Deformation and Fracture Behaviors in Microscale Laser Dynamic Flexible Forming: The Case of Fabricating Micro-Channel on Copper Foil

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Abstract. The case of fabricating micro-channel on copper foil using micro-scale laser dynamic flexible forming (µLDFF) is investigated in this work. To study the deformation and fracture behaviors, the copper foils are subjected to increasing laser power density until the occurrence of fracture. When laser power density ranges from 0.110 GW/cm² to 0.441 GW/cm², smooth micro-channel features are formed on copper foils, and the depth of the micro-channel gradually increases. Melting marks are observed at the micro-die entrance of the sample with 0.441 GW/cm² laser power density. When laser power density is 0.544 GW/cm², partial fractures are observed. The surface of fracture region is rougher than that of micro-cracks and no micro-cracks regions, which is caused by the higher strain in fracture region. And the fracture edge is irregular, which is caused by the soft effect of material. Complete fracture occurs when laser power density is 0.691 GW/cm².

Keywords: Micro-scale laser dynamic flexible forming; Micro-channel; Micro-cracks; Fracture.

1. Introduction

The micro-forming process can fabricate components and features with at least two dimensions in micrometer-sized through using plastic deformation, which has the advantages of near-net-shape, excellent mechanical properties, high productivity and low cost [1]. However, in conventional micro-forming, the clearance between rigid micro-die and micro-punch must be accurately guaranteed, because misalign may lead to serious results such as rupture and wrinkling. Moreover, the micro-punch is difficult to manufacture, and its poor rigidity makes it to be easily deformed and even broke. To overcome the above limitations, many new micro-forming methods have been proposed, such as microscale laser dynamic forming (µLDF).

µLDF is a novel micro-forming technique to fabricate 3D microstructures on metal foils. In µLDF process, only a single micro-die is used to restrict the flow of sample materials. A strong pulsed laser is irradiated on the metal foil surface as flexible micro-punch, and the metal foil is usually coated with ablative material. As the irradiated material vaporizes and ionizes into high temperature and high pressure plasma, a shock wave is formed to load the metal foil. As a result, the metal foil flows into the micro-die under inertial effects [2]. In addition, the material can be superplastically deformed under high strain rates [3]. Because the strain rate in µLDF can reach 10⁶-10⁷ s⁻¹, µLDF can improve the formability in comparison to quasistatic micro-forming [2].

Due to the above advantages, µLDF has attracted great attentions. Li et al. fabricated micro square and hexagonal features on thin foils, and used a Johnson–Cook model to simulate the forming limit and fracture behaviors of thin foils in µLDF [4]. Wielage et al. fabricated micro-bending features on aluminum and copper foils, and measured the forming speed of metal foils under laser shock [5]. Nagarajan et al. fabricated micro-crater features on three different metal foils using flexible pad laser shock forming [6]. Zheng et al. fabricated circular micro-hole feature on T2 pure copper foil, and investigated the grain size effect on punching quality of punched holes in µLDF [7]. Fei et al. fabricated circular micro-convex features on NiTi alloy using laser shock imprinting (LSI), and found that the mechanical properties of LSI sample are improved [8].

The thickness distribution of micro-component is controlled by the spatial distribution of laser shock wave pressure, which has a big influence on the performance. To improve the uniformity of...
thickness distribution, Shen et al. introduced a flexible rubber into μLDF to uniform laser shock wave pressure [9], and this improved μLDF method is microscale laser dynamic flexible forming (μLDFF) [10].

Micro-channel component is widely used in micro electro mechanical systems (MEMS) [11]. Liu et al. proved the feasibility of fabricating micro-channel feature using μLDF [12]. According to the rebound effect in μLDFF when fabricating micro-channel feature, Shen et al. adopted plasticine as pressure-carrying medium to reduce this effect [13]. Zheng et al. fabricated line channel features on copper material using laser shock incremental forming method [14]. However, the deformation and fracture behaviors of fabricating micro-channel using μLDFF have not been studied systematically. So the deformation and fracture behaviors in the case of fabricating micro-channel using μLDFF are investigated by experiment methods. The samples are subjected to increasing laser power density until the occurrence of fracture. Surface profiles are characterized using optical microscopy (OM), and surface topographies are measured using scanning electron microscopy (SEM).

2. Micro-channel Forming Experiment

2.1. Experiment Conditions

Figure 1(a) shows the experimental setup of micro-channel forming, which is made up of confining medium, ablative medium, rubber, sample and micro-channel die. The 500 μm polyurethane rubber is used in micro-channel forming experiment. An 8 ns Nd-YAG laser pulse (wavelength: 1064 nm) is irradiated on the ablative medium (10 μm black paint). The diameter of laser beam is fixed to be about 2 mm. As the black paint absorbs the laser energy, it gets ionized into plasma. The plasma is trapped by confining medium (2 mm K9 glass), and then a compressive shock wave induced by the plasma expansion propagates into the rubber and sample material. Then micro-channel can be formed on 18 μm copper foil, as is shown in figure 1(b).

![Figure 1](image_url)

Figure 1. (a) Schematic of experimental setup of micro-channel forming; (b) 3D plot of the micro-channel sample.

Micro-channel feature is manufactured on AISI 1095 high-carbon steel using electrical discharge machining, which is used as the micro-die. Figure 2(a) is the 3D plot of the micro-channel die, and figure 2(b) is the 2D profile of micro-channel die. To investigate the fracture behaviors of micro-channel forming, the depth of micro-channel die is very deep (up to 200 μm).
2.2. **OM Observations**

OM (Zeiss Axio CSM 700) is used to measure the surface micro topographies and surface roughnesses of the micro-channel samples. The samples in the micro-channel forming experiments were irradiated by increasing laser power density until the occurrence of fracture. Figure 3 shows the micro-channel samples with different laser power densities. When laser power density ranges from 0.110 GW/cm² to 0.441 GW/cm², smooth micro-channel features were formed on copper foil, as shown in figures 3(a)–(d). Figure 4 shows the corresponding 2D profiles under different laser power densities. The 2D profiles possess good geometric symmetry, which confirms that the forming pressure is uniform. And the depth of the micro-channel increases with laser energy. When laser power density increases to 0.544 GW/cm², partial fracture was observed, as is shown in figure 3(e). Complete fracture occurred when laser energy is 0.691 GW/cm² (figure 3(f)). The fracture surface morphologies in figure 3(e) and (f) cannot clearly observed by OM. So the fracture surface morphology in figure 3(e) is characterized by SEM in the subsequent section.

![3D plot and 2D profile of the micro-channel die](image1)

**Figure 2.** 3D plot (a) and 2D profile (b) of the micro-channel die.

![Micro-channel samples with different laser power densities](image2)

**Figure 3.** The micro-channel samples with different laser power densities (GW/cm²) ((a) 0.110; (b) 0.196; (c) 0.306; (d) 0.441; (e) 0.544; (f) 0.691).
Figure 4. 2D profiles of the micro-channels samples.

Figure 5 shows the 3D plots of the center regions of the micro-channel samples with different laser power densities. And the corresponding measurement regions are the yellow rectangle regions in figure 3(a), (c) and (d). Compared with the raw material in figure 5(a), the higher laser energy irradiates, the rougher the surface becomes.

Figure 5. 3D plots of the center regions of the micro-channel samples under different laser power densities (GW/cm²) ((a) raw material; (b) 0.110; (c) 0.306; (d) 0.544).

2.3. SEM Observations
SEM (Hitachi S-3400N) is adopted to characterize the fracture morphologies of the micro-channel samples. Figure 6 shows the SEM observations of the micro-channel sample prior to fracture (0.441 GW/cm² laser power density). Figure 6 (a) shows the whole image of the micro-channel sample, melting marks were observed at the micro-die entrance. And the higher magnification images of melting marks are shown in figure 6(b) and (c). Melting in figure 6 is caused by the temperature rise (T) defined by the following equation [15]:

\[
\rho c_v \frac{dT}{dt} = \mu \delta \dot{\varepsilon}
\]  

(1)

Where \( \rho \) denotes the density of deformed material (\( \rho = 8.9 \times 10^3 \text{ kg/m}^3 \)), \( c_v \) the specific heat (\( c_v = 394 \text{ J/kg} \cdot \text{°C} \)), \( \delta \) the stress, \( t \) the time, \( \mu \) the heat conversion ratio in case of an adiabatic heating (\( \mu = 0.9 \)) and \( \dot{\varepsilon} \) the strain rate. The high strain around micro-die entrance leads to the local high temperature rise, which results in the soft of material.
Figure 6. SEM observations of the micro-channel sample with 0.441 GW/cm² laser power density ((a) the whole image; (b) corresponds to the region "b" in (a); (c) corresponds to the region "c" in (b)).

Figure 7 shows the SEM observations of partial fracture sample (0.544 GW/cm² laser power density). Three different regions can be observed: micro-cracks region (figure 7(b)), no micro-cracks region (figure 7(c)) and complete fracture region (figure 7(d)). Three different regions in figure 7 may be caused the anisotropy effect and soft effect of material. Figure 7(c) and (d) show that the surfaces of micro-cracks and no micro-cracks regions are very rough. As shown in figure 7(e), the surface of complete fracture region is rougher than that of micro-cracks and no micro-cracks regions, which is caused by the higher strain in complete fracture region. And the fracture edge is irregular, as shown in figure 7(f), which is caused by the soft effect of material.

3. Conclusions
To study the deformation and fracture behaviors of samples, the copper foils were subjected to increasing laser power density until the occurrence of fracture. Some important conclusions can be obtained as follows:

1) When laser power density ranges from 0.110 GW/cm² to 0.441 GW/cm², smooth micro-channel features were formed, and the depth of the micro-channel increases with laser power density.
2) Melting marks were observed at the micro-die entrance of the sample with 0.441 GW/cm² laser power density. As laser power density increases to 0.544 GW/cm², partial fracture was observed. Three different regions can be observed: micro-cracks region, no micro-cracks region and complete fracture region. The three different regions may be caused by the anisotropy effect and soft effect of material. The surfaces of micro-cracks and no micro-cracks regions are very rough. And the surface of complete fracture region is rougher than that of micro-cracks and no micro-cracks regions, which is caused by the higher strain in complete fracture region. And the fracture edge is irregular, which is caused by the soft effect of material. Complete fracture occurred when laser power density is 0.691 GW/cm².

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