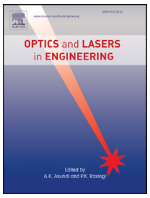
Optics and Lasers in Engineering 105 (2018) 35–42

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng



Effects of laser power density and initial grain size in laser shock punching of pure copper foil

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ARTICLE INFO

Keywords:
Laser shock punching
Grain size effect
Micro punching
Forming quality analysis

ABSTRACT

The effects of laser power density and initial grain size on forming quality of holes in laser shock punching process were investigated in the present study. Three different initial grain sizes as well as three levels of laser power densities were provided, and then laser shock punching experiments of T2 copper foil were conducted. Based upon the experimental results, the characteristics of shape accuracy, fracture surface morphology and microstructures of punched holes were examined. It is revealed that the initial grain size has a noticeable effect on forming quality of holes punched by laser shock. The shape accuracy of punched holes degrades with the increase of grain size. As the laser power density is enhanced, the shape accuracy can be improved except for the case in which the ratio of foil thickness to initial grain size is approximately equal to 1. Compared with the fracture surface morphology in the quasistatic loading conditions, the fracture surface after laser shock can be divided into three zones including rollover, shearing and burr. The distribution of the above three zones strongly relates with the initial grain size. When the laser power density is enhanced, the shearing depth is not increased, but even diminishes in some cases. There is no obvious change of microstructures with the enhancement of laser power density. However, while the initial grain size is close to the foil thickness, single-crystal shear deformation may occur, suggesting that the ratio of foil thickness to initial grain size has an important impact on deformation behavior of metal foil in laser shock punching process.

1. Introduction

With the ongoing development of micro-electromechanical system (MEMS), there is a fast-growing demand for the fabrication of holes with feature dimensions in millimeter and sub-millimeter ranges. To meet the increasing market requirement and further improve the performance of products, many novel manufacturing technologies for holes at micro and meso levels have been developed during recent years. In particular, laser shock punching process has been proposed in which the shock wave induced by a high energy laser pulse is applied to make the metal foil deformation and fracture [1]. The working principle of the process is illustrated in Fig. 1. In order to generate the plasma followed by the shock wave, the power density of the laser pulse is usually up to GW/cm^2 order. In this case, the fracture occurs at high strain rates and then holes can be obtained with the combined action of blank holder and forming die. Due to the high laser power density and short laser pulse duration (usually 5–100 nanoseconds), the impacted material is deformed at high strain rates in the laser shock forming process. Wielage et al. [2] carried out bending experiments to measure the deformation velocity and strain rate by using a TEA-CO$_2$-laser with pulse duration of 100 ns. They found that for 50 µm thick Al foil, the maximum strain rates achieve between 1×10^3 and 2×10^3 s^{-1} corresponding to the laser power densities of 0.1 to 0.8 GW/cm^2. Gao et al. [3] developed a finite element model to simulate the micro scale laser dynamic forming process. According to the simulation results, the transient strain rate reaches 1.6×10^8 s^{-1} for copper foil of 10 µm in thickness by using a Q-switched Nd: YAG laser with pulse duration of 5 ns. Zhou et al. [4] employed a Q-switched Nd: Glass laser with pulse duration of 7 ns to replicate micro grid array structures on 15 µm thick Al foil. Based upon the numerical simulation results, they calculated the strain rate of the laser micro manufacturing ranging from 10^6 to 10^7 s^{-1} while the laser power density is in the 0.58 to 1.52 GW/cm^2 range. Compared with the conventional micro punching process, laser-induced shock wave is employed as a flexible punch. Thus, the technical challenges emerging in the conventional micro punching process like the guarantee of the punch/die clearance and precision fabrication of micro punch can be well avoided. Moreover, the laser shock punching process holds the notable advantages of flexibility, high repeatability, fast set-up, and it is suitable for different metal materials. Over the years, the researches focus on the forming

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https://doi.org/10.1016/j.optlaseng.2017.12.009
Received 1 August 2017; Received in revised form 6 December 2017; Accepted 24 December 2017

mechanism of laser direct punching [1] and punching induced by laser-driven flyer [5,6], punching method assisted by polyurethane rubber [7], and fracture mode of metal foil [8].

With miniaturizing the specimen dimensions in micro punching process, the mechanical properties of the individual grains will dominate the formability of ultra-thin metal foil. This means that both the deformation behavior and product quality are directly affected by the initial grain size of metal foil [9]. According to the experimental results in punching of CuZn15 foil, Kals et al. [10] showed that the ultimate shear strength keeps approximately constant for different values of the length scale with an initial grain size of 25 µm. However, while the initial grain size is increased to 110 µm, a rise in the ultimate shear strength can be observed with the miniaturization. Raulea et al. [11] revealed that both the magnitude and profile of the punching force are reproducible for the polycrystalline aluminum foil, but a strong variation of product shape and punching force is shown for single crystal specimens with different orientations. Xu et al. [12] found that the ratio of blanking clearance to initial grain size is one of the main factors to affect micro plastic deformation behavior in micro blanking of brass foil. The ultimate shearing strength reaches an extreme value when the ratio is equal to 1. Fu et al. [13] carried out researches into the initial grain size effect in progressive forming of micro-scaled bulk part by using sheet metals. They found that the length of blanked cylindrical parts diminishes as the initial grain size increases. In addition, the shape of the blanked cylinder becomes irregular and the inclined fracture surface appears when enlarging grain size. Meng et al. [14] further systematically examined the effect of initial grain size on forming quality of the blanked part and the pierced hole in micro shearing process. The results show that the forming quality worsens with the increase of grain size. Based upon the above investigations, it is proved that the initial grain size plays a nonnegligible role in plastic deformation during punching and is responsible for the undesirable changes in forming quality. However, it should be noted that the mentioned experiments mainly focus on the initial grain size effect in micro punching process under quasistatic loading conditions. Limited research attempts have been made to investigate the effect of initial grain size on forming quality of punched holes subjected to laser shock loading. Wang et al. [15] used H62 brass foils to investigate the initial grain size on dimensional accuracy and rollover diameter of punched gears by using laser shock. Their constructive work shows that the best punching accuracy is achieved for brass foil annealed at 350 °C, but in this case the gears have the maximum rollover diameter. In order to deeply understand the initial grain size effect on forming quality of punched parts, the characteristics of the fracture surface morphology and microstructure of holes need a further concern.

It is obvious that the laser power density plays an important role in the interaction of laser pulse with metal foil. Usually, a high laser power density is beneficial to exert the potential of plastic deformation of metal foil and thus is helpful to achieve large deformation amount. However, in some cases the ultra-high laser power density may deteriorate the forming quality of products. Shen et al. [16] and Liu et al. [17] both found that while the laser power density is too high, the deformation depth of formed parts decreases due to the collision between the metal foil and the rigid die followed by springback. In laser shock punching process, for the reason that the tensile strength of metal foil on the order of 10^5–10^7 s^{-1} is difficult to test, the applied laser power density is generally as high as GW/cm^2 in order to ensure complete separation [8]. However, the influence of laser power density on forming quality of punched holes is still not well understood. In this study, the ratio of foil thickness to initial grain size was adopted to represent the relationship of foil thickness and grain size. Three different initial grain sizes as well as three levels of laser power densities were provided, and then laser shock punching experiments of pure copper foil were conducted. Based upon the experimental results, the effects of laser power density and initial grain size on forming quality of holes were discussed via the evaluation of shape accuracy, fracture surface morphology and microstructure.

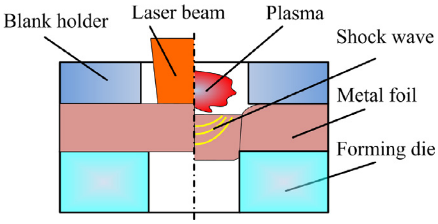

Fig. 1. Working principle of laser shock punching process.

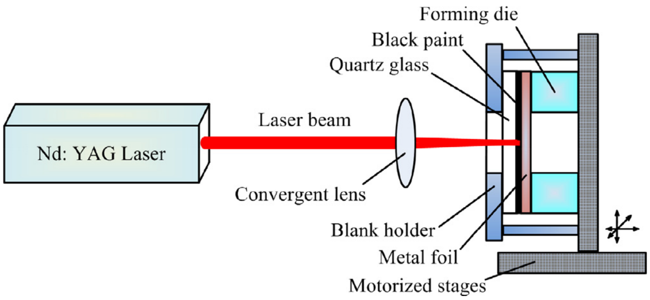

Fig. 2. Experimental assembly of laser shock punching process.

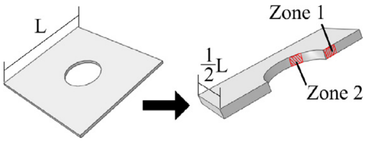

Fig. 3. Preparation of specimens for microscopic analysis.

Table 1
Detailed experimental parameters.

Parameters	Laser beam diameter (mm)	Die hole diameter (mm)	Quartz glass thickness (mm)	Black paint thickness (μm)	Laser power density ($\times 10^{13}$ W/m^2)
Value	2	1.2	2	~50	3.94, 4.38, 4.82

2. Experiments

2.1. Experimental setup

The experimental assembly of laser shock punching process is shown in Fig. 2. The fundamental mechanism and critical processing components can refer to our prior work [8]. One essential component is black paint which acts as an absorbent coating and interacts with the pulsed laser to generate high temperature and high pressure plasma. It has been proved that the absorbent coating can efficiently protect the metal foil from laser ablation. The application of quartz glass as a confining overlay can magnify shock wave pressure up to GPa levels compared with that in the open-air condition [18].

In the experiments, a Q-switched Nd: YAG laser system with a Gaussian spatial distribution beam was employed. The laser wavelength is 1064 nm and the pulse duration is around 8 ns. All of experiments were implemented by a single laser pulse. Laser drilling process was used to fabricate through holes in a stainless steel sheet as forming dies. Before laser shock, the top surface of metal foil was carefully sprayed with black paint. The detailed experimental parameters are listed in Table 1. To accomplish the punching operation and obtain holes with good geometry, the laser beam diameter should be large enough to cover the die hole [19].

After laser shock punching experiments, the dimensions of punched holes were measured by video measuring system (VMS-4030F). The specimens were then cut through the center of holes, as shown in Fig. 3.