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Numerical simulation of laser impact spot welding

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ABSTRACT

Laser impact spot welding (LISW) is a relatively novel high-speed impact welding technology. It has obvious advantages in welding dissimilar metal foil plates which have a large difference in melting point. However, the bonding mechanism of laser impact spot welding and dynamic mechanical behavior during LISW are difficult to be revealed through experiments or theories. In this research, a systematic numerical simulation study of laser impact spot welding was conducted by using smooth particle hydrodynamics method. The results showed that the jet mainly originated from a thin layer of flyer plate (about 1 μm thick). It proved that the jet formation is an important condition for the solid-state welding. With the increase in impact velocity of the flyer plate, the bonding interface of Al/Cu and Ti/Cu became flat, tiny smooth wave and swirl-like wave, respectively. The local melting may occur when the impact velocity was large enough. In addition, the flyer plate would periodically penetrate the base plate under the combined action of impact pressure and shear stress, which would lead to the formation of bonding interface waves. Furthermore, the springback of the flyer plate and the spallation of the base plate were also simulated.

1. Introduction

Laser impact welding is a novel high-speed impact welding technology. During laser impact welding, the high-pressure shock wave induced by intense pulse laser is utilized to drive the flyer plate to collide with the base plate. The basic principle is illustrated in Fig. 1 [1,2]. The intense pulse laser beam focused by the lens will form a certain spot diameter. Then, the absorbent layer under laser irradiation evaporates instantly at the high temperature. At the same time, the vapor also absorbs the laser energy and it forms a high-temperature and high-pressure plasma between the confinement layer and the flyer plate. The plasma continues to absorb the laser energy and expands rapidly between the flyer plate and the confinement layer. Thus, a high surface pressure is formed under the action of the confinement layer, which propagates into the flyer plate as a shock wave [3]. The plastic deformation occurs in the flyer plate impact area when the shock wave pressure exceeds the dynamic yield strength of the flyer plate. Then, the flyer plate collides with the base plate at a high speed, resulting in solid state welding.

Recently, researchers have conducted numerous works on experimental investigation of laser impact welding. Zhang et al. [4] explored the laser impact welding process of aluminum alloy 1100 and low carbon steel 1010. These authors found that the welding joint had a relatively gently curved bonding interface. Their research verified the feasibility of laser impact welding of dissimilar metal materials. Subsequently, Wang et al. [5,6] optimized the flyer plate system (including the confinement layer, absorption layer and connecting layer) in the laser impact welding device. They successfully welded the dissimilar metal foil sheet Al/Ti. Their results showed that the bonding interface of Al/Ti was wave-like and there was no obvious elemental diffusion at the interface. In addition, grain refinement occurred on the base plate. Wang et al. [1] proposed an angle-type laser impact welding method, as depicted in Fig. 1(a). They explored the welding process of dissimilar metal foils, such as Al/Cu and Al/Ti. These authors found that the interface of Al/Cu was flat, while the interface of Al/Ti was tiny smooth wave. In addition, they found that the material hardness value in the welding area was higher than the raw material. Afterward, Wang et al. [2,7] proposed a parallel laser impact spot welding method, as displayed in Fig. 1(b). They successfully welded dissimilar metal foil plates Cu/Al and Ti/Al by LISW. Then, the influence of different welding parameters on welding quality was carefully analyzed [2]. Liu et al. [8] proposed a novel laser high speed impact spot welding method. They welded Ti and Cu metal foils with laser impact spot welding and observed the microstructure of the bonding interface by SEM and EDS.

On the one hand, the laser impact spot welding process is a complicated process. On the other hand, the entire impact welding process

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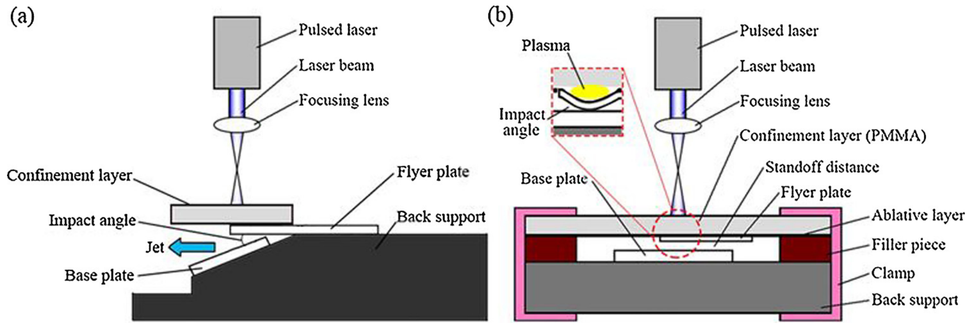

Fig. 1. Diagram of the laser impact welding: (a) Angle welding setup [2]; (b) Parallel welding [2].

takes a very short time. Thus, the existing experimental conditions can not reveal the welding mechanism and the dynamic response of the flyer and base plates. If the mechanisms of laser impact spot welding are not thoroughly revealed, it is difficult for LISW to be applied in the industrial field. Therefore, the use of numerical simulation research for laser impact spot welding is very necessary. Laser impact spot welding is a kind of high speed impact welding (HSIW). In previous researches, various simulation methods were used to study high speed impact welding. Lagrangian method is one of the most widely used simulation methods and its main feature is the ability to accurately track material boundaries and interfaces [9]. However, this method has its own defects when dealing with large deformation of materials. Some specific features in the impact welding process cannot be obtained due to the mesh distortion and deterioration. In addition, excessive mesh distortion will make the calculation impossible and eventually cause premature termination of the calculation [10,11], which will lead to the failure to form waves in the simulation process [12]. Eulerian method is another commonly used simulation method, which can handle large deformations in global motions [13]. However, the interface is constantly being redefined as the mass moves through a fixed Eulerian mesh, which results in different material points for each node in the computation cycle. Thus, it is difficult to track the history of materials in the Eulerian model [14]. The Arbitrary Lagrangian–Eulerian (ALE) method combines the advantages of Lagrangian and Eulerian methods. It improves the accuracy of the simulation under large deformation conditions. However, the ALE method cannot accurately capture the formation of the interface waveform, and cannot continuously simulate the jet formation process [15]. In addition, the ALE method cannot predict the formation of melting regions [16].

It can be found from the above studies that various mesh-based numerical methods have inherent limitations, such as, cases with moving interfaces and mesh distortion. Thus, researchers begin to look for other types of simulation methods. Meshless particle methods have the ability to model large deformations and rapidly moving interfaces. Therefore, this method may be applied to the field of high speed impact welding [17]. Smoothed particle hydrodynamics (SPH) method is a common meshless particle method. In the simulation, the SPH method can capture the movement of the interface and simulate the deformation of the material, which can reproduce the waveform of the welding interface and the formation of jet flow [13]. Furthermore, there is no need to add the mesh during the whole calculation process, which not only can greatly improve the calculation efficiency, but also avoid the mesh distortion problem in the large deformation. Therefore, the method has its particular advantages in dealing with problems such as high speed collisions. Previous researchers have used the SPH method to simulate laser impact welding. Wang et al. [2,18] used SPH method to simulate the laser impact welding process. In those studies, they discussed the influence of impact velocity on the weld interface. However, their numerical simulation was not systematic. Wang et al. [2] performed a simple simulation of laser impact spot welding. They only simulated the pressure distribution, shear stress distribution, and effective plastic strain in LISW. Wang et al. [18] investigated the laser impact synchronous welding and forming process of copper/aluminum and got the simulation of the welding interface morphology by SPH method. However, they did not explore the formation mechanism of waves and the formation process of jets. Although they studied the pressure, shear stress distribution and effective plastic strain, they did not analyze the temperature distribution on both sides of the interface.

In this study, the SPH method was used to systematically simulate and analyze the laser impact spot welding process. In this simulation, not only the LISW process was observed at different time points, but also the formation process of jets during the welding process was simulated. The interface morphology and impact pressure distribution of Al/Cu at different impact velocities were also simulated. In addition, the laser impact spot welding mechanism was studied by simulating the welding interface wave formation process. The temperature distribution on both sides of the interface was analyzed by SPH method. The temperature simulation results were used to compare with the melting phenomenon in the experiment. Furthermore, the springback phenomenon of flyer plate and the spallation phenomenon of base plate were revealed, respectively.

2. Numerical simulation preparations

2.1. Simulation software and SPH method introduction

The current numerical simulation software with SPH algorithm module mainly includes ANSYS /LS-DYNA and AUTODYN. Both of them can avoid mesh distortion and deterioration. However, compared with AUTODYN software, ANSYS /LS-DYNA software can not establish the SPH model directly. It needs to establish the finite element mesh model through ANSYS and then convert it into a SPH model. The operation is extremely inconvenient. At the same time, the setting of artificial viscosity is critical to the numerical problem of high speed impact dynamics. However, there is no detailed setting in ANSYS/LS-DYNA. Therefore, this paper uses SPH method in AUTODYN to simulate laser impact spot welding.

Smooth particle hydrodynamics (SPH) is a meshless particle method based on Lagrangian algorithm. In this SPH simulation, a set of interacting particles is used to describe the fluid motion. Each particle can carry various physical quantities such as speed and quality. The mechanical behavior of the whole system is obtained by solving the dynamic equations of the particle group and tracking the motion orbit of each particle. Therefore, the motion of discrete particles with mass and density information can be seen as a fluid motion process in the flow field. On the one hand, the meshless numerical simulation method can avoid the mesh distortion or reconstruction that may occur in the process of simulating large deformation and high strain rate of materials. On the other hand, it also helps to improve the efficiency of calculation. Therefore, the SPH simulation method was used in this paper.