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Experimental research on laser shock forming metal foils with femtosecond laser

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ABSTRACT

Laser shock forming metal foils with femtosecond (fs) laser has been investigated experimentally in this article. A new transparent material was used as confining layer. Two destroying mechanisms of the confining layer have been observed and analyzed. With appropriate processing parameters, we have validated that macro plastic deformations (micro dents) can be formed on metal foils through fs laser-induced shock wave. Surface morphologies and 3D profiles of dents were measured. Results show that there exists a relatively optimum pulse range for obtaining better shock effects. Too short pulse duration will induce serious nonlinear absorption of confining layer, while too large pulse duration will decrease light intensities. Both are detrimental for improving laser shock effect. One abnormal phenomenon about the influence of impact times on dent depths has been found. Through analysis and experiments, we analyzed that loose constraint condition of samples led to flattening effect on deeper dents and then decrease the dent depths. Confining layer can significantly enhance laser shock effect and improve plastic deformation, which is same as ns laser. The new confining layer has been proved to be suitable for fs laser shock forming.

1. Introduction

The irradiation of intense laser on solid material can induce mechanical shock wave through rapid formation and expansion of dense plasma on the material surface. Then the strong shock wave propagates into the material resulting in microstructure change, plastic deformation, material spallation, compressive residual stress and so on. So laser driven shock wave has been widely used in manufacturing and material processing, such as strengthening metal surface (laser shock processing, LSP) [1–3], directly forming metal parts (laser shock forming, LSF) [4–6], measuring the bond strength between film and substrate (laser spallation) [7–9]. Nonetheless, most of the above applications mainly applied nanosecond (ns) lasers [1–9]. In fact, femtosecond (fs) laser, as a more intense laser, can generate more higher amplitude shock wave on material surface, which has been verified earlier [10–12]. However, manufacturing through fs laser-induced shockwave has not been attached as much attention as ns lasers, because of its too short laser pulse duration (meaning that the pressure duration is also too short). Its machining ability has once been doubted [13,14].

In recent years, with the development of microelectronics and micromechanics, femtosecond laser has found its unique advantages in micromachining or micromanufacturing due to its high precision and lacking of heat affected zone [15,16]. So it is in the field of laser shock techniques [13,18,19]. Some researchers have begun explorations on fs laser shock processing or forming. Hitoshi Nakano et al. carried out laser shock peening of stainless steel and found that with appropriate parameters, fs laser shock processing can also obtain prominent strengthening effect just like ns laser shock processing [13]. Benxin Wu developed a physics-based predictive model to simulate LSP with fs laser (fs-LSP), and provide a further verification of the feasibility of fs-LSP [17]. About laser shock forming, Japanese researchers have made great progresses, realizing fs laser peen forming to bend sheet metal, and further applying elastic pre-bending to enhance bending efficiency [18,19]. Manfred Dirscherl also discovered material micro bending by ultrafast laser induced shockwaves through theoretical and experimental investigations [20].

Although the feasibility of fs laser shock processing and forming have been verified and confirmed, micro manufacturing by fs laser-induced shock wave is relatively complicated due to its much higher pressure and shorter interacting time. Many microscopic processes of fs laser induced shock wave are distinctively different

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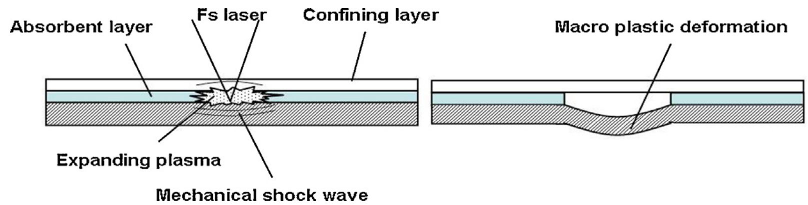

Fig. 1. Principle of laser shock forming.

from ns laser. For example, in contrast to ns laser, laser irradiation has ceased before plasma expansion, so fs laser-induced shock wave cannot be supported by laser energy [21]. Generally speaking, a systematic research about laser shock technique with fs laser has not been conducted to date, and related research work and reports are also rarely.

In this paper, we report the experimental results of laser shock forming of metal foils with femtosecond laser. A new transparent material was used as confining layer for fs laser-induced shock wave. The nonlinear absorption of transparent confining layer has been observed and its influence on laser shock effect has been revealed. The influences of fs laser pulse duration, impact times, constraint conditions of specimens, and confining layer on fs laser shock forming have been examined.

2. Mechanisms of fs laser shock forming

As shown in Fig. 1, focused fs laser irradiates on the surface of target. Laser beam penetrates the transparent confining layer to irradiate on the absorbent layer, which absorbs laser energy, evaporates and ionizes into plasma. The expansion of plasma launches high amplitude shock waves into the material inducing plastic strain. For laser shock forming, the target is usually metal sheet or metal foil, which is much thinner than that of laser shock processing, and the bottom of the target is not restricted. So with appropriate process parameters, the entire target can be plastically stretched or drawn to form certain macro plastic deformation. Laser shock forming with nanosecond lasers has been widely researched [4–6]. In this article, we will study fs laser shock forming.

3. Experimental

Fig. 2 shows the schematic diagram of experimental setup. The laser used for experiments was a standard chirped Ti: Sapphire system comprising a seed laser and an amplifier, with a central wavelength of about 800 nm and the maximum energy about 550 μJ. Laser pulse frequency could be changed from 1 Hz to 1 kHz. In our experiments, we only used 1 Hz for conveniently controlling the laser impact times on one point. The normally used pulse duration of this laser is about 100 fs. In this experiment, for investigating the influence of laser pulse duration on shock effect, laser pulse duration was changed between 100 and 800 fs through changing the positions of compressor and stretcher gratings within the laser system. The diameter of output laser beam from laser is about 6 mm and then laser was focused onto the specimens by a focusing lens with 1 m focal length. The specimens were placed behind the focal point. Through changing the distances between specimens and focal point, different laser spot sizes on the specimens could be obtained. For facilitating the plastic flow during fs laser shock forming to promote macro plastic deformation formation, metal targets were fixed on the supporting seat only through one adhesive point of double-faced adhesive tape as shown in Fig. 2. There is a big round hole with the diameter *D* about 5 mm in supporting seat, to leave space for stretching or drawing plastic deformation. In this article, laser spot sizes on metal targets are about hundreds of micrometers, so *D* is much greater than laser spot sizes. The hole edge nearly has no effect on forming of macro plastic deformation. So the technique researched in this article is actually laser shock forming without mold.

Rolled pure copper foils and aluminum foils with the dimensions of about 15 mm × 15 mm were used as metal targets. We used two kinds of thickness: 20 μm and 30 μm in our experiments. To enhance the formability of the specimen, Cu foils were annealed at 500 °C for 1 h and Al foils were annealed at 350 °C for 10 min. Then the specimens were exposed to furnace cooling to room temperature. To avoid oxidation, the heat treatments were conducted in vacuum condition.

Black paint was chosen as surface absorbent layer. The commonly used confining layers are water or glass. In this article, we used another new material-gum water (a commercial office product and the main ingredient of it is polyvinyl alcohol) to confine expanding plasma. Before laser shock experiment, the foil surfaces were firstly sprayed black paint as absorbent layer. After the paint dried, the gum water then was spread above the paint. Laser shock experiments were conducted after gum water dried. The thickness of dried paint layer was about 15 μm and the dried gum water layer about 50 μm measured by microcaliper. To guarantee gum water was qualified as confining layer, the absorption spectrum of liquid gum water has been measured as shown in Fig. 3. The linear absorption of gum water at 800 nm is very weak, which means that gum water is suitable as confining layer for laser shock technique.

Various analytical techniques were used for characterization of samples before and after laser shock forming. After laser shock experiments, surface morphologies of samples with absorbent

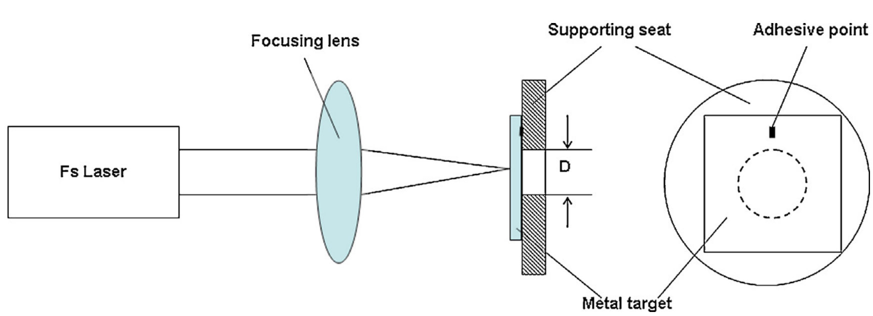

Fig. 2. Schematic illustration of experimental setup.