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Experimental and numerical investigation of laser shock synchronous welding and forming of Copper/Aluminum

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ABSTRACT

A novel laser shock synchronous welding and forming method is introduced, which utilizes laser-induced shock waves to accelerate the flyer plate towards the base plate to achieve the joining of dissimilar metals and forming in a specific shape of mold. The samples were obtained with different laser energies and standoff distances. The surface morphology and roughness of the samples were greatly affected by the laser energy and standoff distances. Fittability was investigated to examine the forming accuracy. The results showed that the samples replicate the mold features well. Straight and wavy interfaces with unbonded regions in the center were observed through metallographic analysis. Moreover, Energy Disperse Spectroscopy analysis was conducted on the welding interface, and the results indicated that a short-distance elemental diffusion emerged in the welding interface. The nanoindentation hardness of the welding regions was measured to evaluate the welding interface. In addition, the Smoothed Particle Hydrodynamics method was employed to simulate the welding and forming process. It was shown that different standoff distances significantly affected the size of the welding regions and interface waveform characteristics. The numerical analysis results indicated that the opposite shear stress direction and effective plastic strain above a certain threshold are essential to successfully obtain welding and forming workpiece.

1. Introduction

With the increasing demands in the fields of electronics, energy generation/storage and medical devices, the miniaturization of components become the current trend. Micro-forming technology related to micro metal parts is becoming increasingly important. However, the traditional miniature parts manufacturing processes cannot meet the industrial demand due to their high cost, low processing efficiency and the low formability of the metals.

Laser shock forming, which combines the advantages of high strain rate embossing and laser shock metal forming, displays excellent capability for the fabrication of micro components in micro electro mechanical systems (MEMS). It can increase the ductility of brittle and hard-to-form materials. In addition, with ultrahigh strain rates of approximately 10^6 to 10^7 per second during the process, the ability to form complex shapes is improved because the inertia effect contributes to the significant improvement in the ultimate plastic strain [1,2]. Cheng et al. [3] conducted a microscale laser dynamic forming (uLDF) experiment, and the results revealed that during the laser-induced shock wave forming process, the forming ability of materials was higher than quasi-static forming. Liu et al. [4] investigated the micro-embossing process and the emergence of a fracture along the edge of the micro-mold, analyzing the relationship between the strain states and thickness distribution along the cross-section of the micro-channel. Li et al. [5] studied the fracture mode and forming limitation of laser dynamic forming (LDF) and extended single-pulse laser forming into multi-pulse laser forming. Ye et al. [6] studied the plastic deformation mechanism of mold-free microforming by utilizing fs laser shock and investigated the influence of pulse durations, clamping modes and impacting times on deformation performance. Wang et al. [7] presented a novel laser shock forming (LSF) technique for the plastic forming of pure copper and titanium sheets with a forming/blanking compound die.

There is a growing recognition that multi-material assembly, especially the joining of dissimilar metals, is of great significant and interest. Micro-parts can take advantage of both metals' characteristics and thus acquire comprehensive mechanical properties. Impact welding, as a solid state and collision welding process, is among the most efficient methods to meet these demands. Impact welding is well recognized for its ability to directly join a wide variety of both similar and dissimilar metals [8]. The remarkable advantage of impact welding is that it can join metals with large melting point gaps. In addition, it can minimize the

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formation of intermetallic phases and reduce the heat-affected zone, which develops easily when using conventional welding methods. Generally, impact-welding processes include explosive welding (EXW) [9,10], magnetic pulse welding (MPW) [11,12], vaporizing foil welding [13,14] and hydrogen energy-based impact welding [15]. They all share the same basic principle as impact-driven solid state welding but are applied at different length scales. Explosive welding is well suited for large planar interfaces, up to meters in extent. However, it would not be a good choice when the materials are small and thin. Magnetic pulse welding can provide linear and circular welding, but the equipment limits the total stored energy and thus typically restricts the weld lengths to widths of millimeters to centimeters. In addition, this method relies on the intrinsic electrical conductivity of the flyer plate. Recently, Vivek [14] investigated vaporizing foil welding and successfully achieved the welding of aluminum to copper and stainless steel by a vaporizing foil actuator. Gracious [15] studied hydrogen energy-based impact welding and found the nosed flyer billet angle have a significant influence on the wavy bonding patterns in the welding interface.

With the rapid development of laser techniques, laser-induced shock waves have been widely used as a loading method in laser impact welding. Laser impact welding has attracted increasing attention, and many exploratory investigations have been performed. Daehn and Lippold [16] proposed laser impact welding (LIW) and developed low-temperature spot impact welding. One distinctive advantage is that it appears applicable to relatively thin samples and length scales. Wang et al. [17] studied the LIW process and focused on the investigation of three different geometric arrangements of the base plates, flat, angled and corrugated, and then tested the effect of the backing material on the launch efficiency and collision velocity during the welding process. However, the cost of manufacturing different shapes of substrates is high. Wang et al. [18,19] conducted an experimental study with similar and dissimilar materials, and both aluminum to aluminum and aluminum to copper were successfully welded. In addition, the wavy morphology and hardness of the welding interface were observed and measured.

The processes for fabricating composite parts are mainly divided into two steps. Primarily, traditional methods are utilized to weld dissimilar metal materials, and the composite materials are used to form the workpiece. However, reports of completing the welding process and forming process of metal sheets in a single procedure are rare. Zhang [20] used a high-speed projectile to strike two adjacent metal sheets and forced them into a die/pin setup. The results showed that the metal sheets could be partly welded and successfully duplicated the shape of the die/pin.

This study introduces the laser shock synchronous welding and forming process of copper and aluminum, which can complete the welding and forming process in a single process. The objective of this study is to focus on the relationship between microstructure and technical parameters. A series of experiments were conducted with different laser energies and standoff distances. The welding and forming samples were examined in terms of their morphology, surface roughness, fittability and welding interface and other features. In addition, Smoothed Particle Hydrodynamics method was applied to study the mechanism of the laser shock synchronous welding and forming process.

2. Experimental setup

As shown in Fig. 1(a), the basic concept of the laser shock synchronous welding and forming process is schematically

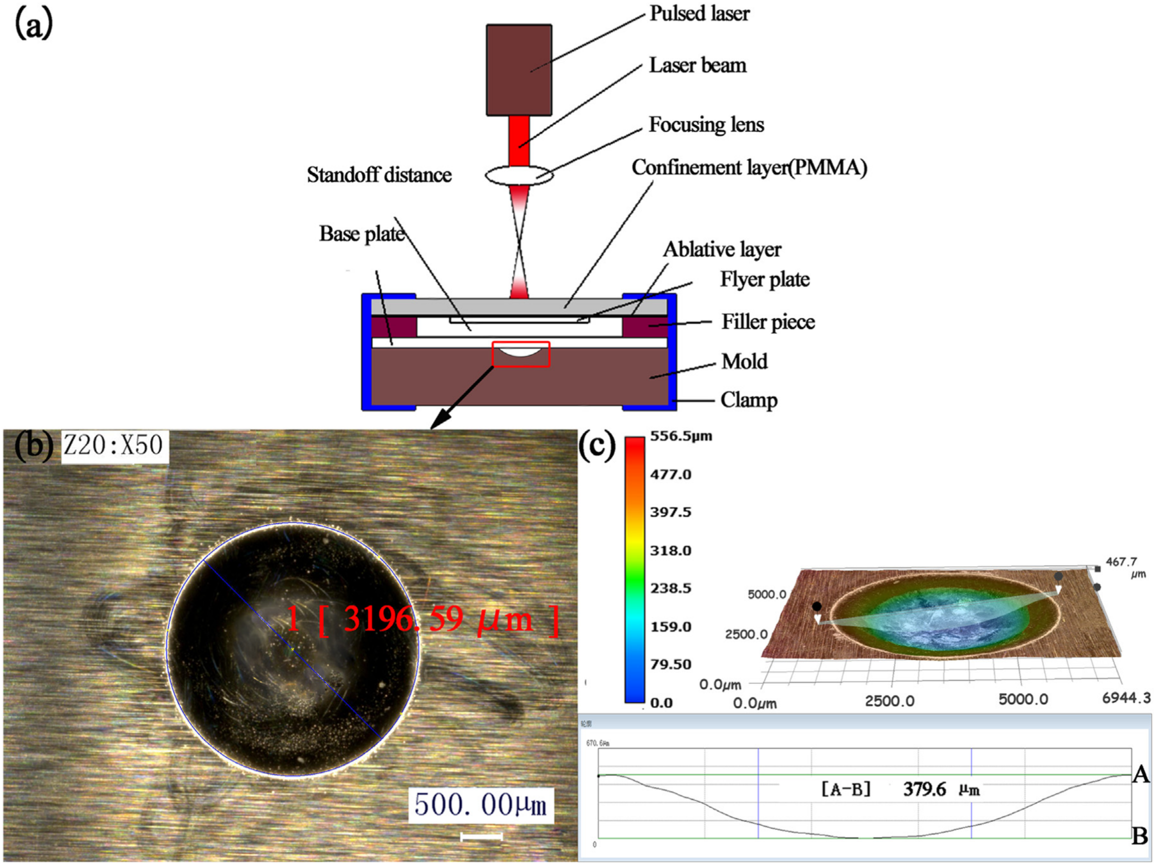

Fig. 1. Schematic diagram of laser shock synchronous welding and forming process: (a) schematic diagram of setup; (b) 2D profile of the mold; (c) 3D profile of the mold.