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Investigation of laser-induced plasma evolution in flexible pad laser shock forming with high speed camera

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ABSTRACT

This study investigated the effect of plasma evolution, which dominates the forming load, on the fabrication of microcraters in flexible pad laser shock forming (FPLSF) using a high speed camera. It has been found that the plasma lifetime starting from plasma formation, expansion, decaying to vanishing was less than 13.3 μs at single pulse ablation, 350 times longer than the pulse duration. When 45 pulses were applied as 5 cycles with 9 pulse train in each, the plasma size increased gradually to its maximum at the fifth or sixth pulse. There was no interference between the plasma generated from each pulse. The first pulse was sufficient for the fabrication of a crater. The crater depth and diameter increased only by 10% and 25% respectively at ablation with 45 pulses. At 45 pulses ablation for fluence from 7.3 J/cm^2 to 20.9 J/cm^2 in water confinement, the change factor appeared in descending sequence from laser fluence, maximum plasma diameter, maximum plasma pressure, to crater depth by the order of 2.86, 2.18, 1.69 and 1.47 respectively. In glass, the plasma diameter increased by 3.28 times at increasing laser fluence. The confined plasma in glass resulted in deeper craters. The smaller craters in water were attributed to the forming load diminution due to the plasma expansion, shockwave attenuation in ablative overlay, and the laser energy reduction.

1. Introduction

Flexible pad laser shock forming (FPLSF) is a microfabrication technique used to create microfeatures on metallic foils that can be applicable in producing various microcomponents for electronics, optics, and biomedical devices [1]. It is a sheet metal forming process using laser-induced shock pressure as the deformation force and a flexible pad as a support. Hemispherical microcraters of radius of about 500 μm and depth ranging from 80 μm to 200 μm were formed on 25 μm thick copper foils. In FPLSF, the deformation geometry is influenced predominantly by the laser-induced shock pressure which depends upon various process parameters including laser fluence, number of pulses, ablative overlay, flexible pad, confinement medium, and confinement thickness. The significant mechanism behind the induced shock pressure is the formation and propagation of plasma upon laser irradiation. The laser-induced plasma largely affects the magnitude and duration of shockwaves and hence the plastic deformation of the metal foil.

A comparison of crater shapes between water and glass confinements in FPLSF revealed a significant difference in shapes at higher laser fluences; hemi-spherical craters were produced on copper foils with water confinement whereas shockwave structures were formed on copper with glass confinement [2]. This behavior was attributed to the difference in plasma and shockwave propagation between different confinement layers. However, further analysis of plasma characteristics is required to understand the effect of the confinement layer on the deformation crater shapes.

The effect of confinement layer thickness on the plastic deformation of metal foil is found to be influenced by the plasma characteristics [2–4]. When the shockwave emanating from the irradiation zone reaches the top surface of the water confinement, the water will be detached from the target surface and hence there will be no confinement of plasma [3]. This effect will cause a reduction in plasma pressure if the shockwave reaches the top water surface before the arrival of the peak laser pulse. Therefore, the confinement of plasma depends upon the confinement thickness and the shockwave velocity. Ocana et al. [4] found using numerical simulation that the plasma pressure increases with the increase in

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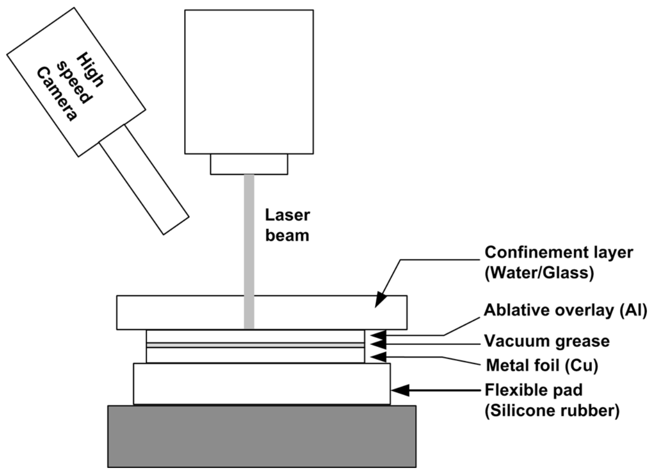

Fig. 1. Schematic of flexible pad laser shock forming with high speed camera for plasma visualization.

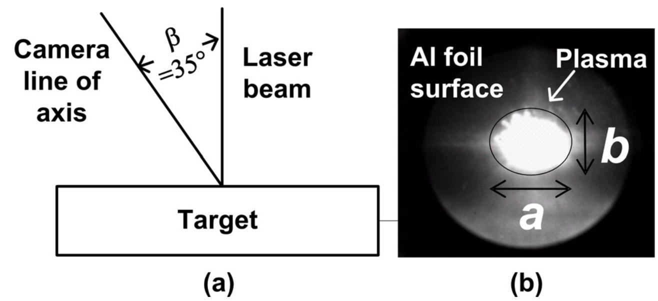

Fig. 2. Measurement method for the plasma diameter: (a) orientation of camera with the laser beam, (b) image of plasma acquired by high speed camera.

confinement thickness. However, the effect of confinement thickness on the plasma behavior is yet to be examined experimentally.

Therefore, to understand the process mechanisms involved in FPLSF, it is necessary to study the formation and expansion of plasma with respect to different process parameters such as laser fluence, confinement medium, and confinement layer thickness.

Characterization of plasma has been performed extensively both quantitatively and qualitatively. Visual observation of plasma/plume in laser-material interaction has been achieved by different methods such as dye laser resonance absorption photography [5,6], shadowgraphy [7,8], speckle photography [9], frame and streak photography [10], and high-speed photography [11–13]. Typical characterization parameters include plasma plume size, plume edge position, plume velocity, and the plasma lifetime [13,14]. Franco et al. [15] used the streak photography technique to study the spatial and temporal evolution of laser-induced plasma by measuring the plasma absorption, initiation time, lifetime, and axial column length of the plasma. Fast photography by an ICCD camera was used to analyze the change in length and diameter of the plume core and plume periphery regions with time at different laser fluences [16]. Seto et al. [11] used two ultrahigh speed cameras (1125 fps) to analyze the plasma shape and the keyhole formation in laser welding. High-speed photography is found to be an effective method to visualize and characterize the plasma to study its evolution with time [11,12]. In most of these analyses, the geometry of the plasma was characterized to understand the plasma evolution.

In this work, the evolution of plasma with time was studied using a high-speed camera. The plasma evolution was characterized by measuring the plasma size using the plasma images acquired by the high speed camera. A comparison between the plasma size and the depth and diameter of the craters formed by FPLSF has been performed to study the effect of laser-induced plasma on the plastic deformation of metal foils. The influence of different process parameters such as laser fluence, confinement layer medium and its thickness on the plasma propagation has been analyzed in detail.

2. Experimental method

2.1. FPLSF setup

The schematic illustration of FPLSF along with the plasma visualization setup using a high speed camera is shown in Fig. 1. In FPLSF, the metal foil is placed over a flexible pad which has hyperelastic material properties. A sacrificial material, the ablative overlay, is placed on top of the metal foil and exposed to high energy laser irradiation. The ablative overlay is covered with a confinement layer that is transparent to the laser beam. The laser beam passes through the confinement, vaporizes the ablative overlay and generates plasma instantaneously. The formed plasma expands as it absorbs more laser energy. As the plasma expansion is confined by the confinement layer, it creates a shockwave towards the metal foil which induces plastic deformation in the foil if the shockwave pressure exceeds the dynamic yield strength of the metal. The flexible pad experiences large elastic deformation along with the plastic deformation of the metal foil and retracts to its original position upon removal of the copper foil.

FPLSF experiments were conducted using high power pulsed Nd:YAG laser with the following specifications: pulse width = 38 ns, wavelength = 1.064 μm, maximum pulse energy = 75 mJ at 6 KHz frequency. The laser beam was square-shaped (0.6 mm side) with flat-top intensity profile. Single laser pulse and 45 pulses were used in the experiments. Laser fluence ranging between 7.3 J/cm^2 and 20.9 J/cm^2 were used for the irradiation. Copper foil with 25 μm thickness was used as the workpiece. The copper foil was placed over a silicone rubber sheet (900 μm thick) which was used as the flexible pad. Aluminum foil with thickness of 15 μm acted as the ablative overlay on which the laser irradiation was applied. A thin layer of vacuum grease ensured tight sealing between the copper foil and the aluminum foil. Either fused silica glass (6 mm thickness) or deionized water was used as the confinement layer medium. All the experiments were repeated three times and average values were used.

Talyscan surface profiler was used to measure the depth and diameter of the deformed craters. Scanning electron microscopy and optical microscopy were used to visualize the surfaces of the craters in copper foil and aluminum foil ablative overlay. A photodetector and an oscilloscope were used to determine the time profile of the laser pulse.

2.2. Plasma visualization and characterization

Photron FASTCAM SA5 high-speed camera was used to capture the formed plasma in this study. The camera has a maximum exposure time of 1 μs and a wide range of frame rates [50–150,000 fps (frames/s)], out of which 5000 fps was mainly used in order to capture the entire plasma image. In addition, the plasma images were captured at the maximum frame rate (150,000 fps) of the camera to understand the evolution of plasma. The camera was positioned at an angle of β (35°) to the path of the laser beam as illustrated in Fig. 2a. The entire evolution of laser-induced plasma from its formation to the vanishing was recorded for the analysis.

The shape and size of the plasma change with the observation angle (β) of the camera. Therefore, change factor of plasma size was used instead of the absolute plasma sizes in this analysis. The