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Experimental and numerical study on fragmentation mechanism of copper sheet in laser dynamic forming

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Abstract

The fragmentation mechanism of copper sheet in laser dynamic forming (LDF) process is investigated. The investigation of the fragmentation mechanism in the moving sample is quite difficult, so finite element method is adopted to provide detailed information on the stress state during micro-forming. The shock loading was generated using laser–shock–rubber loading technique in which a layer of rubber is inserted to improve laser shock efficiency. When laser power density is 0.491 GW cm⁻², the obvious circular fragmentation is located at the center region of rear surface. When laser power density is 0.658 GW cm⁻², the diameter of the fragmentation region increased, and what’s more, circumferential and radial cracks were formed in the fragmentation region. The void linkages and terrace-like pattern were also observed. Finite element model reveals that the fragmentation in the moving sheet is not caused by the initial rubber direct loading, but the deceleration at the last stage of forming. Because the curvature in the tip has the highest value at the stopping point, deceleration passes through its maximum value and then causes fragmentation at the last stage of forming. When laser power density is 0.658 GW cm⁻², the single layer fragmentation, multiple layer fragmentation, circumferential crack, and radial cracks occur in that sequence.

1. Introduction

Laser dynamic forming (LDF) is a new high velocity forming (HVF) technique using laser induced high-amplitude shock wave for a contactless forming of the thin metal sheets [1]. The strain rate in LDF can reach 10⁶ − 10⁸ s⁻¹ [2, 3]. The material deformation and fracture behaviors at high strain rates differ greatly from that under quasi-static loading [4, 5]. The material deformation behaviors under laser shock wave have been extensively studied in various forming processes, such as bending [6], bulge [7, 8], embossing [9, 10], imprinting [11–17]. And present fracture works during LDF focus on shearing fracture along the micro-mold edges [4]. This kind of shearing fracture can be used for laser high speed punching [18–20].

Spall is another typical dynamic fracture that occurs inside the sample, which is caused by the tensile stresses. As shown in figure 1, when a compressive shock wave \( U_T \) reaches the free surface of a stationary flat plate, it is reflected as a tensile wave. Resultant tensile wave \( U_T \) is generated after summing the incident compressive shock wave \( U_T \). If the resultant tensile wave \( U_T \) is high enough, it will result in internal spalling [21]. Numerous works on the laser-induced spalling were observed on rear surface (the opposite to the laser irradiated side) for laser pulses of nanosecond duration [22]. There are works in which the spalling process is consistently investigated precisely from the irradiated (front) side [23]. Frontal spalling occurs for laser pulses of picosecond duration [24]. Of course, for long pulses (ns) the frontal spallation is absent and only rear-side spallation takes place. A notable exception is diamond-like carbon (DLC) films under laser pulses of picosecond and nanosecond durations, the spall takes place on laser irradiated surface for DLC films [25].

The fragmentation in this work is similar to the rear-side spallation, which is located at the center region of rear surface. And circumferential and radial cracks were formed in the fragmentation region with the laser
energy. Although fragmentation phenomenon has been observed in free forming [26], studies on the fragmentation mechanism in LDF process are scare. Preventing fragmentation is of great significance to the successful forming of micro-part. Motivated by this challenge, a laser-shock-rubber loading technique is used to investigate the dynamic fragmentation and fracture behaviors during the metal sheets micro-forming. In this new loading technique, a layer of rubber is inserted to improve laser shock efficiency [27]. Due to the fact that the fragmentation occurs in the moving sample during micro-forming, the investigation of the mechanisms is quite difficult. In order to capture the fragmentation initiation time and site, finite element method is used to provide detailed information on the stress state, which helps better understand the fragmentation mechanism during micro-forming.

2. Experiment conditions

Figure 2(a) shows the experimental setup of LDF process. An 8 ns Nd:YAG laser pulse (maximum pulse energy: 2 J, wavelength: 1064 nm) is irradiated on the ablative medium (about 10 μm black paint) sandwiched between the rubber and the K9 glass confining medium. The laser irradiated area is fixed to be about 2 mm in diameter. Upon absorbing the laser energy, black paint gets ionized into plasma. Due to the plasma expansion, a
compressive shock wave propagates into the rubber and metal sheet. The 100 μm polyurethane rubber with the Shore A hardness 70° is used to improve laser shock efficiency [27]. The 40 μm copper sheet is selected for forming material. And the diameter of circular micro-mold is 1 mm. When the stress amplitude is relatively low, a bulge feature without fragmentation can be generated on metal sheet (see figure 2(b)). If the stress amplitude is high enough, a bulge feature with fragmentation can be generated (see figure 2(c)).

3. Numerical simulations procedure

The detailed description of numerical simulations procedure in ANSYS/LS-DYNA has been introduced in reference [28]. The introduction of loading model and materials constitutive models are only briefly outlined in this work. The corresponding 3D finite element model is shown in figure 3.

3.1. Loading

In LDF experiment, the intensity distributing of laser beam is Gaussian distribution. The diameter of laser beam (2 mm) is larger than that of micro-mold (1 mm). And rubber used in the LDF experiment can exert uniform shock wave pressure [29]. So the spatial distribution of laser shock wave is uniform in simulation. The shock pressure, P(t), can be calculated by Fabbro model [30] as follows:

\[
P(t) = 0.01 \sqrt{\alpha/(2\alpha + 3)} \sqrt{ZI_0}
\]

(1)

Where \( \alpha \) is the fraction of the internal energy devoted to the thermal energy (\( \alpha = 0.1 \) for glass confinement), Z the shock impedance between the confining medium and the ablative medium respectively, and \( I_0 \) the absorbed power density. The shock impedance, Z, is defined as follows:

\[
2/Z = 1/Z_1 + 1/Z_2
\]

(2)

the subscripts, 1 and 2, denote the ablative medium and the confining medium (\( Z_1 = 1.21 \times 10^7 \) kg m\(^{-2}\) s\(^{-1}\), \( Z_2 = 1.3 \times 10^8 \) kg m\(^{-2}\) s\(^{-1}\)). Table 1 shows the calculated shock pressures under different laser power densities.

3.2. Sample materials constitutive model

The Johnson–Cook model is used to simulate the fragmentation and fracture behaviors of copper sample. The Von Mises flow stress in this model can be expressed as follows [31]:

\[
q = (A + B\varepsilon^m)[1 + C \ln (\dot{\varepsilon}/\varepsilon_0)][1 - (T^\theta)^m]
\]

(3)

Where A, B, C, n and m are considered to be material constants, \( \varepsilon \) is the equivalent plastic strain, and, \( \dot{\varepsilon} \) and \( \varepsilon_0 \) are strain rate and the reference strain rate under quasistatic loading. The thermal softening term \( T^\theta \) can be expressed as:
Where $T$ is the absolute temperature, $T_{\text{room}}$ is the room temperature, and $T_{\text{melt}}$ is the melting point of specific material. The Johnson–Cook failure criterion \cite{32} defines the equivalent plastic strain at the onset of damage as:

$$
\varepsilon_f = \left[ d_1 + d_2 \exp \left( d_3 \frac{p}{q} \right) \right] \left[ 1 + d_4 \ln \left( \frac{\varepsilon}{\varepsilon_0} \right) \right] (1 + d_5 T^*) \quad (5)
$$

in which $d_1 - d_5$ are the failure parameters, $\varepsilon_f$ is the strain at failure, $\varepsilon_0$ is the reference strain rate and $\frac{p}{q}$ is a dimensionless pressure-deviatoric stress ratio ($p$ is the pressure stress and $q$ is the Von Mises stress). The parameters of copper used in Johnson–Cook model are listed in Table 2 \cite{32}.

Table 2. The values of critical parameters for Cu in Johnson–Cook model \cite{32}.

| Parameter | Value |
|-----------|-------|
| $A$ (MPa) | 89.63 |
| $B$ (MPa) | 291.64 |
| $C$       | 0.025 |
| $n$       | 0.31  |
| $m$       | 1.09  |
| $T_{\text{room}}$ (°C) | 27 |
| $T_{\text{melt}}$ (°C) | 1200 |
| $\varepsilon_0$ (s$^{-1}$) | 1.0 |
| $d_1$     | 0.3   |
| $d_2$     | 0.28  |
| $d_3$     | -3.03 |
| $d_4$     | 0.014 |
| $d_5$     | 1.12  |

Table 3. Mechanical properties of rubber materials \cite{27}.

| Material    | Hardness Shore A(°) | M-R constant $C_{10}$ (MPa) | M-R constant $C_{01}$ (MPa) | Poisson's ratio ($\mu$) |
|-------------|---------------------|-----------------------------|-----------------------------|------------------------|
| Polyurethane| 70                  | 0.736                       | 0.184                       | 0.49997                |

$T^* = \frac{(T - T_{\text{room}})}{(T_{\text{melt}} - T_{\text{room}})} \quad (4)$

Where $T$ is the absolute temperature, $T_{\text{room}}$ is the room temperature, and $T_{\text{melt}}$ is the melting point of specific material. The Johnson–Cook failure criterion \cite{32} defines the equivalent plastic strain at the onset of damage as:

Figure 4. Comparison of the forming depth between the experimental and numerical results.

Table 3. Mechanical properties of rubber materials \cite{27}.
3.3. Rubber materials constitutive model

The rubber material is described by mooney–Rivlin model [33], and the strain energy in this model is defined as follows:

\[ \sigma_{ij} = \frac{\partial W}{\partial e_{ij}} \]  

Figure 5. The typical stages of forming and fragmentation with Von Mises stress contours (MPa).

Figure 6. The typical stages of the distribution of velocity vector (m/s).
In which \( W \) is the strain energy per unit of reference volume; \( k \) is the bulk modulus; \( I_1, I_2 \) and \( I_3 \) are the strain invariants, and \( I_3 = 1 \) for incompressible material behavior. \( C_{km} \) is the hyperelastic constants. Generally, \( C_{10} \) and \( C_{20} \) are used to describe the hyperelastic deformation of the rubber. Table 3 shows the parameters of polyurethane rubber \[27\].

4. Results and discussions

4.1. Single layer fragmentation

When laser power density ranges from 0.196 GW cm\(^{-2}\) to 0.393 GW cm\(^{-2}\), fragmentation does not occur. Figure 4 shows the comparison of the forming depth between the experimental and numerical results. This predicted forming results are consistent with the experimental results. The deformation behaviors have been systematically investigated in the previous work \[28\]. So the present work focuses on the fragmentation behaviors of copper sample which will be discussed in details below.

Figure 5 shows the typical stages of forming and fragmentation when laser power density is 0.491 GW cm\(^{-2}\). And it shows the time variation of Von Mises stress contours of the sample. The finite element model reveals that the fragmentation occurs at the last stage of forming. It can be founded that the fragmentation initiates from the rear face at the center region of the formed bulge. And the diameter of the fragmentation region is increased gradually with time.
The compression wave imparts momentum to the thin plate, so it gives the plate the initial velocity distribution (distribution along the lateral dimensions of the plate, as is shown in figure 6(a)). And then the plate moves by inertia. When moving, the plate bends, as is shown in figures 6(b)–(d). The elastic forces of solid copper decelerate to the bending. Ultimately, these forces stop the plate. Deceleration stops initial velocity. The situation is similar to the bending of films by laser action considered in the references [16, 17, 34]. The only difference is that in these papers the film was in a molten state during bending (only edges of a laser spot were solid). Therefore, deceleration appears thanks to surface tension.

While in figures 5 and 6 above the deceleration is caused by resistance to stretching of the solid elastic-plastic matter. In both cases the decelerating forces act in tangential direction to the plate and decelerate the plate thanks to a curvature of the plate. Fragmentation occurs at the last stage of forming, at this stage, deceleration passes through its maximum value. Because the curvature in the tip has the highest value at the stopping point. However, as mentioned in the introduction, the standard laser-induced spallation is considered to be the result of resultant tensile stresses developed by the interaction of laser-induced compressive wave and its reflected

![Figure 9. The evolutions of the stress states of five typical elements along the radius direction (a) from 0 ns–4000 ns; (b) from 0 ns–500 ns; (c) from 500 ns–1000 ns).](image-url)
tensile wave. This unusual fragmentation feature in this work qualitatively differs the reviewed paper from the papers with a standard spallation picture as shown in figure 1. The accuracy of this finite element model is confirmed by the experimental results in terms of the region and shape of fragmentation, as shown in figure 7. This verification shows that the numerical model is reliable, so that the following work is based on this finite elements simulation.

In order to characterize the surface state after fragmentation, the surface three-dimensional (3D) topographies of fragmentation and non-fragmentation regions are measured by Zeiss Axio CSM 700 confocal microscope. Figure 8(a) shows the whole cupola sample, and the higher magnification image of the fragmentation region is shown in figure 8(b). Two typical measured regions are outlined by the blue rectangles using the dashed line in figure 8(b). Figure 8(c) shows the surface 3D topography of non-fragmentation region, it shows the regular rolling marks which is similar with the surface state of raw material. This means that there is no obvious surface state change after forming when the fragmentation does not occur. Figure 8(d) shows the surface 3D topography of fragmentation region, its surface is very rough and uneven. From the two-dimensional (2D) profile of the fragmentation region (the measurement region is the red line in figure 8(b)) in figure 8(e), it clearly confirms that one layer of copper is peeled off. And the 2D profile is highly irregular, which is consistent with the observed surface 3D topography.

According to the above results, the circular fragmentation is located at the center region of rear surface. This may be due to the fact that the different formed regions have different stress states and strain rates. In order to capture the detailed information on the stress state and strain rate, a forming case without fragmentation (0.393 GW cm$^{-2}$) is selected for analyzing. Figure 9 shows the evolutions of the stress states of five typical elements along the radius direction (X0, X0.1, X0.2, X0.3 and X0.4), and the displacement history of the center point of the Cu plate is added to conveniently observe the corresponding forming stage. Figure 10 shows the evolutions of the stress states of three typical elements along the thickness direction (Y0, Y20 and Y40). It should be noted that all the elements (X0-X0.4 and Y0-Y40) are all located at the inner (relative to the micro-mold) surface (Let’s call it a surface U (upper.) of the Cu plate. Three distinct stages of stress states can be detected in figures 9 and 10.

At stage I the sample is loaded by the rubber, a compressive impulse is generated on the front surface and then propagates to sample. There are two obvious oscillation stages on the stress curves at the stage I, which is due to shock waves propagating along the thickness direction, as is shown in figures 10(a)–(c). Thus there are

![Figure 10](https://example.com/figure10.png)

**Figure 10.** The evolutions of the stress states of three typical elements along the thickness direction ((a) from 0 ns–4000 ns; (b) from 0 ns–500 ns; (c) from 500 ns–1000 ns; (d) the acceleration and displacement histories of the center points).
two obvious acceleration processes in the acceleration history of the center point in figure 10(d). To better observe the acceleration process, the displacement histories of two center points (points A and B) are shown in figure 10(d). Point A is located on the center of the rear surface of rubber, and point B is located on the center of the front surface of Cu plate, as shown in figure 10(d). The displacement histories of points A and B coincide with each other during stage I, which indicates that the rubber loads the Cu plate.

The Cu plate thickness is 40 μm, and the speed of sound in Cu is about 4 km/s. Acoustic wave passes this plate during time interval $t_s = 10$ ns. According to figure 10 the stage I lasts 500–1000 ns ((50–100)$t_s$). Thus, there is slow acceleration of a plate at the stage I, as is shown in figure 10(d). The first oscillation occurs from 100 ns to 400 ns, as is shown in figure 10(b), which is caused by the rubber’s first loading. The maximum amplitude of the reflected wave (reflected first time from the element Y0) is 136 MPa, as is shown in figure 10(b). And table 4 shows the maximum amplitudes of the first reflected waves on element Y0 under different laser power densities.

As the rubber loads the sample again, the second oscillation occurs from 500 ns to 800 ns, as is shown in figure 10(c). It can be found that the amplitude of the first oscillation is higher than that of the second oscillation, which is due to the fact that the shock energy transferred to the sample under the rubber’s first loading is higher than that of the rubber’s second loading [28]. The Cu plate at the stage I is in an effective gravity field with a 'free fall' acceleration. The plate is an effective gravity at the stage I. The lower (inner) surface (surface U) of the Cu plate in the inset in figure 9 is the upper surface of a Cu plate relative to the gravity field (therefore ‘U’): hydrostatic pressure rises from this surface U to the surface B (bottom) of a contact of Cu with rubber. Hydrostatic pressure at the contact (surface B) is equal to $P_h = \rho * a * d_f$. Where $\rho$ is the density of the Cu plate (8.9 g cm$^{-3}$), $a$ is the acceleration of the Cu plate, and $d_f$ is the thickness of the Cu plate (40 μm). $P_h$ is the corresponding pressure of accelerating the Cu plate. This lower/inner/upper surface (surface U) is a contact with air. Thus, it (=surface U) is unloaded during all the accelerative stage I. Therefore, the sum of a normal to this surface U and tangential to the surface U stresses must be equal to zero during the stage I. The tangential stress at the surface U is small at the stage I because at this stage the surface U is only slightly curved, as is shown in figure 11. The situation is similar to the acceleration of a plate (made from condensed matter) by laser corona pressure in the reference [35].

In stage II, as the forming process proceeds, the film is moving by inertia. The degree of bulging (curvature) of the film increases, so the film area is growing until the displacement of the center point reaches the maximum. During this stage, there is an obvious bump in the stress history for elements X0.4 and X0.3. These bumps in the stress curves are due to the fact that the rubber loads the regions of elements X0.4 and X0.3 again. As shown in figure 10(d), the displacement histories of points A and B separate from each other during stage II, which indicates that the rubber does not contact with the Cu plate in the center region.

![Figure 11. Cu plate in gravity field at the stage I.](image)

**Table 4.** The maximum amplitude of the first reflected wave on element Y0 under different laser power densities.

| Power density (GW cm$^{-2}$) | 0.196 | 0.267 | 0.393 | 0.491 | 0.658 |
|--------------------------------|-------|-------|-------|-------|-------|
| Shock pressure (MPa)           | 96    | 112   | 136   | 152   | 176   |
In stage III, the plastic deformation is almost finished (the displacement almost stays at a plateau value). Deceleration passes through its maximum value, so fragmentation occurs at the last stage of forming. From figure 9, it can be found that the amplitude of the stress is decreased from X0 to X0.4. Because the curvature in the tip (X0) has the highest value at the stopping point. From these discussions, it can be found that the fragmentation in the moving sheet is not caused by the initial rubber direct loading, but the deceleration at the last stage of forming.

Figure 12(a) shows the time history of effective plastic strain of five typical elements on the rear surface. It can be found that the effective plastic strain is decreased from X0 to X0.4. The maximum plastic strain occurs in the
Figure 14. (a) The predicted fragmentation and fracture results; (b) the experimental fragmentation and fracture results; (c) the predicted terrace-like pattern; (d) the experimental terrace-like pattern.

Figure 15. (a) Void linkages inside sample material; (b) cross section microscopy of the fragmentation region; (c) bump on the surface of fragmentation.
center region and the maximum strain rate also takes place in this region, as shown in figure 12(b). The strain rates in X0.4 and X0.3 are higher than that in X0.2, and this is also ascribed to the rubber-generated second loading [28] at X0.4 and X0.3 regions. Through the above discussions, it can be found that plastic deformation initiates at the edge then proceeds toward the center, so the forming energy concentrates on the center region in the last unloading stage. And the rubber-generated second loading increases the forming energy spread to the center region. If the forming energy is too high, the fragmentation takes place.

4.2. Multiple layer fragmentation and subsequent fractures

When laser power density is 0.658 GW cm$^{-2}$, as shown in figure 13, the fragmentation takes place in the similar manner. But the diameter of the fragmentation region is increased, and circumferential fracture occurs in the fragmentation region. And there are also several radial cracks existing around the circumferential fracture. The multiple layer fragmentation, circumferential crack, and radial cracks occur in that sequence. Figures 14(a) and (b) show that the predicted fragmentation and fracture results are in good agreement with the experiment results. At 2600 ns multiple layer fragmentation occurs. Multiple layer fragmentation is also observed in the experiment, and it generates the terrace-like pattern on rear surface. Figures 14(c) and (d) respectively shows the predicted and experimental terrace-like pattern induced by multiple layer fragmentation. Multilevel fragmentation makes the sample become thinner, which leads to circumferential fracture. At last, radial fractures occur near the circumferential fracture.

To further investigate the fragmentation and subsequent fractures mechanisms, a severely fractured sample described in figure 14(b) was prepared for cross section observation. Figure 15(b) shows the cross section microscopy of the fragmentation region. Figure 15(a) and (c) reveal two important characteristics: (1) As shown in the blue arrow of figure 15(a), void linkages inside sample material were clearly observed near the rear surface. During fragmentation, the voids nucleation, voids growth, voids coalescence and fragmentation take place in that sequence. Void linkages state is in the voids coalescence stage. The material is not separated from the rear surface may be due to the fact that the amplitude and duration of the local stress are not sufficient. This may indicate that the internal stress distribution of the formed region is not uniform. (2) As indicated using the red arrow in figure 15(c), one layer of material was peeled away and the bump was formed on the surface of fragmentation (blue arrow shows the bump). It is a sign of the occurrence of multilevel fragmentation. The possibility of multilevel spallations under a single laser pulse has been observed by Kononenko et al [25]. And the number of spalled layers gradually increased with the laser energy until it reached a maximum [25]. Multilevel fragmentation will make the material become thinner, which will lead to fracture.

Figures 16(a) and (b) show the cross section microscopy of the fracture regions. There is no obvious neck near the fracture edges, which means that little plastic deformation occurs before fracture. It can be inferred from the fracture microscopy that fragmentation can speed up fracture behavior. From figure 16(a), several micro-voids can be clearly observed on the fragmentation surface, as indicated using the red arrow. The diameters of these micro-voids were measured to be about 2–5 μm. Void linkages are also observed in figure 16(b) and the diameters of the micro-voids (see the blue arrow in figure 16(b)) are less than that observed in figure 16(a). If the micro-voids in figure 16(b) experience adequate stresses, they will grow bigger until fragmentation. As shown by the red arrow in figure 16(b), an obvious crack originates on the fragmentation surface and propagates inwards. The present results in figure 16 confirmed that fracture takes place after fragmentation.

Figure 16. (a) Cross section microscopy of the fracture region with micro-voids; (b) cross section microscopy of the fracture region with micro-voids and cracks.
5. Conclusions

In this work, dynamic fragmentation and fracture behaviors during LDF are studied. The shock loading is generated using laser-shock-rubber loading technique in which a layer of rubber is inserted to improve laser shock efficiency. Some important findings are listed as follows:

(1) When laser power density is 0.491 GW cm$^{-2}$, the obvious circular fragmentation is located at the center region of rear surface, and the fragmentation surface is very rough and uneven.

(2) When laser power density is 0.658 GW cm$^{-2}$, the diameter of the fragmentation region is increased, and what’s more, circumferential and radial cracks are formed in the fragmentation region. The void linkages and terrace-like pattern induced by multiple layer fragmentation are observed.

(3) This predicted single layer fragmentation result is consistent with the experimental results. From the experimental and simulation results, it can be found that the fragmentation in the moving sheet is not caused by the initial rubber direct loading, but the deceleration at the last stage of forming.

(4) The simulation results show that the single layer fragmentation, multiple layer fragmentation, circumferential crack, and radial cracks occur in that sequence. The predicted fragmentation and fracture results are in good agreement with the experiment results.

6. CRediT authorship contribution statement

Songling Chen: Conceptualization, Data curation, Investigation, Writing - original draft, Project administration. Pin Li: Supervision, Resources, Writing - review & editing, Investigation. Xijin Zhen: Investigation, Methodology, Data curation, Formal analysis. Zongbao Shen: Funding acquisition, Methodology, Validation, Writing - review & editing. Huixia Liu: Funding acquisition, Investigation, Resources. Xiao Wang: Investigation, Data curation.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

The authors declare that they have no conflict of interest.

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