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Investigation of the forming pressure and formability of metal foil by laser-driven multi-layered flyer

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ABSTRACT

Metal foil forming by laser-driven flyer (LDF) is a new micro-forming technology. The performance of the flyer is one of the main factors affecting the forming quality of workpiece. Considering the features of this technology, this paper presents a novel multi-layered flyer. Via magnetron sputtering, the absorption layer (titanium) and the ablation layer (aluminum) are produced on the confining medium. The impactor layer is manufactured by special cutting (a micro-punching method) and adhered to the center of the ablation layer by a gluing method. A pressure measurement system is conducted to measure the shockwave forming pressure of the laser-driven flyer, and a series of forming experiments are carried out to investigate the forming ability of the multi-layered flyer. Experimental results show that the multi-layered flyer can enhance the laser coupling efficiency to the flyer and achieve higher forming pressure than the single-layered flyer. Especially, the multi-layered flyer with the nonmetallic impactor layer of 100 μm polyurethane rubber has good forming quality in the laser-driven flyer micro-forming (LDFμF).

1. Introduction

Since laser-driven flyer (LDF) technology is first proposed by the U.S. SANDIA laboratory in the late 1970s, it has been widely used in many research fields such as laser detonation, high-pressure physics, astrophysics and material sciences [1–8]. Recently, with the rapid development of laser technology, laser-driven flyer technology has gradually become an important dynamic high-pressure loading technique [9–13]. Liu et al. has applied this technique to the micro-forming of metal foil and introduced a novel laser indirect shock forming system, which uses LDF as the loading method in micro-forming [14–16]. The technique has been used in micro-hole punching forming [14] and micro-embossing [15]. As known to us, the laser shock micro-forming is also a new material processing technology [17–19]. The efficiency of the technology may be higher than that of the laser-driven flyer micro-forming (LDFμF). In the LDFμF, the laser energy needs to be converted to the kinetic energy of the flyer. The flyer speed will be influenced by the air resistance, so the efficiency of the LDFμF will be reduced to some extent. But, the technology of the LDFμF has some advantages over the direct laser shock forming. The LDFμF technique not only can protect the workpiece from thermal effect, but also can increase the forming pressure. This technology is characterized as non-contact, low cost, and high efficiency and can form high strength or hard shaping materials.

For the research of metal foil micro-forming by LDF, the flyer performance is one of the main factors affecting the formed workpiece quality. As illustrated in Fig. 1(a), Liu et al. has adopted a single-layered flyer in laser indirect shock forming, which is made of pure aluminum foil. However, due to the high reflectivity of aluminum, a large fraction of laser energy is lost by reflection. In addition, this flyer is attached to the confining medium by a gluing method and the binding force is low, so the laser induced plasma could be easily dissipated radially. Besides, because of the direct irradiating of laser, the surface of the single-layered flyer will be damaged, and the flyer is easily fractured in the flying process. These indicate that most of the laser energy is not converted to the kinetic energy of the flyer, so the laser coupling efficiency to the flyer (i.e. the ratio of laser energy to the flyer kinetic energy) is not high, and the integrity of the flyer is also not good. That means that the structure of the flyer should be improved.

In some fields, the multi-layered flyer has been applied to overcome those problems existing in the single-layered flyer [20,21]. Stahl and Paisley [22] presented a method to improve the flyer system by introducing a layer of carbon between the confining medium and the flyer, which can increase the laser absorption efficiency. Farnsworth [23] applied a multi-layered flyer (Al/$A1_2O_3$/Al) to initiate an explosion and it performed substantially better than the pure aluminum flyer. To investigate the equation of state (EOS) of condensed matters, Kadono [24] utilized the three-layered flyer (2 μm Al/90 μm PI/1 μm Ta).

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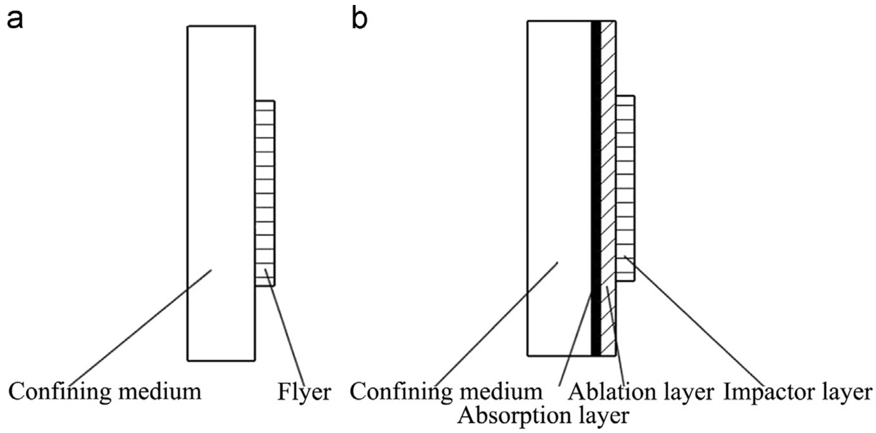

Fig. 1. Schematic diagram of the structure of flyer in the laser-driven flyer technology: (a) the single-layered flyer and (b) the multi-layered flyer.

The laser ablated the aluminum layer and polyimide layer, and the tantalum layer was accelerated as the flyer. The flyer velocity estimated from the acceleration profile was at least 8 km/s. At the same time, the relevant experimental results showed that the planarity and velocities of the multi-layered flyer were generally better than that of the single-layered flyer. Previous studies have indicated that the multi-layered flyer has advantages over the single-layered flyer to some extent.

As illustrated in Fig. 1(b), considering the characteristics of metal foil micro-forming by LDF, this paper presents a novel multi-layered flyer, which is composed of the absorption layer (titanium thin film), the ablation layer (aluminum thin film) and the impactor layer. Compared with the single-layered flyer, the multi-layered flyer can strengthen the binding force in the interface of the confining medium and the flyer, so it can prevent the plasma escaping. Secondly, the integrity of the impactor layer can be assured in the laser-driven flyer micro-forming (LDFμF). Lastly, the laser coupling efficiency to the flyer can be improved. For the multi-layered flyer, the nonmetallic impactor layer of the polyurethane rubber is adopted firstly as the flyer in LDFμF because it has high level of resolution in the submicron ranges. The polyurethane rubber is a hyperelastic material, and generally it is assumed as nearly incompressible during deformation [25]. This rubber is similar to the liquid which has good flow property. If compressed in one direction, it will expand in the other direction, and delivering pressure. This paper aims at demonstrating that the multi-layered flyer can increase the forming pressure of metal foil and improve the forming quality of formed workpiece. The shockwave pressure of LDF is measured by PVDF gauge and discussed accordingly. A series of compared forming experiments are also carried out to study the forming ability of the multi-layered flyer by laser-driven.

2. Multi-layered flyer and experimental design

In order to boost the laser coupling efficiency (i.e. the ratio of laser energy to the flyer kinetic energy) and improve the forming ability of laser-driven flyer micro-forming (LDFμF) technology, a multi-layered flyer is proposed. Titanium is selected as the absorption layer material because of its lower reflectivity and lower vaporization energy. The ablation layer is made of aluminum for its lower vaporization energy [21]. The purity of the titanium target and the aluminum target used in magnetron sputtering is 99.99%, and the chemical composition of the coating film is the same as the corresponding target, as shown in Tables 1 and 2. Through magnetron sputtering, titanium thin film of 12 nm is deposited on the confining medium, and aluminum thin film of 250 nm is deposited on titanium thin film. Fig. 2 shows the microtopography and thickness of thin film which were observed by scanning electron microscopy (SEM) respectively. For the multi-layered flyer, the impactor layer is defined as the component which directly impacts the workpiece. Through special cutting (a micro-punching method), the aluminum or the rubber with the diameter of 3 mm is adopted as the impactor layer and adhered to the center of the ablation layer using a low viscosity epoxy (Loctite Hysol), and around 10 lbs of driving force is placed on top during the 24 h curing process [5].

Table 1
Chemical composition of 99.99% Ti film.

Composition	C	N	O	Al	Bi	P	Mo	Cr	Mn	Fe
Mass (μg/g)	72	0.73	101	3.9	3.9	0.09	2.1	3.5	0.18	7.1

Table 2
Chemical composition of 99.99% Al film.

Composition	Fe	Si	Cu	Zn	Ti
Mass (μg/g)	2.7	2.6	2.2	2.3	1.6

The experimental setup is shown in Fig. 3. A short pulse Spitlight 2000 Nd-YAG laser with Gaussian distribution beam is used. The key parameters are as follows: pulse width (8 ns), wavelength (1064 nm), pulse energy (80–2000 mJ). The spot size is varied by adjusting the defocusing, which could be achieved by adjusting the working platform. The defocusing is defined as the distance between the focus of the laser beam and workpiece, whereby the value is positive when the focus is above the workpiece, while is negative when the focus is below the workpiece surface. In order to get the desired spot diameter (about 2 mm), the defocusing is selected as -10 mm. The medical cover glass spacer is fixed between the confining medium and workpiece which can provide a flying distance for the flyer. The thickness of the glass spacer is 200 μm, and a Φ6 mm hole is machined in the center of the glass. Because of the higher shock impedance, K9 glass is selected as the confining medium, with the diameter of 40 mm and the thickness of 1.56 mm, for it can prolong the shockwave pressure duration.

The process of metal foil micro-forming by laser driven multi-layered flyer is shown in Fig. 4. When a short and intense laser pulse irradiates the absorption layer of the multi-layered flyer, the absorption layer will vaporize as a high-temperature and