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Variation of fracture mode in micro-scale laser shock punching

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Micro-scale laser shock punching is a high strain rate micro-forming method which uses the high-amplitude shock wave pressure induced by pulsed laser irradiation. The response of brass and pure titanium foils under the different ratio of laser beam diameter (d) to die hole diameter (D) in micro-scale laser shock punching was investigated experimentally and numerically. The typical fracture surface morphologies were observed using scanning electron microscope. Numerical simulations were conducted to predict the stress state of the workpiece before and after fracture. The influence of the ratio d/D on dynamic deformation and fracture of metal foils was characterized. The results demonstrate that both the crack locations and fracture surface morphologies of metal foils are strongly related to the ratio d/D. The fracture mode varies from a shear fracture mode to a mixed fracture mode, then to a tensile fracture mode as the ratio decreases. The stress state under the different ratio is discussed in detail and believed to be responsible for the variation.

1. Introduction

Micro-punching is one of the micro-metal forming technologies and now industrial demands for small holes on thin sheet metal have been increasing. In the conventional micro-punching system, the punching of sheet metal is performed by metallic punches and dies, as illustrated in Fig. 1(a). A practical problem associated with the conventional micro-punching is that the punch/die clearance required may not always be met. Additionally, it would be a challenge to tools fabrication and to the guidance of the tools [1–3]. In order to overcome these problems, improvements of the conventional micro-forming process and inventions of new processes are brought forward. Using a flexible tool instead of a metal punch, known as the flexible punching method, has been proposed and attracted wide attention [4,5].

Since the first experimental research in the 1960s using a high power laser pulse to generate shock waves in solid targets, it is observed that laser-induced shock waves have the ability to produce fracture in metal targets [6–8]. The occurrence of fracture depends on the intensity of the laser pulse, the pulse duration, the metal target thickness, and material parameters. While a laser pulse with the intensity as high as GW/cm^2 order impacts a thin target, the fracture can occur at high strain rates, providing a note-worthy method to fabricate micro-holes on thin metal sheets. Thus, laser shock induced micro-punching has been developed, which takes advantage of high strain rate plastic forming and laser shock peening. In this process, laser induced shock wave is employed as a flexible punch to generate plastic deformation and fracture of the metal foil, as seen in Fig. 1(b). It should be noted that the forming mechanism of micro-scale laser shock punching is different from that of laser drilling and laser piercing. A hole is generated by ejecting molten material back through the hole entrance until breakthrough, after which molten material can exit through the bottom of the hole during laser drilling and laser piercing [9–12]. However, laser induced shock wave is employed as deformation energy to manufacture micro-components in micro-scale laser shock punching. Fracture occurs while the shock wave pressure exceeds the dynamic fracture strength of the material. Then a hole remains on the metal target.

There has been a lot of effort in experiments and simulations to investigate the forming mechanism and deformation behavior of materials in laser shock induced micro-punching. Liu et al. [13] established the micro-high speed punching process and circular micro-holes of 250 μm in diameter were successfully punched on copper foils of 10 μm in thickness by a single laser pulse. A laser-driven flyer punching technology was developed in which a flyer was employed to impact the workpiece at ultrahigh speed. Holes at the micron scale with high edge quality could be obtained on copper foils [14] and Au thin films [15]. Although laser shock induced micro-punching offers great promise for manufacturing micro-holes on thin metal sheets, the influence of critical

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parameters on fracture surface characteristics of micro-holes is still not well understood. Obviously the micro-hole with high cross section quality as well as with good geometry is beneficial to micro-components. In this sense, it is full of the importance to study the dynamic fracture behavior of metal foils in micro-scale laser shock punching.

This study investigates the response of brass and commercially pure titanium (CP Ti) foils under different ratios of laser beam diameter (d) to die hole diameter (D) in micro-scale laser shock punching using both experimental and numerical methods. The typical morphology of fracture surfaces was characterized using scanning electron microscope (SEM). Numerical simulations were conducted to predict the stress state of the workpiece before and after the fracture. The effect of the ratio d/D on dynamic deformation and fracture behavior of metal foils was investigated.

2. Forming mechanism and experimental procedure

Fig. 2 shows the schematic setup of micro-scale laser shock punching. This process originates from the ability to drive the shock wave into thin sheet metal to cause plastic deformation and fracture by the impact of a high power laser pulse. The sample surface facing laser irradiation is pre-coated with an absorbent coating and then covered by a confining overlay. The absorbent coating absorbs the incident laser energy and is vaporized to form a plasma, providing protection from laser ablation for the metal surface [16]. Black paint is often chosen as the absorbent coating due to its high energy absorbability and easy removal after the process. The confining overlay confines the plasma from expanding rapidly away from the metal surface, resulting in higher shock wave pressure compared with the open-air condition [17,18]. Quartz glass usually acts as the confining overlay. As illustrated in Fig. 2, the laser beam travels through the quartz glass and vaporizes black paint into a high pressure and high temperature plasma instantaneously. The produced plasma expands in the confined regime and then induces shock waves propagating into the metal foil. A forming die is placed under the metal foil for the micro-punching process. While the pressure of the shock wave exceeds the dynamic fracture strength of the metal, fracture occurs and the punching is realized. A blank holder is employed to keep each component in position during the experiments.

The materials used for the experimental investigation are brass and CP Ti foils of 30 μm in thickness. A Q-switched Nd:YAG laser was used in the experiment (wavelength: 1064 nm, pulse duration: 11 ns, and maximum pulse energy: 500 mJ/pulse). The laser pulse energy was measured using an optical power meter (Coherent, type: Field MaxII). The laser energy was constant at 450 mJ in all experiments. The laser pulse was conducted to the metal foil through a series of reflecting mirrors and a convergent lens with a focal length of 100 mm. The laser beam diameter (d) was set to 1.4 mm and calibrated by the Kodak photosensitive paper. A thin layer of black paint (about 50 μm thick) was spread evenly on the foil surface facing laser irradiation as the absorbent coating. The quartz glass with 2 mm in thickness was placed above the foil as the confining overlay. After the punching process, the remained black paint was solved by acetone solution and the foil surface was cleaned by anhydrous alcohol. In order to compare the response of metal foils under the different ratio of laser beam diameter (d) to die hole diameter (D), micro-forming dies with through holes of 0.8, 2.0 and 3.0 mm in diameter were manufactured by the laser micro-drilling process. The scanning electron microscopy (SEM, Hitachi, type: SU-70) was used to observe the fracture surface morphology of samples. All experiments were carried out by a single laser pulse.

3. Simulation scheme

Numerical simulations were conducted using ABAQUS software. An axisymmetric deformation state was assumed since the shape of the die hole is round and the metal is subjected to a circular laser spot. The stress state of the workpiece before and after fracture was mainly concerned. Brass foil of 30 μm in thickness was chosen as the material for the numerical investigation.

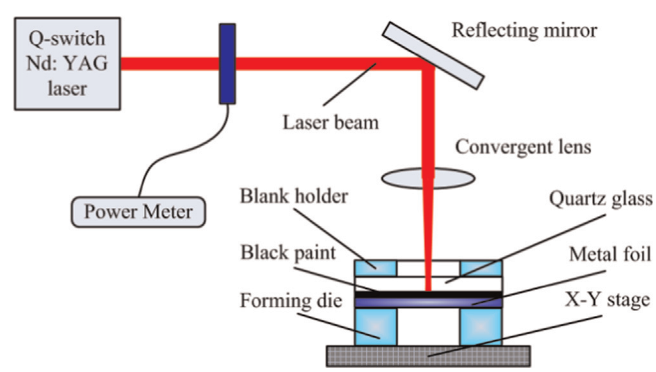

Fig. 2. Schematic setup of micro-scale laser shock punching.

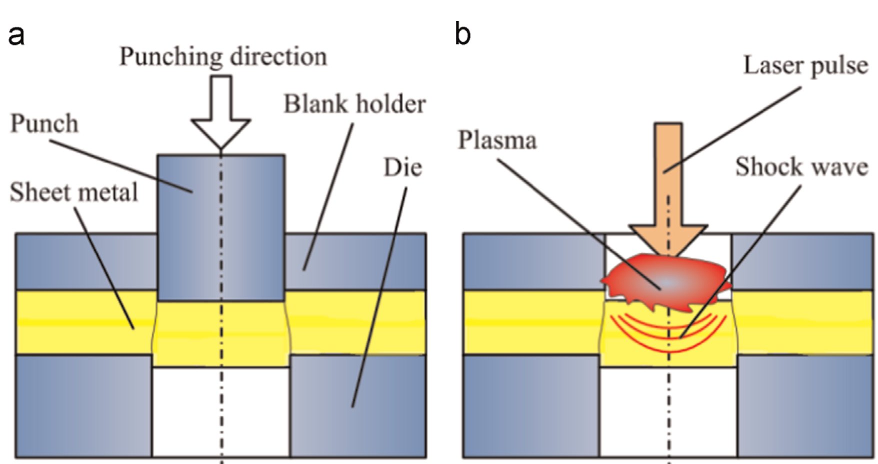

Fig. 1. Schematic diagrams of conventional micro-punching and micro-scale laser shock punching. (a) Conventional micro-punching; (b) micro-scale laser shock punching.