Influence of incident angle on surface integrities of 7075 aluminum alloy covered with the flexible coating material during laser shot peening

Qinxiang Xia #1[a], Junhao Zhang #2[a], Xiuquan Cheng #3[b], Xiao Xu #4[a]
[a] School of Mechanical and Automotive Engineering, South China University of Technology, 510640 / China,
Email #1: meqxxia@scut.edu.cn, #2:415709826@qq.com, #4: simonxx@scut.edu.cn;
[b] School of Aircraft Maintenance Engineering, Guangzhou Civil Aviation College, 510470 /China,
Email: #3: chengxiuquan@caac.net
Corresponding author: Xiuquan Cheng, chengxiuquan@caac.net

Keywords: 7075 aluminum alloy, Laser shot peening, Incident angle, Surface integrities, Online repairmen

Introduction

The aircraft parts are susceptible to the corrosion damage due to the fatigue load, slight rubbing and corrosive environment during the long flight service [1]. For some slight damaged aircraft parts, the damaged aircraft parts can continue to be used after removing the corroded portion by grinding and then strengthening the ground area by shot peening [2]. Online repairment refers to the method that repairing the damaged parts without disassembly. Compared with the off-line repairment, online repairment has the advantages of saving repairment time, reducing repairment cost and maintaining the original coordination accuracy of parts. Laser shot peening has a wide application prospect because of its good accessibility [3]. Oblique angle laser shot peening during the online repairment of the damaged aircraft parts has to be adopted due to the limitation of the cabin space, which brings the difficulties of impacting along the normal direction in each impact.

Focus on the gas turbine blades strengthening, Suh U W et al.[4] designed a device which realized the simultaneous double side oblique laser shot peening and applied for a patent. But the influence of laser incident angle on the strengthening effect was not studied. Leihong Z et al.[5] studied the influence of laser incident angle on sheet forming based on theoretical derivation and experiments. The results show that with the increasing of laser incident angle, the deformation alone the vertical direction decreases while the deformation alone the horizontal direction increases. But it was not mentioned the laser shot peening strengthening process.

The laser incident angle θ is the angle between the axis of laser beam and the normal direction of the target material, which is an index to describe the slope degree of laser oblique impact [6]. Surface integrities refers to the qualities of surface microhardness, surface topography, residual stress, and etc.[7]. The surface microhardness, surface topography and residual stress under the different laser incident angle θ were obtained to investigate the influence of θ on the strengthening effect during laser shot peening for providing the selection guidance of laser incident angle during the actual repairment of the damaged aircraft parts.

Objectives

7075 aluminum alloy is a kind of commonly used material for manufacturing the structure parts of aircraft [8]. In this paper, 7075 aluminum alloy covered with the flexible coating material [9], which includes energy confinement layer and energy absorbent layer [10]. The energy confinement layer is obtained by mixing and curing the bisphenol A-epichlorohydrin epoxy resin and the cycloaliphatic amine curing agent in the ratio of 1.5:1, and the energy absorbent layer consists of a layer of black double-side tape and a layer of black electrical tape; the total thickness of flexible coating material is 2.27mm). To investigate the influence of the laser incident angle θ on the surface integrities of the repaired damaged parts during laser shot peening, the 7075 aluminum alloy covered with the flexible coating material was taken as the researching object. The influence of θ on surface microhardness of the complex curved specimen were studied by large area continuous-impact (LACI) oblique laser shot peening (OLSP) experiment; the influence of θ on surface topography of the simplex plane specimen surface were studied by single-impact (SI) oblique laser shot peening (OLSP) experiment; and the influence of θ during SI OLSP on residual stress of the simplex plane specimen surface were simulated through finite element (FE) simulation.

Methodology

Experimental conditions

The damaged aircraft part should be grinded before laser shot peening repairment, and the complex curved surfaces would be formed after grinding the corrosion areas of the damaged aircraft part, such as oblique plane surface, convex and concave arc surfaces, and so on[11].

The LACI OLSP experiment was carried out by taking the complex curved specimen as the researching object (as shown in Fig.1). Fig. 2 shows the impact area and the peening path adopted during the LACI OLSP experiment. The incident angle θ were 0°, 15°, 30°, 45° and 60° (as shown in Fig.3), the θ at each impact spot will be kept the consistent by adjusting the space direction of the laser outlet continuously according to the shape of the complex curved specimen. The strengthening effect tends to be saturated when the impact number reaches 3 times [12]. Therefore, the numbers of laser impact were selected as 3 times for every shot peening spot. The laser parameters were determined by the type of laser (Nimma-Extra laser) and the overlap rate, an important parameter used to describe the coincidence degree of two adjacent laser spots in the two-dimensional direction[13], the overlap rate was selected as 50% to ensure the balance of efficiency and strengthening effect[12]. The parameters used for the LACI OLSP were listed in Table 1.

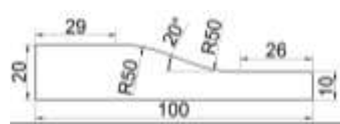


Fig.1 Diagram of specimen with the complex cured surface during LACI OLSP experiment

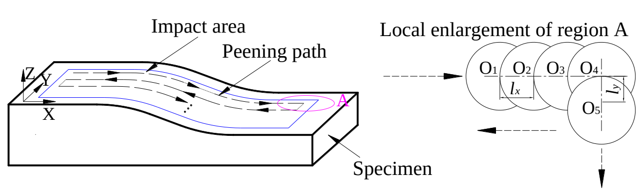


Fig.2 Diagram of laser shot peening path during LACI OLSP experiment

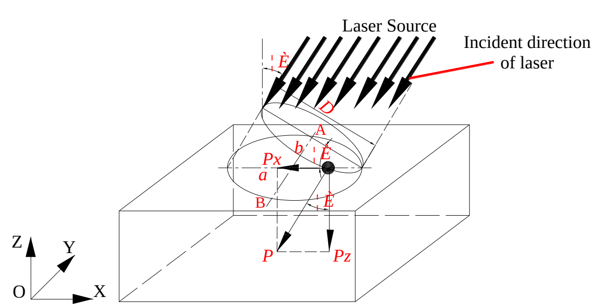


Fig.3 Diagram of oblique laser shot peening

Table 1. Parameters used for the oblique laser shot peening

Wavelength λ/nm	Laser energy E /J	Pulse width τ/ns	Beam diameter D/ mm	Overlap rate η/%
1064	1.6	10	2	50

The SI OLSP experiment was carried out by taking the simplex plane specimen as the researching object due to the limitation of the surface topography measuring instrument. The incident angle θ during the SI OLSP were 0°, 15°, 30°, 45°and 60°; the overlap rate was 100%. The other parameters were consistent with the experiment of the LACI OLSP (as listed in table 1). The surface topography can be characterized by a set of heights δ_i at the measurement point relative to the reference plane (as shown in Fig.4).

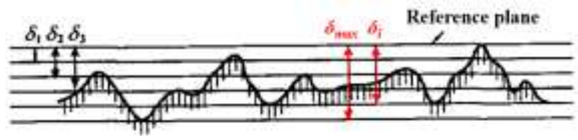


Fig.4 Diagram of surface topography measurement

The surface microhardness and the surface topography were measured by the automatic location table typed digital microhardness tester and the surface topography analyzer, respectively.

Establishment of the finite element model

The SI OLSP process was simulated by taking the simplex plane specimen as the researching object and to explore the influence of the incident angle θ on distributions of residual stress. The laser parameters used in the simulation were the same as that of in table 1, and the peak pressure of shock wave was P=2.09 GPa. The projection shape of laser beam on the specimen surface is verified from circular to elliptical with the increasing of θ (as shown in Fig.3). Therefore, the peened area of target material in the FE model also varies with θ. The three dimensional finite element simulation models were established based on software-ABAQUS (as shown in Fig.5), where the line AB is the symmetrical line of peened area, point A is the intersection point between the short axis and the boundary of peened area, and point B is the symmetric intersection point. In order to improve the computing speed, 1/2 FE models were established, and the symmetric boundary was adopted. The bottom of the models were set to a fixed boundary. In the transverse direction, the shot peened area was discretized with 0.05mm mesh size. In the longitudinal direction, the fine mesh was used near to the shot peened area. The distribution spacing of the seed increases gradually from the upper surface to bottom surface of the model. Besides, the non-critical area of the model was discretized into a coarse mesh. The element type was C3D8R and the number of elements was 118368.

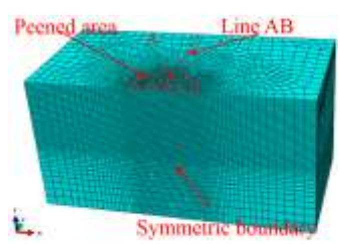


Fig.5 FE model of SI OLSP

Results and analysis

Pressure analysis during single-impact oblique laser shot peening

The projection of the laser beam on the specimen surface will be elliptical when $\theta \neq 0°$during SI OLSP (as shown in Fig.3). Assuming that the "a" represent the length of the long axis of the ellipse, the "b" represent the short axis of the ellipse and the "D" represent the diameter of laser beam, then $a=D/\cos\theta$, $b=D$. The laser shot peening total pressure P can be decomposed [14]:

$$P_x = P\sin\theta, \quad P_z = P\cos\theta \qquad (1)$$

where, P_x is the component pressure paralleling to the specimen surface, P_z is the component pressure perpendicular to the specimen surface.
P_z decreases and P_x increases with the increasing of θ when P is the constant. P_z acts perpendicularly to the specimen surface and applies a compressive pressure on the specimen surface (as shown in Fig.3). P_x acts parallel to the specimen surface, and the effect of P_x on the stress distribution of the specimen surface is shown in Fig.6. The materials at the peened area will flow along the direction of P_x. Therefore, P_x applies a compressive pressure to the material located on the left side of line AB and a tensile pressure to the material located on the right side of line AB.

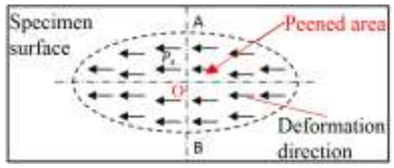


Fig.6 Diagram of influence of P_x on stress distributions

Influence of laser incident angle on surface microhardness
Fig.7 shows the experimental results of the surface microhardness n of the complex curved specimen after LACI OLSP. It shows that n increases after laser shot peening. The maximum n is 203HV, which is higher than the original material by 18.57%. The microhardness enhancement effect decreases with the increasing of θ (as shown in Fig.7). In addition, in the condition of the same surface geometrical feature, n decreases with the increasing of θ; in the condition of the same θ, the rank of n is: concave arc surface> plane surface > convex arc surface. This is mainly because that P_z decreases with the increasing of θ, which leads to the decreasing of the material deformation.

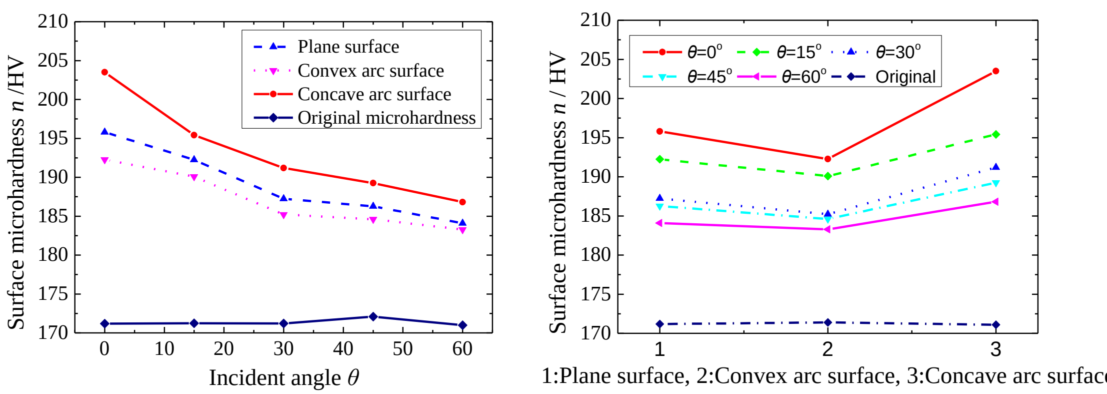
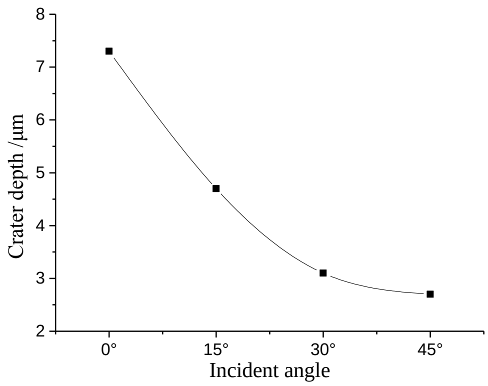
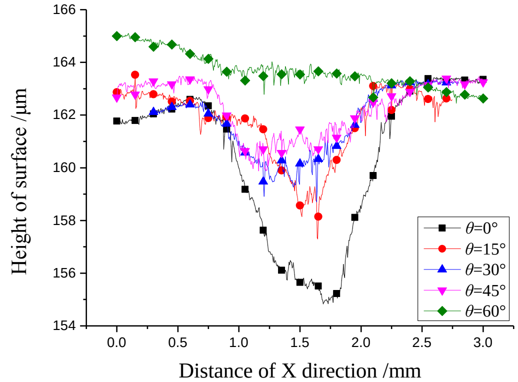


Fig.7 Surface microhardness of peened area after LACI OLSP

Influence of laser incident angle on surface topography
Fig.8 shows the experimental results of the surface topography of the simplex plane specimens after SI OLSP. Fig.8 (a) shows that, the maximum depth δ_{max} (as shown in Fig.4) decreases gradually with the increasing of θ. Fig.8 (b) shows that δ_{max} decreases with the increasing of θ ($\theta \in [0°,45°]$), and the position of δ_{max} deviates away from the crater center gradually. This is because that the main deformation direction of the material at the peened area varies with the θ to keep in line with the incident direction of laser due to the phototropism of the plasma induced by laser shot peening.

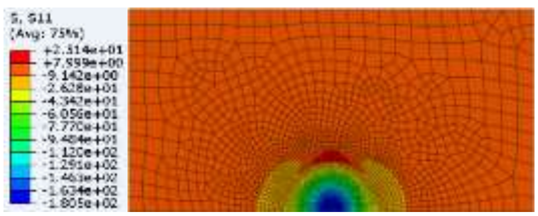


(a) Influence of θ on δ_{max}

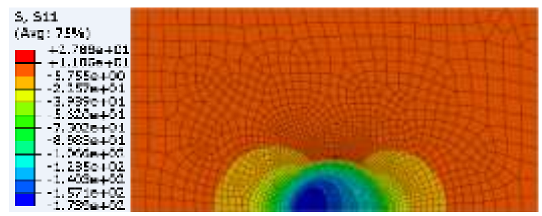


(b) Curves of surface topography

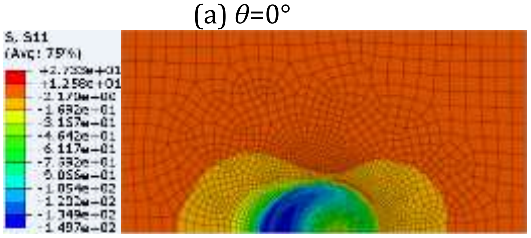
Fig.8 Surface topography of peened area after SI OLSP



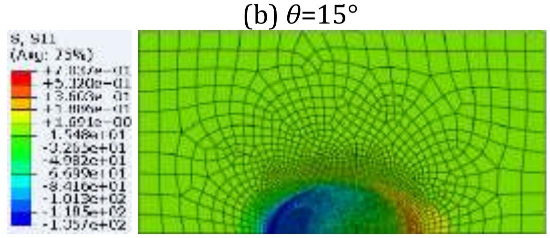
(a) θ=0°



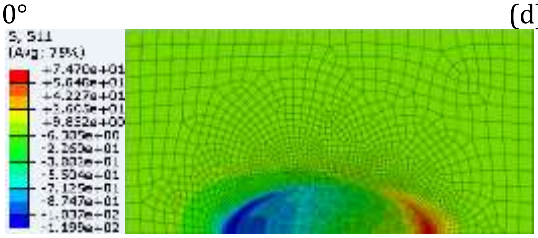
(b) θ=15°



(c) θ=30°

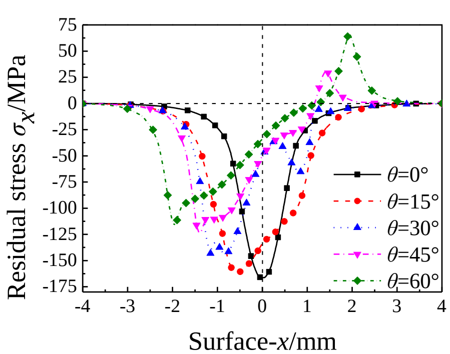


(d) θ=45°

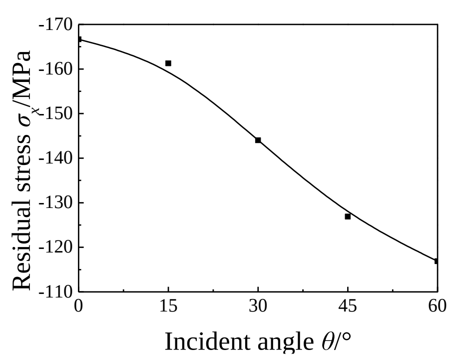


(e) θ=60°

Fig.9 Nephogram of distributions of residual stress σ_x



(a) Distributions of residual stress σ_x



(b) Relationships betweenσ_{xmax} and θ

Fig.10 Distributions of residual stress σ_x after SI OLSP

Influence of laser incident angle on residual stresses distribution

The pressure acting on the peened area is symmetrical about the long axis and asymmetrical about the short axis. Therefore, the laser incident angle θ has a great influence on the stress along the direction of long axis (X direction). Fig.9 shows simulation results of the residual stresses σ_x along the simplex plane specimen surface and Fig.10 shows the distributions of residual stress σ_x after SI OLSP. The compressive maximum residual stress σ_{xmax} is -180.5MPa and occurs at the center of peened area when θ=0° (as shown in Fig.9 (a)). The compressive σ_{xmax} decrease gradually with the increasing of θ, and the position of the compressive σ_{xmax} deviates away from line AB to the left side gradually and the residual tensile stress occurs in the right side of the peened area (as shown in Fig.9 and Fig.10 (a)). This is because that the compressive σ_x in the left side of peened area increases and in the right side decreases caused by the effects of P_x. P_x increases with the increasing of θ, which will further decrease the compressive residual stress on the right side of the peened area and lead to the emergence of tensile residual stress when θ is larger than 45°. Therefore, the peening spot should deviate towards the opposite direction of P_x during the actual repairment to ensure that the maximum compressive stress occurs at the expected location.

Conclusions

The influence of incident angle on the surface integrities of 7075 aluminium alloy covered with flexible coating during laser shot peening were studied and the conclusions are as follows:

1. The laser incident angle has great influence on surface topography, surface microhardness and distributions of residual stress of shot peened area of the target material.
2. The position of the maximum residual compressive stress deviates towards the incident direction of laser during the oblique laser shot peening. The position of the laser impact spot during the actual online repairment should deviate toward the opposite direction to ensure that the location of the maximum residual compressive stress is beneath the expected repairment area.
3. The smaller the laser incident angle, the stronger the surface microhardness enhancement, and the larger the maximum residual compressive stress after laser shot peening.
4. Residual tensile stresses at the edge of the peened area may occur under the large incident angle during oblique laser shot peening. The incident angle should be smaller than 45° when repairing the complex cured surface through the oblique laser shot peening method.

References

[1] A. Jaya, U.H. Tiong, G. Clark. The interaction between corrosion management and structural integrity of aging aircraft[J]. Fatigue & Fracture of Engineering Materials & Structures, 2012, 35(1): 64-73.

[2] Xiangfei Sheng, Qinxiang Xia, Xiuquan Cheng, Lieshu Lin. Residual stress field induced by shot peening based on random-shots for 7075 aluminum alloy[J]. Transactions of nonferrous metals society of China, 2012, 22: 261-267.

[3] Shan Chen. Laser peening technology[J]. Aviation maintenance & engineering, 2004, 5: 30-31 (In Chinese).

[4] U.W. Suh, S. Mannava, T.J. Rockstroh. Simultaneous offset dual sided laser shock peening with oblique angle laser beams: U.S. Patent 6,570,125[P]. 2003-5-27.

[5] Leihong Zhang, Liujie Sun, Xiuhua Ma. Research on the deformation characteristic of the sheet by oblique angle laser shock[J]. Laser Physics, 2013, 23(3): 1-6.

[6] Yongkang Zhang, Leihong Zhang, Jianzhon Zhou, Aixin Feng, Linfeng Zhang, Tao Ge, Xudong Ren. Oblique Angle Laser Shock Experiment and Theoretic Analyse[J]. Chinese Journal of Lasers, 2005, (10): 135-138 (In Chinese).

[7] Shu Huang, Jianzhon Zhou, Yueqing Sun, Yibin Chen, Suqin Jiang. Study on Surface Integrity of 6061-T6 Aluminum Alloy Sheet after Laser Shot Peening[J]. Applied Laser, 2007, (06): 450-455 (In Chinese).

[8] T. M. Yue, L. J. Yan, C. P. Chan. Stress corrosion cracking behavior of Nd: YAG laser-treated aluminum alloy 7075[J]. Applied Surface Science, 2006, 252(14): 5026-5034.

[9] Jiang Wu, Xiuquan Cheng, Qinxiang Xia, Jiayu Li. Experimental research on influence of restraint layer materials on surface strengthening of 7075 aluminum alloy laser shot peening[J]. Surface technology, 2017, (03): 124-129 (In Chinese).
[10] Xudong Ren, Yongkang Zhang, Dunwen Zuo, Jianzhon Zhou, Changwei Gao. Effect of coating on titanium alloy during laser shock processing[J]. Journal of Jiangsu University (Natural Science Edition) , 2006, (01): 10-13 (In Chinese).
[11] XiuQuan Cheng, XiangFei Sheng, QinXiang Xia, Jing Wei. Effect of shot peening intensity on residual stress field of 7075 auminium alloy[C]. 12th International Conference on Shot Peening, 2014: 299-304.
[12] Gaopeng Shuai, Xiao Xu, Xiuquan Cheng, Qinxiang Xia. Numerical analysis on influences of laser shot peening parameters on residual stress distribution for 7075 aluminum alloy[J]. Forging and Stamping Technology, 2016, (12):143-149 (In Chinese).
[13] Yongxiang Hu. Research on the numerical simulation and impact effects of laser shock processing[D]. Shanghai Jiao Tong University, 2008: 84-84 (In Chinese).
[14] Sumin Yin, Leihong Zhang, Xinghua Yang, Dejun Kong. Mathematical analysis of sheet deformation by laser shock in oblique angle[J]. Transactions of the Chinese Society of Agricultural Machinery, 2006, (12):185-188 (In Chinese).

Acknowledgements
This project was financially supported by the National Natural Science Foundation of China (No. 51575117 and 61179051).