Localized indentation and its relationship with overall deformation of thin metal sheets induced by laser peen forming

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Abstract
Laser peen forming (LPF) is a non-contact incremental forming method that introduces plastic deformation by laser shocks to modify the curvature of components. This study focuses on the localized indentation profiles of thin metal sheets induced by a single shock, and explores their relationship with overall plastic deformation after multiple shocks. LPF experiments with different spot sizes and laser power densities are conducted on thin metal sheets with a thickness of 0.5 mm. Two types of indentation profiles are produced, which are crater and conical profiles, after LPF with spot sizes of 0.8 mm and 4.0 mm. It is found that the indentation profile type remains the same except for the depth value after LPF with different power densities. Then, overall deformation behaviors are also investigated with different process parameters. Downward and upward deformation directions are generated after LPF with two spot sizes, respectively. Two deformation directions are also unchanged via adjusting laser power densities only. The overall deformation behavior is found to have a close relationship with the localized indentation profile. Therefore, an effective method is proposed to predict the overall deformation direction by localized indentation after a single shock.
Keywords: Laser peen forming, thin metal sheet, indentation profile, overall deformation.

Introduction
Laser peen forming (LPF) is a novel forming method to bend thin metal sheets. Laser-induced plasma expansion produces stress waves transmitting into the target material, which causes plastic deformation without extra thermal effect. Much attention has been paid to LPF treatment of numerous metallic specimens, including stainless steel [1], aluminum alloys [2], and titanium alloys [3].

Apart from the conventional convex curvature of components induced by LPF [4], Ocaña et al. obtained the concave curvature on 50 μm-thick metal sheets [1]. Hu et al. observed two kinds of deformation directions by changing material thicknesses and laser power densities [5]. Similar experimental results were also discovered by LPF with ultra-short laser pulses [6]. Further investigations showed that laser spot size also took a critical role in deformation behaviors of thin metal sheets with a thickness of 0.5 mm [7]. The section thickness, laser power density, and spot size significantly affect deformation behaviors. Therefore, more attention should be paid to the spot size effect on deformation behaviors as well as laser power densities.

Apart from the overall deformation behavior of thin metal sheets after multiple laser shocks, the localized indentation profile induced by a single shock is also a remarkable feature. Most related work shows a crater profile under the laser peening treatment [8, 9]. However, Clauer et al. pointed out that if the material is thin enough, the laser shock loading will produce a dimple on the topside and a bulge on the backside at the same time [10]. Considering that the accumulation of localized indentations results in the overall deformation behavior of thin metal sheets, the localized indentation profile after each laser shock could be closely related to the overall deformation behaviors. It would provide an efficient method to identify the deformation behaviors induced by LPF. However, limited studies have been conducted on the process parameter effects on indentations, and the relationship between localized indentation profiles and overall deformation behaviors has not been illustrated.

This study investigates process parameter effects on localized indentation profiles and the overall deformation behaviors of thin metal sheets induced by LPF with different spot sizes and laser power densities. The relationship between indentation profile types and overall deformation directions is established. An effective method is proposed to predict the overall deformation direction after multiple shocks by localized indentation after a single shock.

Experimental Methods

LPF experiments were conducted on Ti6Al4V thin sheets with the size of 40×30×0.5 mm^3. Half of the specimens were treated by a single laser shock to analyze the localized indentation profile. The others were treated by multiple laser shocks for overall deformation analysis, and the size of the treated region was 13.6×13.6 mm^2. The designed specimen geometry was machined by wire cutting and polishing. The laser source was a Q-switched Nd: YAG pulsed laser with a wavelength of 1064 nm and a pulse duration of 15 ns in FWHM. The laser beam was fixed during the LPF experiment, and an industrial robot constantly moved specimens to ensure the laser spots covering the specified surface region. The black tape and flow water were used as the absorbent and confinement layers, respectively. Laser pulse energies were 2, 4, 6, 8, 10, and 12 J. The spot diameters were 4.0 and 0.8 mm. The 4.0-mm spots were directly obtained by focusing the beam through a convex lens. The laser power densities were 1.06, 2.12, 3.18, 4.25, 5.31, and 6.37 GW/cm^2, corresponding to pulse energies of 2, 4, 6, 8, 10, and 12 J. Besides, 0.8-mm spots were achieved by adding a suitable aperture to ensure that the laser power density is consistent with that of 4.0-mm spots. After LPF treatments, the indentation profiles were measured using the KS-1100 optical surface profilometer with an accuracy of 0.5 μm.

Results and Discussions

Fig. 1 shows both topside and backside of indentation profiles on thin sheets after single-shock laser peening with the power density of 6.37 GW/cm^2. A crater profile is observed on the topside after a single shock with a spot size of 0.8 mm, as shown in Fig. 1(a). That is, pile-up is generated around the dent. The indentation diameter is 0.8 mm, which corresponds to the spot size. The depth of the profile is about 3.0 μm, and the measured displacement on the backside is only within ±0.2 μm, which could be considered negligible. Conversely, the indentation profile results are transformed into another situation when the spot size is increased to 4.0 mm, as shown in Fig. 1(b). A conical profile is generated on both sides of the thin sheet, which agrees with the phenomenon observed by Clauer et al [10]. Besides, the indentation diameter is much larger than the spot diameter, which is up to 12 mm. The laser spot diameter could be recognized from the change of the profile slope. The indentation depth on the topside is about 61.1 μm, and it is 46.6 μm on the backside. Both of them are over ten times the depth of the previous indentation with the crater profile.

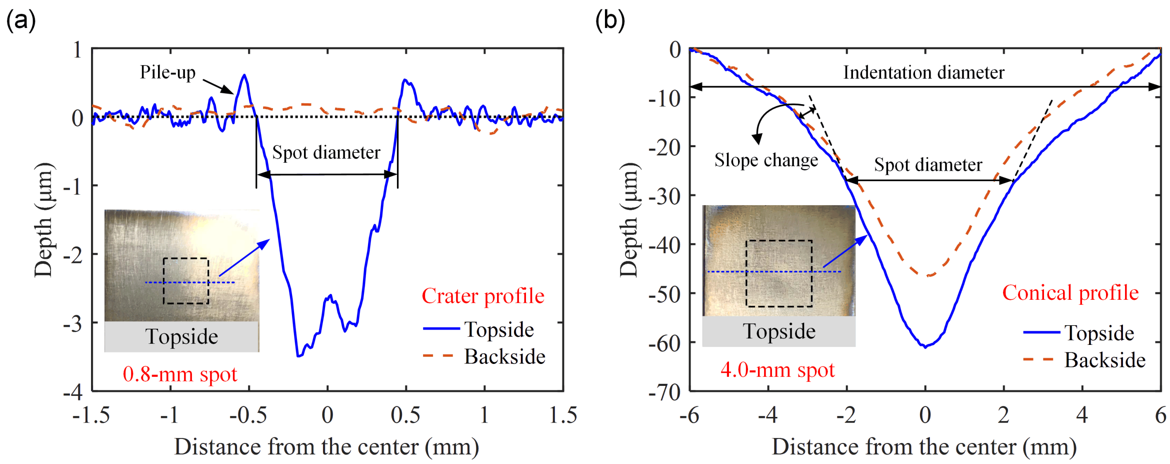

Fig. 1 Indentation profiles of specimens after a single shock with the laser power density of 6.37 GW/cm^2 and spot sizes of (a) 0.8 mm and (b) 4.0 mm.

Decreasing the laser power density from 6.37 to 1.06 GW/cm^2, two indentation types do not change except for the decrease in depth value, as shown in Fig. 2. For the thin metal sheets laser shocked with a spot size of 0.8 mm, all the indentations are crater profiles treated with different laser power densities. The depth value on the topside decreases with the power density, which are 3.0, 2.2, 1.7, 1.3, and 1.0 μm. Besides, all the indentation depths on the backside are negligible. For the thin sheets shocked with a spot size of 4.0 mm, all the indentations are conical profiles treated with different laser power densities. The indentation depths on the topsides also decrease with the laser power density, which are 61.1, 31.8, 21.3, 13.9, 8.1, and 2.0 μm, respectively. The indentation displacements on the backsides show a similar tendency, which are 46.6, 24.9, 14.7, 10.2, 5.9, and 1.5 μm. The experimental results demonstrate that the LPF with distinct spot sizes can change the indentation type of thin metal sheets, while the laser power density only affects the depth value.

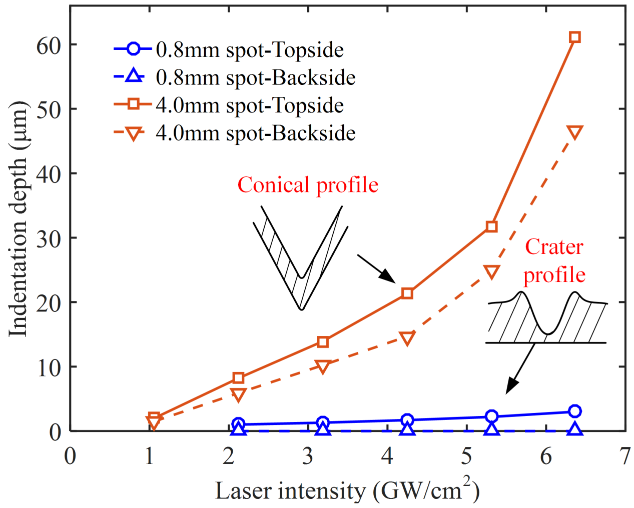

Fig. 2 Indentation depths with different laser intensities and spot sizes.

Fig. 3 provides the overall deformation behaviors of thin metal sheets after multiple laser shocks with different process parameters. It can be observed that the deformation profiles of two sheets are totally different after shocked with different spot sizes, as shown in Fig. 3(a). The thin sheet treated with 0.8-mm spots deforms upward and then downward from the clamping end, leaving a convex curvature with a maximum displacement of -410.5 μm at the free end. For the thin sheet treated with 4.0-mm spots, it deforms downward and then upward, leaving a concave curvature with the maximum displacement of 356.4 μm. The phenomenon of two bending directions induced by LPF has been demonstrated previously, but the study of localized deformation within the impacted region is limited. Essentially, the plastic deformation produced by multiple laser shocks is the accumulation of a single shock. Therefore, the overall deformation in the impacted region after multiple shocks can be regarded as the amplification of the localized indentation induced by a single shock. After multiple laser shocks with 4.0-mm spots, the downward deformation is induced in the impacted region, and the value is -112.8 μm. It is consistent with the conical profile after a single shock. For the thin sheet treated with 0.8-mm spots, the upward deformation is induced in the impacted region after multiple shocks, and the value is 94.5 μm. Dividing the displacement by the number of shocks (about 400), the displacement of the impacted region after a single shock is supposed to be 0.25 μm. Therefore, the slight deformation cannot be characterized in experiments because it is overwhelmed by the crater profile generated on the topside, and no upward displacement can be observed on the backside due to the machining and measurement error.

Fig. 3(b) provides the maximum displacements at the free end with different laser power densities and spot sizes. For the thin sheets treated with 0.8-mm spots, they all bend downward. The displacements are -410.5, -335.1, -211.7, -152.7, and -25.5 μm, varying the laser power density from 6.37 to 2.12 GW/cm^2. For the thin sheets treated with 4.0-mm spots, they all appear to bend upward. The displacements are 356.4, 209.2, 136.2, 97.1, 37.9, and 13.9 μm, corresponding to the power density from 6.37 to 1.06 GW/cm^2. The experimental results show that the spot size can change the bending direction induced by LP, while the laser power density only affects the displacement value. Considering the process parameter effects on the overall deformation behaviors and indentation profiles together, it can be easily observed that the overall deformation behavior after multiple laser shocks is significantly correlated with the localized indentation profile produced by a single shock. All the localized crater profiles lead to downward bending directions, while conical profiles result in upward bending directions. Therefore, it is feasible to predict the overall deformation direction by localized indentation profile after a single shock.

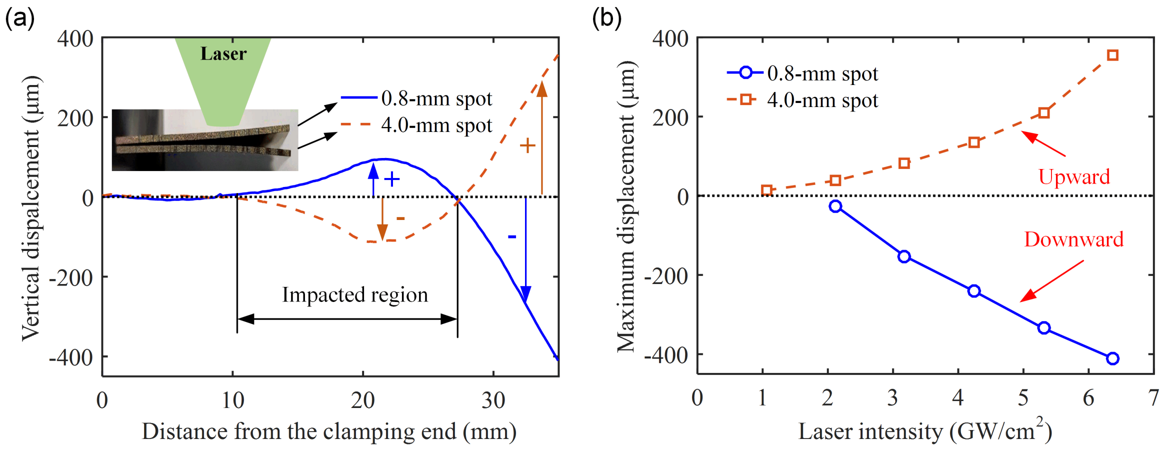

Fig. 3 Overall deformation behaviors after multiple laser shocks with different process parameters: (a) deformation profiles along the central axis under the laser power density of 6.37 GW/cm^2; (b) maximum displacements with different power densities.

Conclusions

This study analyzes the localized indentation profiles and overall deformation behaviors of thin metal sheets in LPF. Ti6Al4V thin sheets with a thickness of 0.5 mm are studied under laser shocks with different laser power densities and spot sizes. The main conclusions are as follows:

(1) Two types of indentations are observed, which are crater and conical profiles. The indentation depth of the crater profile is only a few microns on the topside with negligible deformation on the backside, while the depth of the conical profile can reach tens of microns on both sides.

(2) The indentation type is basically not affected by the laser power density but is mainly determined by the spot size under experimental conditions.

(3) The overall deformation behaviors are found to be closely related to the indentation type, and it is possible to predict the overall deformation direction by localized indentation. A crater profile causes a downward bending direction after multiple laser shocks, while conical profiles lead to upward bending.

Acknowledgments

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