layer depth, the compressive residual stress first increases to the peak and then decreases. The depth of the compressive residual stress layer, the maximum compressive residual stress and its depth increase with the increase of the shot peening intensity, and the maximum values are 157 μm, 743 MPa and 55 μm at an intensity of 0.214 mmA, respectively. The surface residual stress first increases to the maximum value and then decreases with the increase of the shot peening intensity, and the maximum value is 624 MPa at

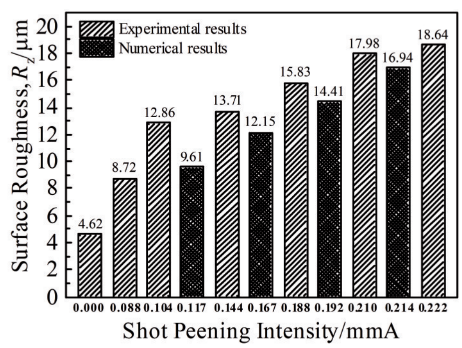

Fig.6 Results of surface roughness under different shot peening intensities

Table 2 Comparison of surface roughness and compressive residual stress field characteristic parameters obtained by experiment and numerical simulation

Method	Shot peening intensity/ mmA	Error/ %	Surface roughness/ μm	Error/ %	Surface residual stress/MPa	Error/ %	Maximum residual stress/MPa	Error/ %	Maximum residual stress depth/μm	Error/ %	Residual stress layer depth/μm	Error/ %
Experimental	0.188	2.1	15.83	9.0	−641	2.7	−732	1.7	51	3.9	144	6.3
Numerical	0.192		14.41		−624		−720		53		153	
Experimental	0.210	1.9	17.98	5.8	−690	14.9	−749	0.8	54	1.9	149	5.4
Numerical	0.214		16.94		−587		−743		55		157	

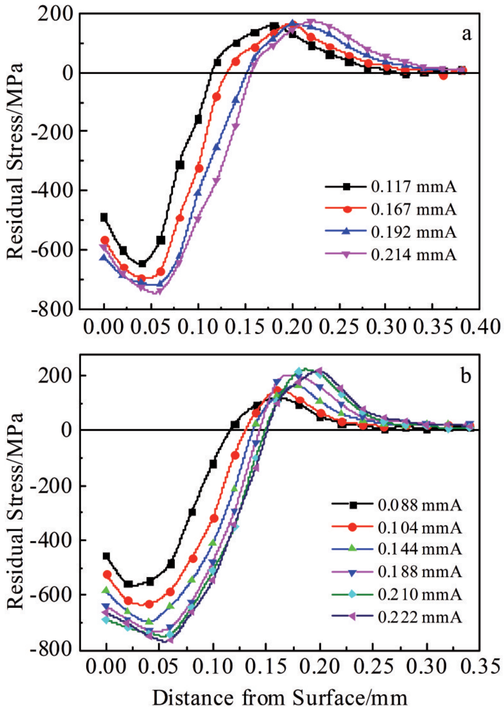

Fig.7 Surface residual stress distributions under different shot peening intensities: (a) numerical results and (b) experimental results

an intensity of 0.192 mmA. In general, when the shot peening intensity is 0.117~0.192 mmA, the better residual stress distribution can be obtained by increasing the shot peening intensity. When the shot peening intensity continues to increase to 0.214 mmA, the distribution of the compressive residual stress changes little, the differences of its characteristic parameters are within 6%, and the compressive residual stress field is nearly saturated.

Fig. 7b shows the experimental results of the residual stress distribution along the depth of TA15 titanium alloy profile under different shot peening intensities. It shows that the changes of the residual stress obtained by the experiment are consistent with the numerical results. The depths of the compressive residual stress layers are about 115~151 μm. The maximum surface compressive residual stress is 690 MPa at an intensity of 0.210 mmA. The maximum compressive residual stress layer depth, the maximum compressive residual stress and its position depth are 151 μm, 769 MPa and 56 μm at an intensity of 0.222 mmA, respectively. When the shot peening intensity increases to 0.188~0.222 mmA, the same as the numerical result, the saturation phenomenon of the compressive residual stress field appears. The comparison results of the measurements of the residual stress field under similar shot peening intensities are listed in Table 2. It shows that the differences between the experimental results and the numerical results are within 15%, and the data are in good agreement.

The cause for the difference is that the shot peening pressure in the experiment does not correspond to the shot peening velocity in the simulation. And there is a certain compressive stress on the material surface before the experiment, but the numerical target is in the stress-free state, and the interaction between the shots is ignored in the simulation process. These factors will lead to the difference between the experimental and numerical results.

3.3 Surface microhardness distribution

Fig. 8 shows the distributions of the microhardness of TA15 titanium alloy profile along the layer depth under different shot peening intensities. It can be seen that the microhardness in TA15 titanium alloy profile surface layer increases significantly after shot peening. When the shot peening intensity is 0.222 mmA, the maximum microhardness of the samples is ~4030 MPa, which is 45% higher than that of the original sample. However, when the shot peening intensity increases to 0.188 mmA, the microhardness in the material surface layer does not increase significantly with the increase of the shot peening intensity, and the variation range is less than 7%, which means that the further increase of the shot peening intensity cannot make the material produce stronger work hardening. With the increase of the layer depth, the microhardness of the material decreases gradually, and tends to be stable in the range of 100~150 μm from the surface, reaching the microhardness values of the matrix materials of 2310~2490 MPa. It can be seen that the depths of the hardened layers are 100~150 μm, which is basically the same as the depth of the compressive residual stress layer obtained by the experiment, and the depth of the hardened layer will increase with the increase of the shot peening intensity.

3.4 Microstructure

Fig. 9 shows the metallographic microstructures of TA15 titanium alloy profile perpendicular to the sprayed surface under different shot peening intensities. It can be seen that the microstructure of TA15 titanium alloy profile without shot peening is the rod-shaped basketweave structure, and its surface is relatively flat. The surface microstructure of the material is consistent with the internal matrix microstructure. After shot peening, the material surface is repeatedly impacted, the surface structure undergoes obvious plastic deformation, the grains are refined, the rod-shaped basketweave structures are broken, and the material surface is uneven. As the shot peening intensity continues to increase, the cracks of different sizes appear on the material surface, and even a folding defect appears on the material surface at the intensity of 0.222 mmA.

3.5 Discussion

The effect of shot peening on the fatigue resistance of the material is actually attributed to the effect of shot peening on the surface integrity of the material[3]. As shown in Fig. 6, the improvement of the shot peening intensity will increase the surface roughness of TA15 titanium alloy profile. This is mainly because the higher the shot peening intensity, the faster the velocity and the greater the energy of the shot, the more severe plastic deformation occurs on the material surface, and the deeper and the larger craters are formed. However, the excessive surface roughness will increase the stress

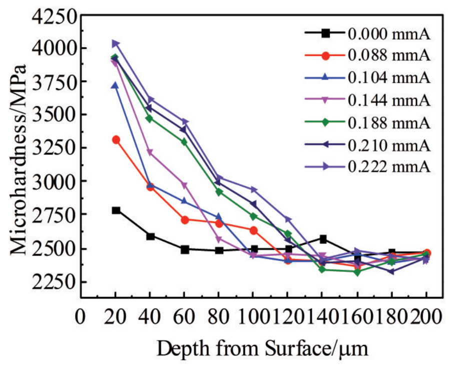

Fig.8 Microhardness distributions in TA15 titanium alloy profile surface layer under different shot peening intensities

concentration on the material surface, weaken the effect of the compressive residual stress, and then induce the fatigue cracks on the surface, which will deteriorate the surface integrity of TA15 titanium alloy profile and reduce the fatigue resistance of the material.

The results shown in Fig. 7 show that the shot peening introduces a certain depth, gradient distribution and high value of the compressive residual stress on the surface of TA15 titanium alloy profile. The compressive residual stress can offset part of the external alternating load, inhibit the initiation and propagation of the fatigue cracks on the material surface, and shift the source of the fatigue cracks from the surface to the subsurface. The internal fatigue limit of the material is higher than the surface fatigue limit, thus improving the fatigue resistance of the material[19]. Increasing the shot peening intensity within a certain range (0.088~0.188 mmA) can obtain a better residual stress distribution, thus improving the fatigue resistance of TA15 titanium alloy profile. However, with the further increase of the shot peening intensity, the compressive residual stress field is close to saturation, the depth of the compressive residual stress layer, the maximum compressive residual stress and its depth do not increase significantly, and the cracks appear on the material surface. Moreover, the residual stress on the material surface is relaxed at an intensity of 0.222 mmA, which is mainly due to the folding defect on the surface of TA15 titanium alloy profile caused by the excessive shot peening intensity, resulting in the material surface damage, as shown in Fig.9g, which releases part of the compressive residual stress[3].

The shot peening introduces the compressive residual stress in the near surface layer of the material, which also leads to the changes in the microstructure and hardness of the material. According to Fig. 8 and Fig. 9, the lattice distortion occurs in the surface microstructure of TA15 titanium alloy profile after shot peening, and a large number of dislocations and slip bands are generated, resulting in the increase of the dislocation density. Due to the movement of the dislocations, the interactions such as entanglement, intersection, and proliferation occur, the surface grains are refined, and the structural defects such as vacancies increase, which hinders the further movement of the dislocations, resulting in the work hardening, forming a hardening layer with a depth of 100~150 μm, and thus prolongs the fatigue life of the material. The increase of the surface hardness of TA15 titanium alloy profile is restricted by the deformation of the plastic deformation layer. With the increase of the plastic deformation, the dislocation density of the material surface layer increases, the work hardening effect is more significant, and the increase of the hardness is more obvious. However, when the shot peening intensity increases to a certain level (0.188 mmA), the effect of the shot peening intensity on the surface layer microstructure of the material and the plastic deformation caused by shot peening on the surface layer tend to be stable. The increase of the shot peening intensity has no significant effect on the surface hardness distribution of the material[20].

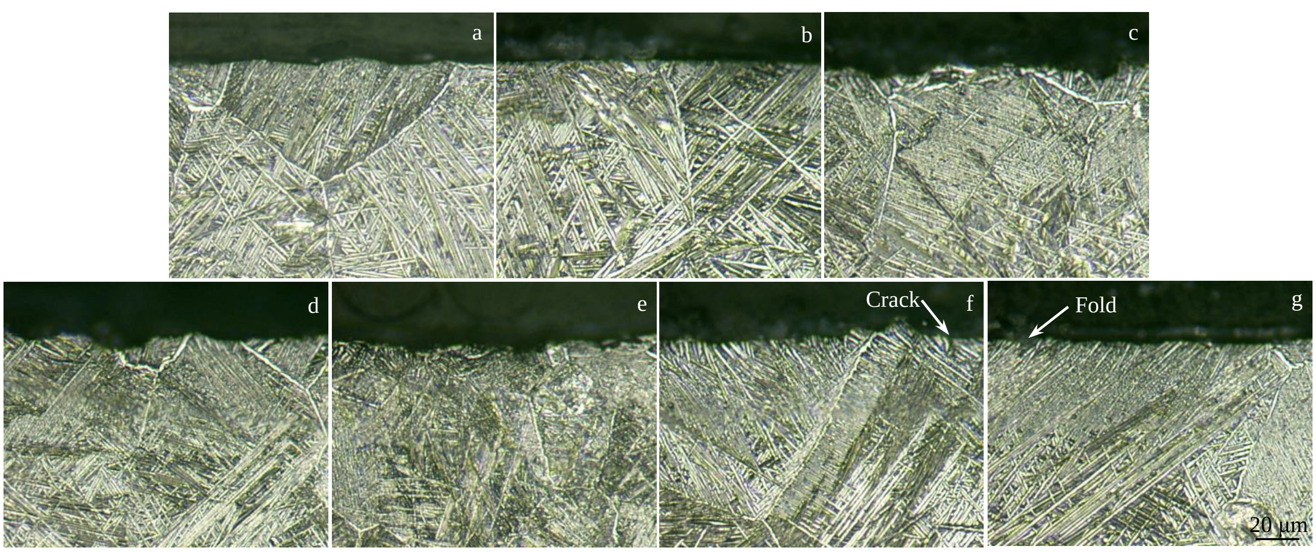

Fig.9 Metallographic microstructures of TA15 titanium alloy profile strengthening layer under different shot peening intensities: (a) 0.000 mmA, (b) 0.088 mmA, (c) 0.104 mmA, (d) 0.144 mmA, (e) 0.188 mmA, (f) 0.210 mmA, and (g) 0.222 mmA

4 Conclusions

1) By introducing the adiabatic temperature rise and updating the strain rate hardening coefficient, the dynamic Johnson-Cook constitutive model can accurately describe the flow stress characteristics of TA15 titanium alloy at high strain rate, which can be used to predict the surface roughness and the residual stress distribution of TA15 titanium alloy profile after shot peening.

2) The shot peening intensity has a great effect on the surface integrity of TA15 hot extruded profile. The increase of the shot peening intensity can get better distribution of the compressive residual stress and the hardness, which delays the initiation and early propagation of the fatigue cracks. However, the excessive shot peening intensity cannot significantly improve the surface integrity, the cracks might appear on the material surface, and the residual stress relaxation even occurs due to the folding defect.

3) Focusing on the best shot peening strengthening effect, the shot peening intensity should be controlled to improve the surface integrity of the material and the fatigue resistance of the material in the shot peening process of TA15 titanium alloy hot extruded profile.

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喷丸强度对TA15钛合金型材表面完整性影响的数值和实验研究

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摘 要：利用有限元模拟和喷丸实验研究了喷丸强度对TA15钛合金热挤压型材表面完整性的影响规律。对比了由数值模拟和喷丸实验得到的表面粗糙度和残余应力分布结果，验证了所建立的喷丸有限元模型的可靠性；研究了喷丸强度对材料表层显微硬度和微观组织的影响。实验结果表明，喷丸处理在TA15钛合金型材表层产生了最大数值为558~764 MPa且深度为115~151 μm的残余压应力层，材料表层发生塑性变形，位错密度增大，晶粒细化，表层硬度提高，形成了深度为100~150 μm的硬化层，同时表面粗糙度增大。最大残余压应力、压应力层深度和表层硬度随喷丸强度的增大而增大，但强度超过0.188 mmA后增加不明显，材料表面出现裂纹，且在0.222 mmA强度下，材料表面因折叠缺陷而发生残余应力松弛，降低了材料表面完整性。

关键词：钛合金；型材；喷丸强化；数值模拟；表面完整性

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