Improving mechanical property and microstructure evolution of 7075 aluminum panel formed by unequal alternate double-sided laser shock forming

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Abstract
With thrust weight ratio increasing, integral panel is an important component to reduce the aircraft weight, and it is a great challenge to ensure the forming accuracy and mechanical property in the large-scale panel. Laser shock forming has a great development prospect in realizing integral panel forming and improving its mechanical properties. This work investigated unequal alternate double-sided laser shock forming, which can make 7075 aluminum panel form and induce the hardened layers in both panel sides. The improvements were analyzed in mechanical properties and microstructure evolution of 7075 aluminum panels after unequal alternate double-sided laser shock forming. In the surface and subsurface layer, the residual stress and microhardness were verified to be enhanced by the laser shock wave. The results of XRD and EBSD provided the evidence of grain refinement. The strengthening mechanism of unequal alternate double-sided laser shock forming was analyzed in this work. The grains are distorted and refined during high strain rate plastic deformation due to dislocation slip and accumulation. The mechanical properties were enhanced by unequal alternate double-sided laser shock forming due to the hardened layers in both panel sides. The hardened layers and grain refinement have a great significance in inhibiting the crack generation and growth.

Keywords Laser shock forming · Laser pulsed energy · Thin panel thickness · Hardened layer · Grain refinement

1 Introduction
To meet the demand for high speed and high quality in aircraft, integral panels with complex structures are widely used in aircraft structures to reduce the weight and assembly time [1]. Due to process limitations, it is difficult to satisfy the forming accuracy and complex structure in the conventional forming methods. On the other hand, as the main component bearing load, integral panel plays an important role in the overall stress of aircraft structure. The fatigue life of integral panel is crucial for aircraft safety [2]. It is a great demand for the forming processing to make the integral panel form accurately and improve the mechanical properties at the same time.

Roll forming and creep-age forming are common form methods, but they have poor adaptability for the complex structure [3, 4]. As a novel forming method, laser shock forming (LSF) is an accurate cold forming method for thin panel, where the panel curvature is altered by the laser shock wave at room temperature. Different from shot peen forming, LSF can improve the hardened layer depth and keep surface intact; meanwhile, it is easier to control the forming parameters [5]. In 2002, Hackel et al. [6] firstly found that 3D bending deformation was induced in metal panel by laser shock processing. In 2007, Ocaña et al. [7] found that stainless steel 304 was bent to different directions when treated by laser shock wave. In laser shock forming, if thin panel is bent toward the...
laser beam, the panel has a concave deformation; on the contrary, if the panel is bent away from the laser beam, the panel has a convex deformation. In 2010, Hu et al. [8] revealed the mechanism of concave and convex deformations. Luo et al. [9] realized the control of complex shape by introducing distributed eigen-moment as an intermediate variable. In LSF, the bending deformation of metal panel is controlled by laser power intensity, overlapping ratio, impact time, and impact path. These controllable process parameters can make LSF be a high-precision forming method in the future; meanwhile, the deformation springback can be inhibited in the cold forming at room temperature; therefore, LSF has obvious advantages in metal panel forming, compared with conventional forming processes.

In the conventional skin stringer riveted structure, the crack separately propagates on the skin or stringer, since the skin and stringer are separate components. But for integral panels, Li et al. [10] thought that any damage may threaten their service life, and the crack propagation resistance of integral panels is crucial for aircraft safety and performance. The crack propagation resistance and bending forming urgently need to be solved for integral panels. Laser shock processing (LSP) is an advanced surface modification method to enhance the fatigue property by inducing the hardened layer and compressive residual stress. For AISI 4140 steel, Ye et al. [11] used LSP to enhance the bending fatigue strength to 1125 MPa. Wang et al. [12] found that the corrosion fatigue property of AISI 420 stainless steel is extended due to microstructure refinement and gradient residual stress induced by laser shock wave. Zhao et al. [13] improved the mechanical properties of titanium alloy treated by LSP in surface residual stress and microhardness. Ren et al. [14] estimated the service life of titanium alloy panel treated with double-sided LSP. Ye et al. [15] verified that LSF, as a derivative from LSP, can make thin panel bend toward or away from laser beam, and induce compressive residual stress in the upper or back surfaces, however, in the back surface, the compressive residual stress is too small, and the surface has no hardened layer, then the compressive stress can be easily released during service time. In order to guarantee the bending deformation and induce hardened layer in both surfaces at the same time, this paper proposes unequal alternate double-sided laser shock forming, where a laser beam with low energy is used to modify one side of thin panel, then another side surface is impacted by another laser beam with high energy to make this panel bend with an angle. And the mechanical properties of thin metal panel can be improved by the unequal alternate double-sided laser shock forming.

In this work, the bending degree was obtained by a visual inspection system. The residual stress and microhardness were investigated in 7075 aluminum panel before and after unequal alternate double-sided laser shock forming, and the surface morphologies were characterized by white-light interference surface profilometer. The microstructure distribution was tested using electron backscattered diffraction (EBSD) and X-ray diffraction (XRD). The improvements were discussed based on theoretical analysis in mechanical properties and microstructure evolution after unequal alternate double-sided laser shock forming. This work expounds on a novel method to form thin panel and improve its mechanical properties.

### 2 Materials and methods

#### 2.1 Material and specimens

7075 aluminum alloy is widely used in aerospace field for high strength properties. Since panel thickness is one of the important parameters for LSF, this work purchased 7075 aluminum panel with a uniform thickness from Shanghai Jinxiao Corporation. Table 1 presents the chemical compositions of 7075 aluminum alloy used in the experiments. In order to analyze the effect of unequal alternate double-sided laser shock forming on mechanical property and microstructure evolution, this work used 7075 aluminum panels with 1 mm and 3 mm thickness as experimental specimens, and the geometric dimension of the panel is 125×25 mm, shown in Fig. 1.

#### 2.2 Laser shock forming experiments

In unequal alternate double-sided LSF experiments, 7075 aluminum panels are formed by a Q-switched Nd:YAG pulsed laser with a spot diameter of 4 mm and the pulse duration of 15 ns, and the pulse frequency is 1 Hz. As Fig. 1 shows, before experiments, one end of the panel is fixed by a fixture. In order to make each impacted nearly perpendicular to the panel surface, the impact path moves from the free end to the fixed end. The overlapping ratio is defined as \( l/d \), set as 50%, where \( l \) is the overlapping width of two adjacent laser spots, and \( d \) is the spot diameter, so laser scanning velocity is 2 mm/s. The coverage of pulsed laser spot is 282%, which is defined as:

\[
C = \frac{S \cdot N}{A} \tag{1}
\]

where \( S \) is the spot area, \( N \) is the number of laser spots in the impacted region, and \( A \) is the total area of the impacted

| Table 1 | The chemical compositions of 7075 aluminum alloy used in the experiments (wt.%) |
|---------|---------------------------------------------------------------------------------|
| Si      | Fe                                | Cu                 | Mn       | Mg       | Cr       | Zn       | Ti       | Al       |
| 0–0.4   | 0–0.5                             | 1.2–2.0            | 0–0.3    | 2.1–2.9  | 0.18–0.28| 5.1–6.1  | 0–0.2    | Balance  |

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region. In unequal alternate double-sided LSF, the panel firstly is pretreated by a laser beam with low energy (4 J) on one side, then formed by another laser beam with high laser pulsed energy (8 J) on another side, and the shock path is same. The panels with 1 mm thickness are induced into concave bending deformation, where the pretreatment surface is marked with A1, the surface shocked by 8 J laser beam is marked with A2, and the unshocked surface of 1 mm panel is marked with A0. The final 3 mm thickness panel is bent with a convex curvature, where the surface treated by 4 J laser beam is marked with B1, the surface shocked by 8 J laser beam is marked with B2, and the untreated surface of 3 mm panel is marked with B0.

2.3 Measurement methods

The visual inspection system for surface manufacturing is an efficient and accurate method for surface defect detection and model reconstruction [16]. In this work, the impact surfaces are detected by the three-dimensional hand-held scanner (EXAscan) with 1 mm step size. Positioned by location point, the metal panel is rebuilt by point cloud used to analyze the bending deformation. The centerline of the point cloud is used to evaluate the deformation degree, which is picked out by python code. To observe the effect of laser shock wave on panel surface, white-light interference surface profilometer (WLI) is performed to measure the surface morphology and roughness. The metal surface can be hardened under laser shock wave, and the surface and cross-section microhardness is detected by Micro-Vickers hardness tester (HV1000) with 100 g loading for 15 s. The final surface hardness is obtained by the test method in the previous work [17]. The final cross-section hardness is decided by the average value of three repeated tests. The residual stress is tested by Proto-LXRD stress measurement system based on sin2ψ method on panel surface before and after unequal alternate double-sided LSF, the phase structure and crystal orientation are detected by X-ray diffraction (XRD) (X’Pert Pro) with a scanning speed of 4°/min in 2θ range from 30° to 80°. Electron backscattered diffraction (EBSD) is performed to analyze the orientation, boundary, and misorientation angle distribution, including an SEM (TESCAN MIRA3, Czech) and an HKL-EBSD system. The cross-sections are electropolished before EBSD measurement.

3 Results and discussion

3.1 Bending deformation

The process of unequal alternate double-sided LSF is shown in Fig. 2(a) and (b). For 1 mm 7075 aluminum panels, the shock wave can propagate to the bottom surface, and the serious plastic with high strain rate leaves a dome pit in the panels, which leads the shocked surface to bend toward laser beam [18]. For 3 mm panel, before the stress wave propagates to the bottom surface, the stress wave decays to elastic stress wave, and the dome pit almost has no effect on the bending deformation, however, the residual stress with a gradient is induced along the depth direction, which is a driving force of convex bending deformation in thick panels [8]. In order to estimate the forming ability of unequal alternate double-sided LSF, the panel surfaces are scanned by the hand-held scanner to obtain the point cloud and reconstruct the bending model before and after the double-sided LSF, then the centerline is picked up from the point cloud of panel surfaces, shown in Fig. 2(c) and (d). As the results show, 1 mm thin panel has a concave deformation, and the...
maximum displacement of the free end is 15.3 mm. 3 mm panel is bent with a convex curvature, and the displacement of the free end is -6.02 mm. Therefore, unequal alternate double-sided LSF can retain great formability in thin metal panels. Besides, the mechanical property and microstructure of 7075 aluminum panel are certainly affected by the unequal alternate double-sided LSF, which will be discussed in the next work.

3.2 Surface morphology

Compared with shot peening, laser shock processing induces a deeper hardened layer on specimen surface and protects the surface integrity [19]. Surface morphology is used to test the effect of laser shock wave on the panel surface in LSF. In order to obtain the surface roughness and observe the surface texture, the curved surface is flattened to a horizontal plane by processing 3D graphics in post-processing. Figure 3 shows the surface morphology of 1 mm 7075 aluminum panel before and after unequal alternate double-sided LSF, and that surface morphology of 3 mm panel is shown in Fig. 4. The observed surface region is set as 12 x 12 mm. Figures 3(c) and 4(c) show the surfaces impacted by 8 J laser beam, and another surfaces shocked by 4 J laser beam are shown in Figs. 3(e) and 4(e). From Fig. 3(c) and (e), 1 mm panel has a concave bending deformation after the second laser shock processing with 8 J energy, which is same as the result in Fig. 2. In the flattened surface, there is some blurry vertical texture on the surface shocked by 8 J laser beam in Fig. 3(d). Compared with the untreated surface in Fig. 3(b), a slight change can be recognized in Fig. 3(f). Different from the deformation of 1 mm panel, 3 mm panel shows a convex bending deformation after unequal alternate double-sided

Fig. 2 The process of unequal alternate double-sided LSF and the centerline of 1 mm and 3 mm 7075 aluminum panels
LSF, shown in Fig. 4(c) and (e). A clear texture can be seen on B2 surface, which is decided by 50% overlapping ratio. Similarly, the shock wave formed by 4 J laser pulsed energy has a slight effect on 3 mm panel surface.

Figure 5 presents the surface roughness calculated in the flattened surface. Surface roughness of 1 mm panel before and after unequal alternate double-sided LSF is shown in Fig. 5(a), and that of 3 mm panel is shown in Fig. 5(b). For the untreated panels, the roughness in 1 mm panel is higher than that in 3 mm panel. The surface roughness may be the critical parameter to cause the difference of texture on A2 and B2 surfaces. The surface roughness in A1 raises from 1.019 μm to 1.405 μm, and that in A2 raises to 1.546 μm. Figure 5(b) shows the same trend in 3 mm panel. The surface roughness increases as raising laser pulsed energy, but the surface maintains great integrity after unequal alternate double-sided LSF.

3.3 Mechanical property

The hardened layer and compressive residual stress can slow down the rate of crack initiation and propagation in material surface during serve time [11]. Microhardness is one of the important parameters to evaluate material mechanical properties. Figure 6 shows the microhardness along the depth direction of 7075 aluminum panel before and after unequal alternate double-sided LSF. Before LSF treatment, the microhardness of 1 mm and 3 mm 7075 aluminum panels is approximately 180 HV. Since 1 mm panel is too thin, the microhardness of the whole section is detected from A2 to A1, shown in Fig. 6(a). For 3 mm panel, the measured depth is set as 1 mm, shown in Fig. 6(b). From Fig. 6(a), the microhardness in A2 and A1 surfaces are both elevated, and the affected depth is about 0.5 mm. The microhardness of A2 surface is improved from 180 HV to 206.8 HV, and
that on A1 surface raises to 191.4 HV. For 3 mm panel, the microhardness of B2 and B1 are separately 204.6 HV and 198.5 HV, and the surface microhardness would increase when laser pulsed energy rises. The depth of hardened layers is 0.2–0.6 mm in 1 mm and 3 mm panel surfaces. Therefore, under the action of laser shock wave, hardened layers

![Fig. 4](image4.jpg)

**Fig. 4** The surface morphology of 3 mm 7075 aluminum panel before and after unequal alternate double-sided LSF. (a) the surface of B0; (c) the surface impacted by 8 J laser pulsed energy in B2; (e) the surface impacted by 4 J laser pulsed energy in B1; (b), (d), and (f) are the flattened surfaces of (a), (c), and (e) separately.

![Fig. 5](image5.jpg)

**Fig. 5** The surface roughness of 1 mm (a) and 3 mm (b) 7075 aluminum panel before and after unequal alternate double-sided LSF.
are induced into both panel surfaces by unequal alternate double-sided LSF [20]. The improvement in microhardness could be a reaction of the microstructure evolution in 7075 aluminum panel, which would be analyzed in future discussion, based on the results of XRD and EBSD.

Figure 7 presents the residual stress along the depth direction of 1 mm and 3 mm 7075 aluminum panels before and after unequal alternate double-sided LSF. The untreated surface has a small compressive residual stress caused by the rolling process and grinding. Since the 3 mm panel is too thick, the in-depth residual stress in the panel is divided into two parts, and the test depth is set as 1 mm below B1 or B2 surface. The compressive residual stresses are induced into double side surfaces of aluminum panels by unequal alternate double-sided LSF. When A1 and B1 are shocked by 4 J laser beam, the impacted region is not affected by the residual stress hole because of the low shocking pressure, and the residual stress increases with the depth increases. However, when A2 and B2 are shocked by 8 J laser beam, the shocking pressure is too high, so that residual stress hole is induced on the surface due to the uneven severe plastic deformation, causing the reduction of surface residual stress in the impacted region. So the residual stresses increase and decrease as the depth increases under A2 or B2 surfaces. Under 4 J laser beam, the maximum residual stress is located on the surface. The residual stress of A1 and B1 reached $-94$ and $-109$ MPa, respectively. Under the shock wave excited by 8 J laser beam, the distribution of residual
stress along depth presents a hook shape, and the maximum residual stress lies in subsurface layer, that is, −173 and −275 MPa under A2 and B2 surface, respectively. The increase in compressive residual stress could be discussed by the microstructure evolution induced by unequal alternate double-sided LSF [21].

3.4 XRD analysis

XRD is used to analyze the chemical composition and molecular structure to determine the crystal structure [22]. Under the effect of laser shock wave, the high strain plastic deformation induces grain refinement and distortion, and the diffraction peaks shift in XRD can be used as the evidence of lattice distortion in material interior [23]. Figure 8 shows the X-ray diffraction patterns of 1 mm panel surface before and after unequal alternate double-sided LSF, and Fig. 9 shows that of 3 mm panel surface before and after unequal alternate double-sided LSF. Figures 8(a) and 9(a) present the whole diffraction patterns from 30° to 80°. The results show that four lattice plane has been detected, including (1,1,1), (2,0,0), (2,2,0), and (3,1,1). The type of lattice plane and peak position are same as the results of Zhou et al.’s work [24]. There is no new peak after laser impact, indicating no new phase is induced into 1 mm or 3 mm 7075 aluminum panel and the crystal structure is not changed by laser shock wave. The four peaks in 1 mm panel are compared individually in Fig. 8(b), (c), (d), and (e). Compared with A0, the peak intensity of (1,1,1), (2,2,0) and (3,1,1) in A1 has a great change, but there nearly is no diffraction peaks shift, implying that the shock wave induced by 4 J laser pulsed energy urges a conversion between different phases, and there is almost no lattice distortion. In A2, every peak intensity has been changed by the effect of laser shock wave, and diffraction peaks shift a small angle to the left. Therefore, there is the conversion between different phases and lattice distortion on A2 surface. The four peaks in 3 mm panel are listed in Fig. 9(b), (c), (d), and (e). Compared with the peaks in B0 surface, there are a few differences between the peak intensity in B1 and B2 surfaces, but all diffraction peaks shift a small angle to the left. Therefore, the lattice is distorted by the laser shock wave in 3 mm panel surfaces. The lattice distortion is contributed to the residual stress distribution in the surface and subsurface layer of the formed panels [23, 25].

The full widths at half maximum (FWHM) of diffraction peak (111), (200), (2,2,0), and (3,1,1) are listed in Table 2. Compared with A0, FHWMs of the four diffraction peaks are broadened after LSF in both side surfaces, and high laser pulsed energy would urge FWHM to increase. The same regular result can also be found in 3 mm 7075 aluminum panel. In general, the peak broadening is caused by grain refinement, lattice deformation, and microstrain development [26]. Under the effect of laser shock wave, high strain plastic deformation promotes the dislocation slip and accumulation [27], which is attributed to the grain refinement, and some microstrains are induced into surface layer. Hence, FWHM increasing can be qualitatively used as the evidence of grain refinement and lattice distortion in unequal alternate double-sided LSF.

3.5 Cross-sectional microstructure morphology by EBSD

Under the effect of shock wave, the microstructure is refined for the dislocation slip and accumulation, which is beneficial to the resistance in residual stress relaxation and crack propagation [28]. Figure 10 exhibits the cross-sectional electron backscattered diffraction (EBSD) morphology of 1 mm 7075 aluminum panel containing A1 (the upper surface in Fig. 10(a)) and A2 (the bottom surface in Fig. 10(a)) surfaces. From Fig. 10(a), (b), and (d), compared with the microstructure near A1 surface, the columnar grains are refined by high shock pressure near A2, and the grains in the intermediate layer are elongated for the macroscopic pit deformation. In 1 mm panel, the depth of the grain refined layer is more than 0.5 mm, so the grains in the intermediate layer are compressed into a slim shape for the duplicate effect of 4 J and 8 J laser shock in the two surfaces. Kernel average misorientation (KAM) map can qualitatively reflect the homogenization degree of plastic deformation. The high value means the severe plastic deformation or the high defect density, which presents the stress distribution in the deformation. From Fig. 10(d), the cross-section has high residual stress, especially near surfaces and intermediate layer, since the shock wave can spread through the entire panel and be reflected back on the back surface [29], on the other hand, the shock wave may propagates to the intermediate layer more than two times in one laser shock. From inverse pole figure (IPF) and pole figure in Fig. 10(b) and (c), the grains in 1 mm panel have no obvious orientation, and the material is isotropy. Figure 10(e) shows the boundary misorientation angle distribution in the cross-section. The misorientation angle range is 0–3°, belonging to the low-angle boundary (LAB). The fraction of deformed grain is 11.77%, shown in Fig. 10(f). The boundary misorientation angle and deformed grain are attributed to the dislocation slip and recombination.

Since 3 mm panel is too thick, the microstructure in the panel cross-section is separated into two parts: the cross-sectional EBSD morphology of the panel near B2 surface is exhibited in Fig. 11, and that near B1 surface is shown in Fig. 12. Due to the difference in the manufacturing processes, the grain sizes in 1 mm and 3 mm panels are different. Compared Fig. 11(a) with Fig. 12(a), the surface grains are more refined under B2. The degree of grain refinement increases with laser pulsed energy rising, and the refinement decreases along the depth direction. Compared with
Fig. 8 X-ray diffraction patterns of 1 mm panel surface before and after unequal alternate double-sided LSF
Fig. 9 X-ray diffraction patterns of 3 mm panel surface before and after unequal alternate double-sided LSF
Fig. 12(d), the stress in B2 surface and subsurface is generally higher than that of B1. The residual stress can be elevated with laser pulsed energy increasing. Under the interaction of high strain rate and stress, the grains are distorted in B2 and B1 surface and subsurface, and the deformed fraction in Fig. 11(f) is higher than that in Fig. 12(f). From Fig. 11(e) and Fig. 12(e), the boundary misorientation angle of B2 surface and is in the range of 0–2°, and that of B1 surface and is in the range of 0–1°, indicating that the residual stress is induced into material surface and subsurface by laser shock wave, accompanied by grain distortion. According to the above results, the hardened layers are induced into both panel surfaces after unequal alternate double-sided LSF, which plays a significant role in improving the fatigue life of thin metal panels.

3.6 The mechanism of unequal alternate double-sided LSF

The bending deformation, improvement in mechanical property, and microstructure evolution of 7075 aluminum panel formed by unequal alternate double-sided LSF are analyzed in the paper, and the mechanism schematics of unequal alternate double-sided LSF are summarized in Fig. 13. In the thin panel, the shock wave can travel through the panel, and the plastic deformation is induced in the limited impacted region for the downward inertia of shock loading. Under the shock loading, thin panel is bent toward laser beam due to the geometry compatibility. In thick panel, the plastic deformation region is limited in the surface and subsurface, and the stress wave attenuates in material until it disappears, so the residual stress decreases along the depth direction with a gradient. A negative bending moment M is imported by the stress gradient, which drives the convex deformation in thick panel [8]. In unequal alternate double-sided LSF, laser beam with low energy is used to induce a hardened layer in one panel side, even though a small bending deformation is led into panel at the same time. Then, the laser beam with high energy is applied on another panel side to bend the panel to the expected shape and induces another hardened layer in the side (shown in Fig. 13).

Table 2 FWHWs of the diffraction peaks (111), (200), (2,2,0), and (3,1,1) in 7075 aluminum panel before and after unequal alternate double-sided LSF

| Panel surface | Phase | (1,1,1) | (2,0,0) | (2,2,0) | (3,1,1) |
|---------------|-------|---------|---------|---------|---------|
| A0            |       | 0.2378  | 0.2816  | 0.3271  | 0.4251  |
| A1            |       | 0.2592  | 0.2861  | 0.3749  | 0.4286  |
| A2            |       | 0.2950  | 0.3149  | 0.3820  | 0.4915  |
| B0            |       | 0.2461  | 0.2741  | 0.3448  | 0.4205  |
| B1            |       | 0.2518  | 0.2866  | 0.3643  | 0.4529  |
| B2            |       | 0.2866  | 0.3221  | 0.4167  | 0.5309  |

Fig. 10 Cross-sectional EBSD morphology of 1 mm thickness 7075 aluminum panel. (a) Grain boundary distribution in the cross-section; (b) IPF figure of the cross-section; (c) pole figure of the cross-section; (d) kernel average misorientation (KAM) map in the cross-section; (e) boundary misorientation angle distribution in the cross-section; (f) deformed fraction in the cross-section.
Under the action of shock wave, high strain rate plastic deformation occurs on material surface. With the increase of propagation distance, the plastic wave gradually changes into elastic wave. At this time, the depth of plastic deformation layer reaches the maximum, which is related to the peak shock pressure and material properties, which can be estimated as follows [30]:

![Cross-sectional EBSD morphology of 3 mm thickness 7075 aluminum panel near B2 surface. (a) Grain boundary distribution in the cross-section; (b) IPF figure of the cross-section; (c) pole figure of the cross-section; (d) KAM map in the cross-section; (e) boundary misorientation angle distribution in the cross-section; (f) deformed fraction in the cross-section](image1)

![Cross-sectional EBSD morphology of 3 mm thickness 7075 aluminum panel near B1 surface. (a) Grain boundary distribution in the cross-section; (b) IPF figure of the cross-section; (c) pole figure of the cross-section; (d) KAM map in the cross-section; (e) boundary misorientation angle distribution in the cross-section; (f) deformed fraction in the cross-section](image2)
where \( C_{el} \) and \( C_{pl} \) are respectively the elastic and plastic wave velocities in material, \( T \) is the shock wave duration, \( P \) is the peak shock pressure, and \( \sigma_{HEL} \) is the elastic limit stress of material. After laser shock processing, the surface residual stress is calculated by Fabbro and Peyre, shown as \( [31] \):

\[
\sigma_{surf} = \sigma_0 - [\mu \varepsilon_p (1 + \nu)/(1 - \nu) + \sigma_0] \left[ 1 - \frac{4\sqrt{2}}{\pi} (1 + \nu) \frac{L_p}{r\sqrt{2}} \right]
\]  

(3)

where \( \sigma_0 \) is the surface initial residual stress, \( \mu \) is Raman coefficient, \( \nu \) is Poisson’s ratio, \( \varepsilon_p \) is plastic strain, and \( r \) is laser spot radius.

As observed from the cross-sectional microstructure morphology by EBSD, the stress distribution can be distinguished in KAM map, and the distorted grains are marked in the grain boundary distribution map. The grain rearrangement is activated during the high strain rate plastic deformation, leading to grain distortion and refinement (Fig. 13). According to the theories of Johnston and Gilman [32], dislocation density is proportional to plastic strain, indicating that dislocation density increases when plastic strain is improved. During the shock process, the plastic strain layer experiences high strain rate plastic deformation, and a large number of dislocations accumulated and tangled, producing dislocation walls and dislocation cells. Due to high strain rate, dislocations are easy to slip and promote grain refinement. When there are high-density dislocations in material, the macroscopic performance is work hardening. In Bailey-Hirsch [33] model, the hardness can be estimated as:

\[
HV = HV_0 + \alpha G b \sqrt{\rho}
\]  

(4)

where \( HV_0 \) is the material initial hardness, \( \alpha \) is a constant about material, \( G \) is the shear modulus, \( b \) is the Burgers vector, and \( \rho \) is the dislocation density. On the other hand, according to Hall–Petch [34] theory, the work hardening of materials is also related to grain size,

\[
HV = HV_0 + \frac{K_{HV}}{\sqrt{d}}
\]  

(5)

where \( K_{HV} \) is a coefficient of work hardening and \( d \) is the grain size. Grain refinement can also harden the material, so the improvement of material mechanical properties and work hardening come from dislocation strengthening and grain refinement strengthening, which inhibits the crack generation and growth.

4 Conclusions

The bending behavior of 7075 aluminum panel by unequal alternate double-sided LSF is analyzed in this work. The mechanical properties and microstructure evolution in panel surfaces are investigated. The conclusions are summarized as follows:

1. In unequal alternate double-sided LSF, the first laser beam with low energy is used to modify one panel surface; then, the panel is formed by laser beam with high energy at another surface. The unequal alternate double-sided LSF has a great ability in panel forming and both side surfaces are strengthened by the two laser beams.

2. The surface texture after laser impact is affected by the laser pulsed energy and surface roughness. The texture depth would increase while laser pulsed energy rises,
and the texture is clear and complete if the surface roughness is small.

3. The mechanical properties in both sides of thin panel are improved by unequal alternate double-sided LSF. The laser pulsed energies are different, which are directly related to the distribution of residual stress. For 1 mm panel, the maximum residual stresses in both side surfaces are respectively ~94 and ~173 MPa, and the corresponding residual stresses in 3 mm panel are ~109 MPa and ~275 MPa. And the depth of hardened layers is 0.2–0.6 mm in 1 mm and 3 mm panels.

4. The results and analysis about mechanical property and microstructure in 7075 aluminum panel indicate that the panels can be formed and strengthened by unequal alternate double-sided LSF. The improvement of residual stress and microhardness comes from the high dislocation density and grain refinement.

Author contribution Jiaqi He: preparation of samples. Ying Lu and Boyu Sun: measurements of experiment data. Hongchao Qiao: comment and revision for the paper. Jibin Zhao: formulations of the problem. Yuqi Yang: summarization of the experiments, writing original paper.

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Availability of data and materials The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval This work does not involve the human ethical issues. And we promise to follow the COPE guidelines on how to deal with potential acts of misconduct.

Consent to participate All authors consent to participate this work.

Consent for publication All authors have agreed to publish this manuscript.

Competing interests The authors declare no competing interests.

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