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Research on the impact velocity of magnetic impulse welding of pipe fitting

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ABSTRACT

Magnetic impulse welding, which is uniquely advantageous in welding heterologous pipe fittings, is a new welding technology based on high-speed magnetic impulse shaping and solid-phase diffusion welding. The impact velocity of the welding points of Al–Fe heterologous pipe fittings was studied by combining numerical simulation and technological test with the assistance of constitutive relations of 3A21Al alloy under a high strain rate. The momentary movement speeds when the outer tube (A1) impacts the inner tube under four different voltages were analyzed to obtain the critical voltage for welding inner and outer tubes. The speed of the welding points of the outer tube noticeably increased with the rise in the discharge voltage. The weld interfaces of both the inner and outer tubes produced regular zigzag waves when the impact velocity reached 350 m/s. The energy spectrum analysis revealed that pipes undergo severe deformation under high-speed impact, and the increased temperature enhances the activity of the atoms among other elements, thus producing a surface mass flow under strong impact and granulated substances.

1. Introduction

Recently, the problem of lightweighting has gained more attention from around the world [1], with the increasing importance of employing new measures to solving it to improve the application of aluminum products. Notably, the application of the "steel–aluminum" dual metallic welding structure has become the preferred alternative to lightweighting in industrial production, which surely involves the connection between aluminum and steel [2].

Since the 1960s, scholars from different countries have performed detailed research on the connection between the structures of aluminum and steel. The welding of the aluminum–steel structure involves various methods used in the field of welding [3], such as explosion welding [4], friction welding [5], brazing welding [6], and laser beam welding [7].

Some welding techniques such as electric resistance welding (ERW) and brazing welding are carried out under high temperatures, which produces brittle intermetallic compound on the interface of the aluminum–steel structure, thus reducing the quality of the welding point. On the other hand, explosion welding is a technique that is commonly applied in the solid phase connection between same metals (e.g. steel–steel, Al–Al, Cu–Cu) or different metals (e.g. Al–steel, Cu–steel). However, this technique utilizes explosives for its energy supply and the resulting powder charge is very complicated, thus requiring a higher labor intensity and production costs, making it difficult to achieve automatic production.

Magnetic pulse welding (MPW) technologies based on solid state impact or collision welding can provide linear or circular welds, which has been established as fast, reliable and cost-effective. Meanwhile, the magnetic pulse welding technology is characterized as a very short welding process that is accomplished within a microsecond. Furthermore, the increased temperature caused by the heat of the inner and outer tube impact is not enough to produce chemical compounds composed of Al and Fe. Therefore, no metallic compounds will be produced in the transition zone, and this method will not reduce the quality of the welding point significantly [8]. In addition, the use of magnetic pulse welding technology has many advantages, such as having controllable discharge energy, high production efficiency, and a unique advantage in fitting welding.

A typical MPW system includes a power supply, a switching system, and a coil. The parts to be welded are inserted into the coil with the capacitor bank being charged, and then the switch is triggered in transient time, the current flows through the coil. After that, the current is applied to the coil, a high-density magnetic flux is created around the coil, and as a result an eddy current is created in the workpieces. The eddy currents oppose the magnetic field in the coil and a repulsive force is created. This force can drive the workpieces together at an extremely high rate of speed and creates a type of weld.

Over the past decade, MPW has been successfully applied for tube to tube impulse welding with both similar and dissimilar

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metals [9]. For example, Hokari et al. welded aluminum tube to copper tube, and found it was more susceptible to deform outer tube made of aluminum than copper [10]. Aizawa et al. investigated the welding process parameters and reported characteristics of dissimilar materials (Al–Fe) [11]. Ben-Artzy et al. found that intermetallic phases (IMP) of different compositions were created during welding of the Al–Mg couple by rapid solidification of a thin melted layer at the interface [12].

Previous studies on magnetic pulse welding were focused on factors such as parameter optimization [13], electromagnetic force [14], interface appearance [15], finite element simulation [16], and organization, among many others [17]. Problems encountered during the welding process, such as the relationship between the movement speed of the outer tube moving toward the inner tube and the discharge voltage, the impact of movement speed of the outer tube on welding strength, etc. were left out.

In the present study, numerical simulation mean and the constitutive relation of a 3A21Al alloy under dynamic load established by the Hopkinson bar test were applied to study the voltage impact on electromagnetic field, magnetic field force, and on the movement speed of the outer tube. Then, a high-speed camera system was utilized to measure the movement speed of the contour of the outer tube edge during magnetic impulse welding under different voltages. The results were compared with those obtained from the numerical simulation. Finally, the impact of the movement speed of the outer tube on the strength of the magnetic impulse welding point and on the microstructure was analyzed.

2. Experimental material and method

2.1. Experimental material

Steels 20 and 3A21 (Al alloy) were selected as materials of the inner and outer tubes, and the sizes of which are shown in Table 1. The tubes were heated to the annealed condition to soften the outer material. The inner tube must have an angle of 4° in the joining zones to establish a better welding effect. The mechanical properties of the 3A21 after the annealing process are shown in Table 2.

2.2. Experimental method

2.2.1. Magnetic impulse welding equipment

A 20-kJ electromagnetic forming machine with a capacitance of 100 μF and a maximum charging voltage of 20 kV was used as the test equipment. The coil was wound from the rectangular wire with a cross-section measuring 7 mm × 5 mm. Considering that the overlap joint end is 15 mm long, and that the turns of the coil are restricted, the field shaper structure whose main material is red copper was applied. Fig. 1 shows the assembly and the structure of the field shaper.

2.2.2. Measuring system

A high-speed camera system (FASTCAM SA5 1000 K-M2) was used to measure the movement of the outer tube, as shown in Fig. 2. The FASTCAM SA5 has a maximum shooting speed of one million frames per second and the shortest exposure time of 370 ns. With respect to the speed of the pipe-pipe welding point, the instantaneous speed before the outer tube comes into contact with the inner tube is the most important factor to measure. However, during measurement, the outer tube produces a different axial deformation that will cause other positions to collide and produce sparks even before the measurement point comes into contact with the inner tube. The measurement result will thus be influenced directly. Therefore, the inner tube was removed, and only the outer tube was installed during measurement.

The pictures recorded by the high-speed camera were imported into the AUTOCAD software, and the inner wall diameters of the outer tube in different moments were measured using the label function of the AUTOCAD software. To guarantee the accuracy of the measurement, a circumference of 45° was taken as intervals, and four directions were selected for the measurement. The average value was then obtained (Fig. 3).

Table 1
Sizes of inner and outer tubes.

Material	Outer diameter (mm)	Inner diameter (mm)	Thickness (mm)
3A21-O	20	18	1
Steel 20	15.2	8	3.2

Table 2
Mechanical properties of 3A21 after annealing.

Yield strength (MPa)	Tensile strength (MPa)	Poisson's ratio
42	97	0.33

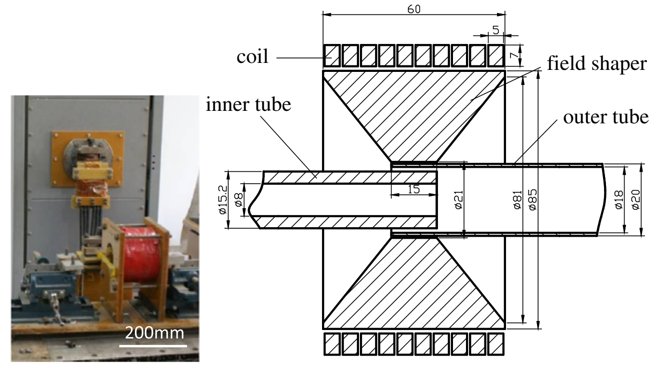

Fig. 1. Test equipment and installation.

2.3. Establishment of a finite element model for electromagnetic field analysis during magnetic impulse welding

2.3.1. Coupling method selection

The electromagnetic welding process involves multi-disciplinary crossing, and it is unable to establish and solve the coupled equation between structural changes and electromagnetic fields during deformation [18]. As a result, current studies are focused mainly on electromagnetic field analysis and workpiece deformation analysis [19]. This paper applied the loose coupling method to establish the finite element model. Using the finite element software ANSYS as the platform, the electromagnetic field was determined using the ANSYS/Multiphysics module, thus obtaining the space-time distribution of the magnetic pressure. Furthermore, the deformation of the outer tube was analyzed through the ANSYS/LS-DYNA module, with the magnetic pressure serving as the boundary condition. The flow chart of the simulation is shown in Fig. 4.

2.3.2. Electromagnetic field analytical model

In ANSYS/Multiphysics, a circuit can be directly connected to the current supply in the finite element area through one share node or a group of share nodes to achieve coupling. Coil, field shaper, inner and outer tubes, and air section applied the SOLID117 unit with a circuit-magnetic coupling function for gridding dividing. During the electromagnetic welding, air dielectric can be regarded as an isotropic homogeneous medium with infinite