Rare Metal Materials and Engineering
Volume 49, Issue 10, October 2020
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Rare Metal Materials and Engineering, 2020, 49(10): 3395-3401.

ARTICLE

Over Peening Effect of Al7050 Mid-thick Plates with Continued Multiple Laser Shock Peening Impacts at the Same Position

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Abstract: An over peening effect was presented based on the researches of surface integrity and internal spall of Al7050 mid-thick plates with continued multiple laser shock peening (LSP) impacts at the same position. The dimensions of the samples were 50 mm×50 mm×5 mm (length×width×thickness). Laser process parameters were laser energy of 30 J, square spots of 4 mm×4 mm, pulse width of 15 ns and continued multiple LSP impacts at the same position (LSP-1~LSP-8). Surface morphology, surface residual stress, and micro-hardness in depth and cross-sectional microstructure were measured by super depth 3D microscope system, X-ray diffraction instrument, Vickers indenter and optical microscope (OM), respectively. The results indicate that high micro-dent depressions of 197.8 μm and ridges of 130.8 μm are generated after continued LSP-5. Surface compressive residual stress changes into tensile residual stress from continued LSP-4 to continued LSP-5. After continued LSP-5, work softing with low micro-hardness is found in the bottom layer. Continued LSP-5 is the spall threshold of Al7050 mid-thick plates. The research is beneficial to avoid the spall and improve the strengthening effect in the industry application of LSP.

Key words: Al7050 mid-thick plates; laser shock peening (LSP); over peening effect; surface integrity; internal spall

Al7050 alloy is recognized as a structural material, which has been widely used in aeronautics and aerospace industries because of its high ratios of stiffness/weight and strength/ weight[1,2]. However, fatigue fracture failure happened in advance and fatigue crack initiated at the surface due to poor working condition[3]. Thus its surface modification was intensively studied[4]. Laser shock peening (LSP) is an advanced surface treatment technology, which has been successfully applied to improve the fatigue performances of Al7050 alloy[5,6]. When peak pressure of laser shock wave is greater than Hugonoit elastic limit (HEL) of the target, surface integrity is improved. It resulted in the enhancement of mechanical property[7], corrosion resistance[8], foreign object damage resistance[9] and fatigue life[10]. However, internal spall may be induced by LSP with sufficient pressure amplitude and pressure duration, which would rapidly decrease the fatigue life of the material. The spall formation procedure is as follows[11]: (1) Two rarefaction waves are generated. One comes from the incident unloading wave. The other is due to the reflection of incident shock wave from the bottom surface. (2) Dynamic tensile stress inside the material is induced due to the interaction of two rarefaction waves. (3) The spall occurs by sufficient magnitude and duration of dynamic tensile stress. For example, spall strength of Al-HP RX (high-purity recrystallized aluminum) with 500 μm thickness is 3.7 GPa during LSP with 2.9 μs^{-1} strain rate. Therefore, it is very important to study the over peening effect in the field of surface modification of LSPed metals.

Many researchers focused their attention on the improvement of surface integrity and fatigue performance of Al7050 alloy with LSP. Ren et al[5,12] found that deep compressive residual stress and high dislocation density in the surface layer after LSP played a role in the fatigue crack initiation and growth resistance of Al7050 alloy. Luong and Hill[4] revealed

Received date: October 21, 2019
Foundation item: National Science and Technology Major Project of China (2016YFB1102700); National Natural Science Foundation of China (51875542); Civil Aircraft Research Project (MJ-2016-F-16); Aviation Fund (20185425009)
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that deep compressive residual stress induced by LSP improved the high cycle fatigue performance of Al7050-T7451. Zhang et al[13] indicated that two-sided LSP with four paths more effectively restrained the fatigue crack initiation and growth of Al7050-T7451. Above researched results were based on the fact that peak pressure of laser shock wave was within HEL~2HEL of material and LSP impact times at the same position were less than LSP-5. However, it has not been considered in an over peening effect of Al7050 mid-thick plates with LSP.

It is inevitably required to understand the knowledge of dynamic deformation and spall from the protection of aerospace components. The spall behavior of Al alloy has been extensively studied. Many researchers focused their attention on how spall strength depends on the loading condition and influence of microstructure on spall failure of Al alloy. Wang et al[14] found that spall strength of pure aluminum rapidly increased with the tensile strain rate at about 10^6 s^{-1} by laser irradiation experiments. Brewer et al[15] found that the spall fracture surface morphology of thin aluminum targets could be characterized by brittle intragranular fracture or ductile transgranular fracture. The spall strength increased with increasing the ductile fracture character. Dalton et al[16] and Pedrazas et al[17] extended the fundamental understanding by examining the effect of impurity particle, grain size and inclusions on the spall of aluminum with laser shocked load. Nevertheless, internal spall of Al7050 mid-thickness with LSP has never been reported.

In this paper, an over peening effect of Al7050 mid-thick plates treated by continued multiple LSP impacts at the same position was presented based on surface integrity and internal spall. The surface integrity included surface morphology, surface residual stress, micro-hardness and microstructure. Optimized process was also discussed. The research results provided an important reference for the industry application of Al7050 alloy with LSP.

1 Experiment

Al7050 mid-thick plate with the dimensions of 50 mm×50 mm×5 mm (length×width×thickness) was selected as experimental material. Its chemical composition (wt%) is listed in Table 1. Its mechanical properties are elastic modulus of 72 GPa, Poisson's ratio of 0.33, and HEL of 1.1 GPa[18]. The surface of sample was treated by continued multiple LSP impacts at the same position. High laser energy of 30 J was used to study the over peening effect. A water curtain and a 3M aluminum foil were used as transparent confining layer and absorbed layer, respectively. Experimental parameters of LSP are listed in Table 2.

LSP experiments were carried out with a Q-switched Nd: YAG laser system and overlapping square spots, as shown in Fig.1. The experimental LSP setup comprised of (i) A Nd:YAG laser system with circular laser beam, a wavelength of 1064 nm and pulse width of 15 ns; (ii) A beam delivery system consisting of a focus lens and a beam shaping lens, which made circular spots focus onto square spots at the surface of Al7050 alloy; (iii) A 6-axis manipulator; (iv) A deionized water curtain supplying system with a water container.

Surface integrity and internal spall of Al7050 alloy treated by continued multiple LSP impacts at the same position were measured, including surface morphology, surface residual stress, and micro-hardness in depth, and cross-sectional microstructure and cross-sectional spall characteristic.

The surface morphology along the X direction path at the center of spot was measured by the super depth 3D microscope system with VHX-5000. The surface residual stress in the Y direction along the X direction path at the center of spot was determined by LXRD equipment using X-ray diffraction with sin2Ψ method, as shown in Fig.2. The measurement spacing was 2 mm. X-ray beam diameter was about 2 mm. X-ray source was Cr target and the diffraction plane was α-phase (311) plane. The diffraction angle was 139°.

Micro-hardness in depth of the cross sectional samples at the center of spots was measured by a HXD-1000TMC LCD Vickers indenter with a load of 1960 N and a dwell time of 5 s. The measurement spacing was 0.15 mm between successive points and micro-hardness value of each point was determined by 2~3 indentations. The cross-sectional microstructures at the center of spots were observed by optical microscope (OM). The corrosive liquid was hydrofluoric:nitric acid:water=1:2:7 with corrosive time of 10 s.

Table 1 Chemical composition of Al7050 alloy (wt%)

Zn	Mg	Cu	Cr	Zr	Si	Fe	Al
5.7~6.7	1.9~2.6	2.0~2.6	≤0.04	0.08~0.15	≤0.12	0.15	Bal.

Table 2 Experimental parameters of LSP

Laser energy/J	Pulse width/ns	Continued multiple LSP impacts	Spot size/mm	Confining layer, h/mm	Absorbing layer, h/mm	Frequency/Hz
30	15	LSP-1~LSP-8	4×4	1~2	0.12	1

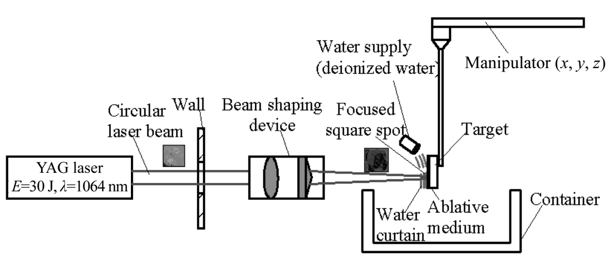

Fig.1 Schematic diagram of LSP setup

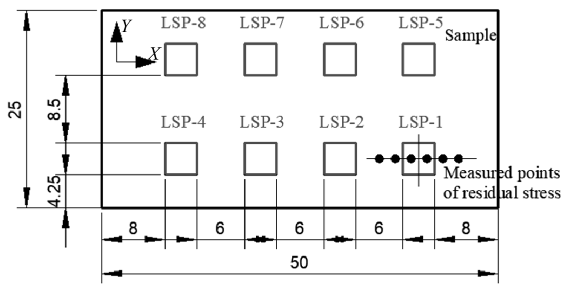

Fig.2 Measured points of residual stress in LSP regions

2 Results and Discussion

2.1 Surface morphology

Fig.3 presents the surface morphologies of Al7050 alloy treated by continued multiple LSP impacts at the same position along the *X* direction at the center of spots. The surface profiles with maximum depressions *H* in the *X* direction are presented and 0.1 H from the upper limit of the surface profiles is defined as the measuring datum line. Intersection spacing between the measuring datum line and the surface profile is defined as laser shocked size which is about 5 mm after LSP-1, as shown in Fig.3a. Micro-dent depressions *H* are about 43.5 μm for LSP-1, 142.9 μm for continued LSP-4, 197.8 μm for continued LSP-5, 291 μm for continued LSP-8. Micro-dent ridges are 23.7 μm for LSP-1, 82.3 μm for continued LSP-4, 130.8 μm for continued LSP-5, 197 μm for continued LSP-8. Fig.4 shows the micro-dent depth and the height of ridges of Al7050 alloy with continued multiple LSP impacts at the same position. From Fig.4, the increasement amplitude of micro-dent ridges is maximum value with 58.9 % from continued LSP-4 to continued LSP-5. Therefore, continued LSP at the same positions should be less than continued LSP-5 in order to decrease the surface roughness of Al7050 alloy.

2.2 Surface residual stress

Fig.5 shows surface residual stress of Al7050 alloy in *Y* direction along the *X* direction path at the center of spots. LSP introduces compressive residual stresses in the surface layer and compressive residual stresses decrease with the increment of impact times. Compressive residual stress changes into tensile residual stress from continued LSP-4 to continued LSP-5, which may be attributed to focused effect of edge by high laser energy and multiple impacts. Surface residual stresses are –40 MPa for LSP-0, –148.8 MPa for LSP-1, –46.2 MPa for continued LSP-2, –54.4 MPa for continued LSP-3, –75.6 MPa for continued LSP-4, and 82 MPa for continued LSP-5, and 92.4 MPa for continued LSP-6, 125.5 MPa for continued LSP-7 and 99.6 MPa for continued LSP-8. Therefore, continued LSP should be less than continued LSP-5. In addition, surface compressive residual stress after LSP-1 is low with –148.8 MPa, which may be ascribed to focused effect of edge induced by LSP peak pressure of more than 2.5 HEL of Al7050 alloy.

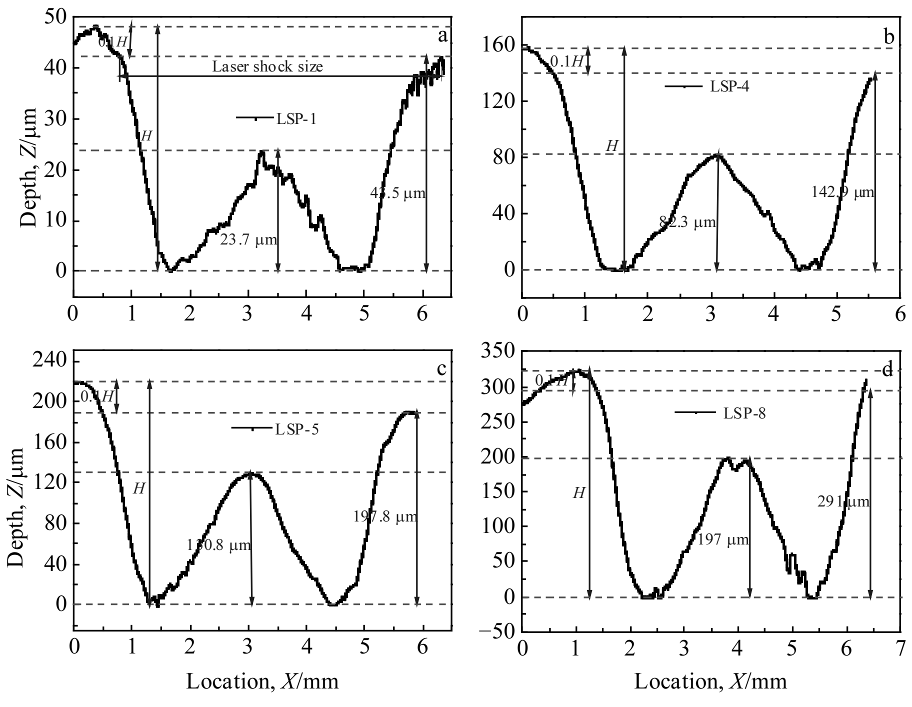

Fig.3 Surface morphologies of Al7050 alloy treated by continued multiple LSP impacts at the same position along the *X* direction path at the center of spots: (a) LSP-1, (b) LSP-4, (c) LSP-5, and (d) LSP-8

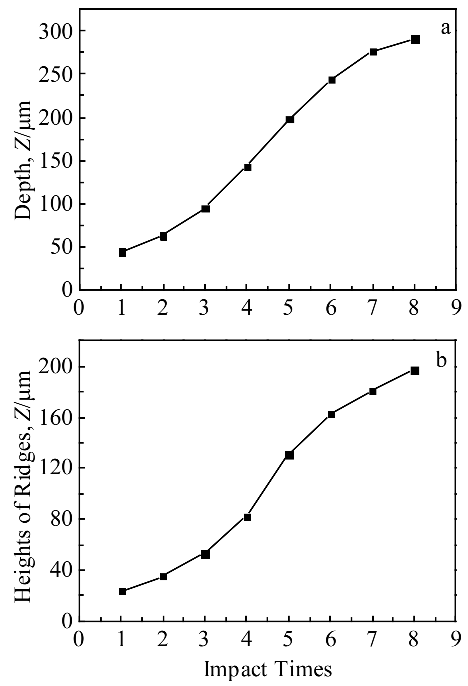

Fig.4 Micro-dent depth (a) and the height of ridges (b) of Al7050 alloy with continued multiple LSP impacts at the same position

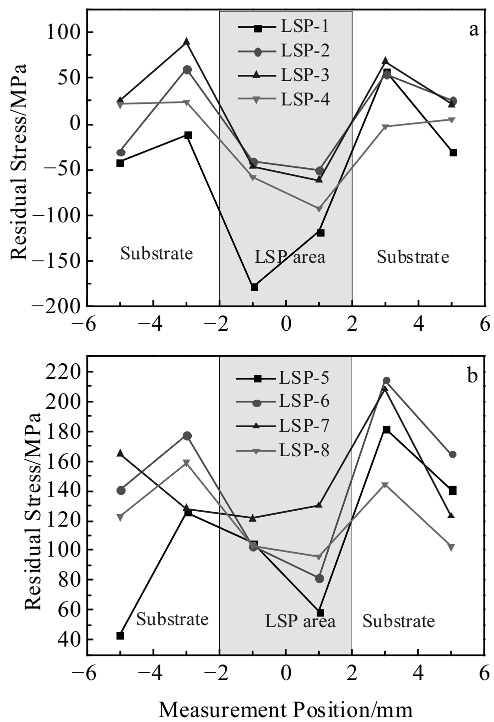

Fig.5 Surface residual stress of Al7050 alloy in *Y* direction along the *X* direction path at the center of spots: (a) continued LSP-1~LSP-4 and (b) continued LSP-5~LSP-8

The compressive residual stresses induced by LSP are the most significant contribution to the improvement of fatigue properties[19,20]. It could cause the crack closure effect, increase the level of crack opening load and reduce the effective load range, which retarded fatigue crack propagation[21]. Therefore, continued LSP at the same position should be less than continued LSP-5.

2.3 Micro-hardness at the cross section

Fig.6 shows cross-sectional micro-hardness of Al7050 alloy treated by continued multiple LSP impacts at the same position. Micro-hardness of as-received material is about 1135 MPa by the analysis of cross-sectional micro-hardness, as shown in Fig.6a. Micro-hardnesses of Al7050 alloy increase to about 1183 MPa for continued LSP-4 and 1180 MPa for continued LSP-5 in the surface layer, as shown in Fig.6b and Fig.6c. This reason may be attributed to cold working hardening layer, high density dislocations and nanograins in the surface layer induced by LSP. The cross-sectional micro-hardness after LSP gradually decreases with the increment of the distance from the surface. Similar results have been reported about TC11 alloy [22] and TC17 alloy [23]. These results may be ascribed to attenuation of the pressure amplitude of laser shock wave in the target. And micro-hardness gradually increases from the center of dent to the edge of dent in the surface layer with –250 μm (Fig.6d). Great hardness of Al7050 alloy after LSP can bring a good property of fatigue resistance and prevent the foreign object damage (FOD) to some extent.

However, work soft after continued LSP-4 and spall after continued LSP-5 is generated in the bottom layer of Al7050 alloy, as shown in Fig.6b and Fig.6c. Micro-hardnesses fall to 1113 MPa after continued LSP-4 and 1109 MPa after continued LSP-5 in the bottom layer, which may be ascribed to high amplitude and long duration of dynamic tensile stress induced by LSP. Therefore, continued LSP at the same position should be less than continued LSP-5, which may avoid the spall phenomenon and work soft caused by dynamic tensile stress.

2.4 Microstructure at the cross section

Fig.7 presents the microstructure of cross-section of Al7050 alloy with continued LSP-5. Fig.7b~Fig.7d are the higher magnification of the box A, B and C in Fig.7a, respectively. Fig.7b is the refined grain in the surface layer after LSP. Fig.7c is the bottom layer after LSP. Grain in the substrate is shown in Fig.7d. Compared with the grains in the substrate, grains are refined in the surface layer after LSP. With increasing the distance from LSPed surface, the plastic deformation decreases and the grain size increases. It is interesting to note that the spall forms in the bottom layer after LSP-5.

Fig.8 presents OM morphologies of Al7050 alloy with different impact times in the bottom layer[24]. It can be clearly seen from Fig.8 that the spall forms after continued LSP-5.

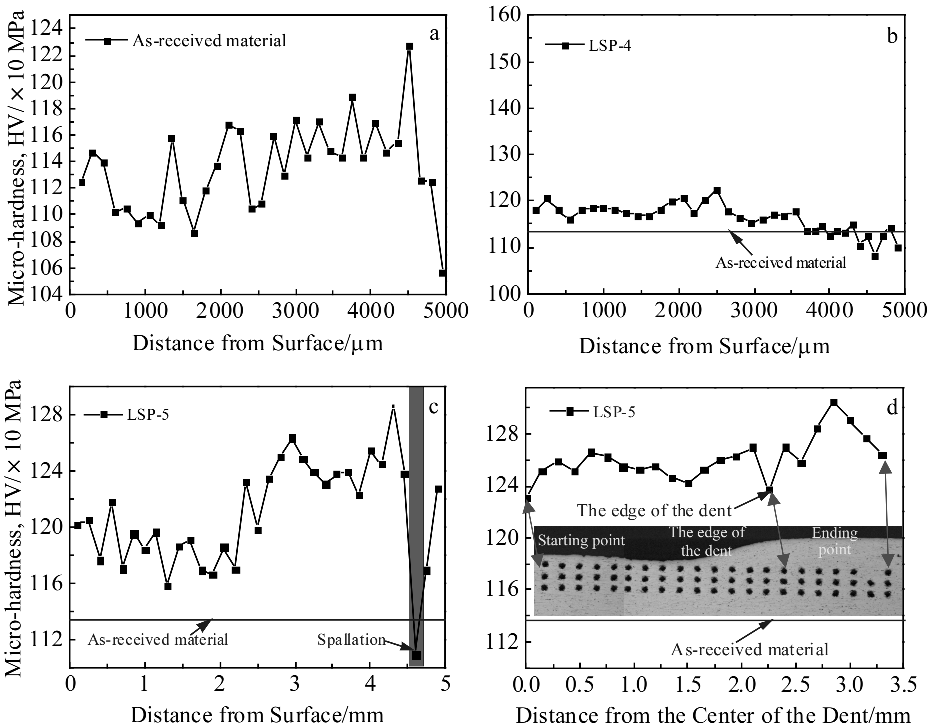

Fig.6 Micro-hardness of cross-section of Al7050 alloy treated by continued multiple LSP impacts at the same position: (a) as-received material, (b) continued LSP-4, (c) continued LSP-5, and (d) micro-hardness in the surface layer after continued LSP-5

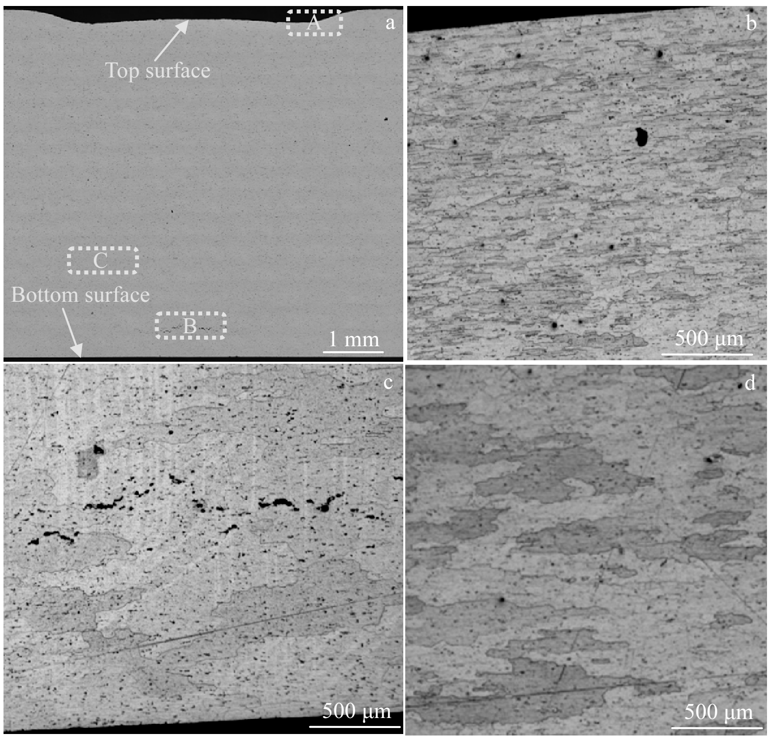

Fig.7 Microstructures of cross-section of Al7050 alloy with continued LSP-5: (a) whole cross-sectional microstructure, (b~d) the higher magnifications of the box A, B and C in Fig.7a, respectively

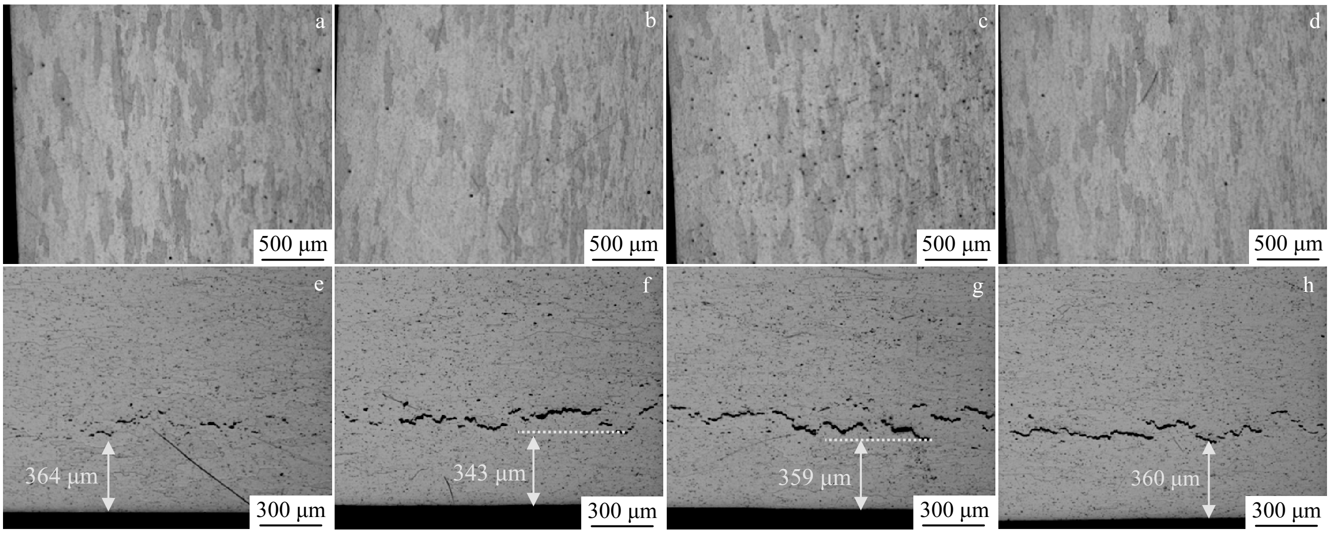

Fig.8 OM morphologies of 7050 Al with different impact times in the bottom layer: (a) LSP-1, (b) LSP-2, (c) LSP-3, (d) LSP-4, (e) LSP-5, (f) LSP-6, (g) LSP-7, and (h) LSP-8

The spall thicknesses are 364, 343, 359 and 360 μm for continued LSP-5, LSP-6, LSP-7, and LSP-8, respectively.

3 Conclusions

1) The increasing amplitude of micro-dent ridges reaches the maximum value from continued LSP-4 to continued LSP-5, up to 58.9%.

2) Surface compressive residual stress changes to tensile residual stress from continued LSP-4 to continued LSP-5.

3) Micro-hardness increases with continued LSP times in the surface layer and reaches a saturation value. Micro-hardness decreases in the bottom layer because of work soft and spall caused by dynamic tensile stress.

4) Continued LSP-5 is the spall threshold of Al7050 mid-thick plates.

References

1 Carvalho A L M, Voorwald H J C. *Materials Science and Engineering A*[J], 2009, 505(1-2): 31

2 Brown Rebecca, Tang Wei, Reynolds A P. *Materials Science and Engineering A*[J], 2009, 513(11): 115

3 Schubbe Joel J. *Engineering Fracture Mechanics*[J], 2009, 76(8): 1037

4 Luong H, Hill M R. *Materials Science and Engineering A*[J], 2010, 527(3): 699

5 Ren X D, Zhan Q B, Yang H M *et al*. *Materials and Design*[J], 2013, 44: 149

6 Ren X D, Zhang Y K, Zhang T *et al*. *Materials and Design*[J], 2011, 32(3): 1138

7 Saklakoglu N, Gencalp Irizalp S, Akman E *et al*. *Optics and Lasers Technology*[J], 2014, 64: 235

8 Wang Hao, Ning Chengyi, Huang Yihui *et al*. *Optics and Lasers in Engineering*[J], 2017, 90: 179

9 Zabeen S, Preuss M, Withers P J. *Acta Materialia*[J], 2015, 83: 216

10 Bergant Zoran, Trdan Uro, Grum Janez. *International Journal of Fatigue*[J], 2016, 87: 444

11 Kanel G I. *International Journal of Fracture*[J], 2010, 163(1-2): 173

12 Ren X D, Zhang Y K, Yongzhuo H F *et al*. *Materials Science and Engineering A*[J], 2011, 528(6): 2899

13 Zhang L, Lu J Z, Zhang Y K *et al*. *Materials and Design*[J], 2011, 32(2): 480

14 Wang Y, He H, Wang L *et al*. *Journal of Applied Physics*[J], 2006, 100: 1325

15 Brewer J L, Dalton D A, Jackson E D *et al*. *Metallurgical & Materials Transactions A*[J], 2007, 38(11): 2666

16 Dalton D A, Worthington D L, Sherek P A *et al*. *Journal of Applied Physics*[J], 2011, 110(10): 473

17 Pedrazas N A, Worthington D L, Dalton D A *et al*. *Materials Science & Engineering A*[J], 2012, 536: 117

18 Yang C, Hodgson P D, Liu Q *et al*. *Journal of Materials Processing Technology*[J], 2008, 201(1): 303

19 Fabbro R, Fournier J, Ballard P *et al*. *Journal of Applied Physics*[J], 1990, 68(2): 775

20 Zhang X Q, Li H, Yu X L *et al*. *Materials and Design*[J], 2015, 65: 425

21 Kashaev Nikolai, Ventzke Volker, Horstmann Manfred *et al*. *International Journal of Fatigue*[J], 2017, 98: 223

22 Nie Xiangfan, He Weifeng, Zang shunlai *et al*. *Surface and Coatings Technology*[J], 2014, 253(25): 68

23 Nie Xiangfan, He Weifeng, Li Qipeng *et al*. *Journal of Laser Applications*[J], 2013, 25(4): 1892

24 Wu Junfeng, Zou Shikun, Che Zhigang *et al*. *Rare Metal Materials and Engineering*[J], 2019, 48(4): 1096

连续激光冲击强化 7050 铝合金中厚板的过喷效应

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摘　要：基于连续激光冲击强化 7050 铝合金中厚板的表面完整性和内部层裂，提出了一种激光冲击强化的过喷效应。7050 铝合金中厚板尺寸为 50 mm×50 mm×5 mm（长×宽×高）。激光工艺参数为激光能量 30 J，光斑尺寸 4 mm×4 mm，脉宽 15 ns 和单点连续多次激光冲击（LSP-1~LSP-8）。表面形貌，表面残余应力，深度方向显微硬度和截面微观组织分别用超景深三维形貌仪，X 射线衍射仪，显微硬度仪和金相显微镜测试分析。研究结果表明：单点连续 5 次激光冲击诱导 7050 铝合金中厚板表面微凹坑凸起高度为 197.8 μm 和山脊高度为 130.8 μm。从单点连续 4 次激光冲击到单点连续 5 次激光冲击，试样表面残余应力由压应力转换为拉应力。单点连续 5 次激光冲击后，试样背层产生了低显微硬度的加工软化现象。单点连续 5 次激光冲击为 7050 铝合金中厚板的层裂阈值。研究结果有益于激光冲击强化工业应用中避免层裂和改善强化效果。

关键词：7050 铝合金中厚板；激光冲击强化；过喷效应；表面完整性；内部层裂

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