A Study on the Critical Thickness of the Inner Tube for Magnetic Pulse Welding Using FEM and BEM

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Abstract

Due to high efficiency and quality in welding dissimilar metals, Magnetic Pulse Welding (MPW) has attracted much attention. In this study, 3A21 aluminium alloy used as outer tube was welded to 20Fe tube by MPW. In order to investigate the critical thickness of the inner tube (20Fe) which is subjected to huge impact pressure from the outer tube (3A21), both numerical simulations and experiments were carried out.

For the purpose of investigating the critical thickness of the inner tube under various impact velocities, four discharge voltages (9 kV, 11 kV, 13 kV and 14 kV) were employed in the MPW experiment. The diameters of inner tube at different locations were measured to obtain its plastic deformation at various discharge voltages. The simulations considering the coupled effects of the mechanical, thermal and electromagnetic process were performed to research the impact velocity and deformation of tubular fittings in the electromagnetic module (EM) in LS-DYNA. An inverse method was proposed to find the dynamic yield stress of inner tube, and the predicted yield stress was then employed in models with critical thickness. Both of the impact velocity and deformation were verified experimentally.

Keywords

Magnetic pulse welding, Dissimilar metals, Boundary element method

1 Introduction

With the globally increased energy prices and with strict environment regulations, severe limits have been made for industrial enterprises to increase energy efficiency and reduce carbon emissions. Thus energy-efficient and environmentally friendly technologies are becoming increasingly important in manufacturing. Due to its well controllability, no pollution and high efficiency, the use of magnetic force in industry has attracted much attention. For decades now, the application of magnetic force has been extended to areas such as forming, cutting, process combinations and magnetic pulse welding (MPW) (Psyk et al., 2011).

As a solid phase welding process, MPW is usually used for the welding of dissimilar metals. Due to the complexity of the multi-field coupling of MPW, many efforts have been made to investigate the electromagnetic process with numerical simulations. Meng et al. (2015) investigated the effect of process parameters of MPW on the mechanical and microstructure properties of dissimilar metal joints of 6063-O and 20 Fe, and finite element method (FEM) was used to find the proper discharge voltages. Simulations based on ANSYS/LS-DYNA software platform were carried out by Fan et al. (2016) to study the deformation of bi-metal tubes in MPW cladding; results have showed that the plastic deformation of flyer tube was mainly decided by the inclined angles. FEM was employed by J. Y. Shim et al. (2011) to analysis the interaction of work-piece and coil in MPW process. According to Xu et al. (2013), the impact velocity of MPW of pipe-fitting was simulated using ANSYS/LS-DYNA and the simulation was verified by experiments. Kore S D et al. (2010) used the commercial software ANSYS/EMAG and ABAQUS to study the impact velocity and pressure profile on the work-piece, and a criterion for the weld formation in the MPW process was obtained based on the simulation.

Previous studies mentioned above were mainly using FEM to investigate the effect of process parameters on the forming of MPW. Few reports have been found to study the effect of structural parameters, especially the thickness of the tube of MPW with a boundary element method (BEM). In the present study, the critical thickness of inner tube suffering impact load was explored through numerical simulations and experiments. Numerical simulations were performed with a combined FEM-BEM method through an electromagnetic (EM) module in LS-DYNA, and the impact velocities of the outer tubes and deformation of the inner tubes in the MPW process at different discharge voltages were studied. A reverse method was proposed to obtain the material parameters of the inner tubes suffering impact pressure, and the predicted yield stress was then employed in simulations. The impact velocities of the outer tubes and deformation of the inner tubes were verified experimentally.

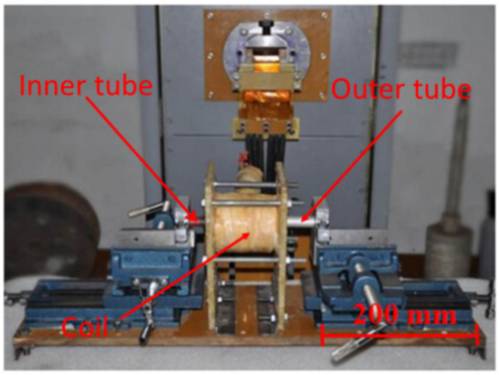
2 Experiment and Method

20Fe and 3A21 (Al alloy) were selected as materials of the inner and outer tubes, respectively. The thickness of outer tube was 1 mm with external diameter of 20 mm. In order to acquire the critical thickness of inner tubes under various discharge voltages, the inner tubes were prepared with thicknesses ranging from 1.5mm to 4.0mm and the interval was 0.1mm. Table 1 shows the size of the inner and outer tubes.

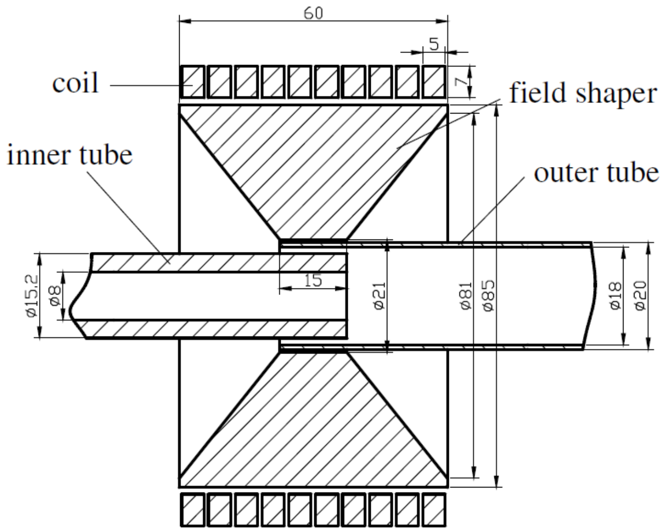
To perform the MPW experiment, a 20 kJ electromagnetic forming machine with a capacitance of 100 μF and maximum charging voltage 20 kV was employed. Fig. 1(a) shows the MPW equipment. The outer tube was driven by magnetic force generated by current in the coil and induced current in the outer tube, then the inner tube and outer tube were bonded together. Fig. 1(b) is the size of the coil and field shaper and their assembly relationships. For the purpose of simplifying experiments, gap between the inner tube and outer tube was fixed to 1.4mm and length of overlapped joint was 15mm.

Materials	Outer diameter（mm）	Inner diameter (mm)	Thickness (mm)
3A21	20.0	18.0	1.0
20Fe	15.2	7.2-12.2	1.5-4.0

Table 1: *Size of the inner and outer tubes*



(a) picture of the equipment



(b) dimensions of the setup and work-pieces

Figure 1: *The MPW setup*

A high-speed camera system (FASTCAM SA5 1000 K-M2) was used to obtain the impact velocities of outer tubes at various discharge voltages, and the FASTCAM SA5 1000 K-M2 system could shoot at a speed of one million frames per second at most. In order to find out the critical thickness of inner tube, MPW experiments were carried out at various discharge voltages. To obtain accurate and reliable results, three repeat experiments were carried out at each thickness of the inner tube. Fig. 2(a) shows the MPW pipe fittings under voltage of 14 kV. The inner diameter of inner tube would show no change after experiments when the thickness reached a certain value, then the value was considered as the critical thickness. The deformation of inner tube was evaluated by measuring its inner diameter at different locations, which was shown in Fig. 2(b).

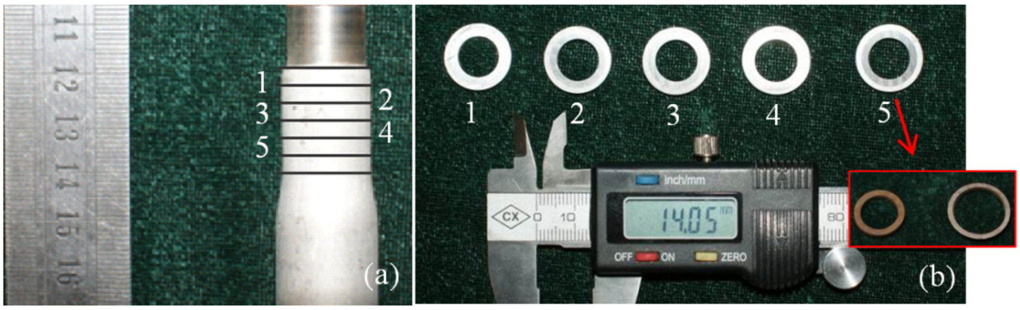


***Figure 2**: MPW pipe fittings and Measurements of the inner diameter: (a) MPW pipe fittings under voltage of 14 kV; (b) cross-sections at measurement locations*

The variations of diameters of inner tubes after MPW are shown in Fig. 3. $\bar{t}$ is dimensionless and represents the ration of thickness to external radius and Δd denotes the deformation of inner diameter of inner tube. The deformation of inner tubes decreases with the increase of thickness at a certain discharge voltage, and thicker tube is needed to restrict its deformation when the discharge voltage increases.

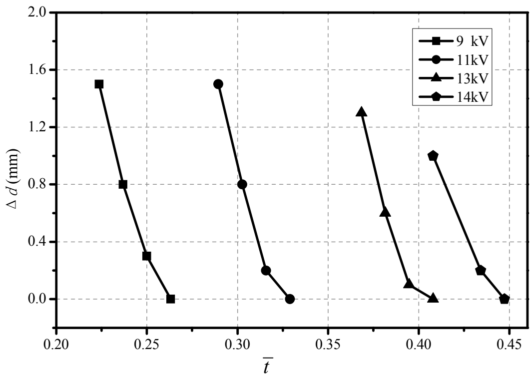


***Figure 3**: Deformation of inner tube under various discharges*

3 Numerical Simulation

3.1 Establishment of Coupled Numerical Model

MPW is a very complex transient impact process which involves the coupling effects of mechanical field, thermal field and electromagnetic field. Xu et al. (2013) employed a loose coupling method to study the changes of mechanical field and magnetic field, which ignored the effect of deformation of work-piece on electromagnetic field. However, deformation of work-piece has a significant influence on the precision of simulation (Bartels G et al., 2009).

In this study, a model was established in the electromagnetism module (EM) in LS-DYNA which coupling the mechanical, thermal and electromagnetic process. This module allows introducing source electrical current into coils to solve the coupled electric field, magnetic field and structural field. FEM was selected for the analysis of solid structures which was coupled with a Boundary Element Method (BEM) for air. Fig. 4 shows the established numerical model of the MPW.

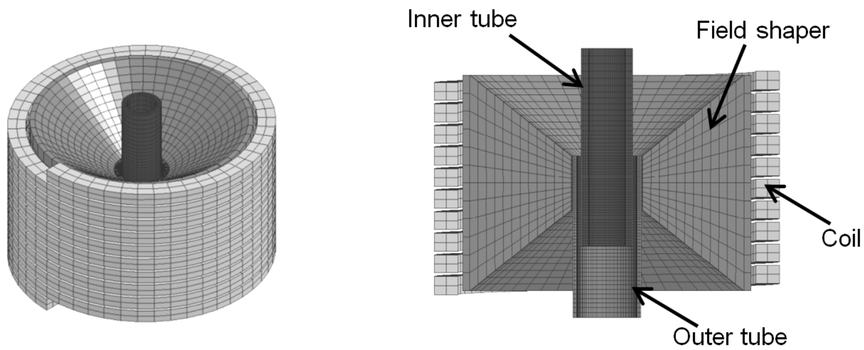


Figure 4*: The established 3D model for the coupled-field analysis*

3.2 Inverse Method on the Acquisition of Mechanic Parameters of Inner Tube

MPW as a transient impact process, the inner tube suffers very high pressure in a short time. The mechanic properties of material such as yield stress, breaking strength in this situation show huge difference compared to that under static loading (Johnson G R and Cook W H, 1983). Rusinek et al. (2007) reported that under the shock of several hundred meters speed, the yield stress could be several times of that at quasi-static process.

Due to critical situation caused by extremely high pressure, the material's dynamic property is hard to obtain experimentally. An inverse method was introduced to acquire the dynamic yield stress of inner tubes in this paper. The critical thickness of inner tube obtained experimentally at every discharge voltage was employed. The inner tube was set to an ideal elastic-plastic material with high yield strength, and then the maximum stress distributed in the inner tube in the process of collision was considered to be its modified dynamic yield stress. The modified yield stress was regarded as a value related to the discharge voltage. Finally, the predicted modified yield stress of inner tube was used in the simulation and the results were verified experimentally. The flow chart to acquire the critical thickness of inner tube is shown in Fig. 5.

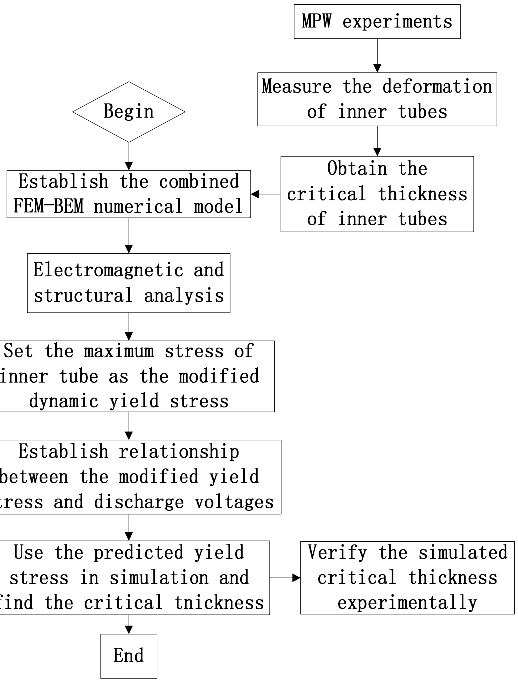
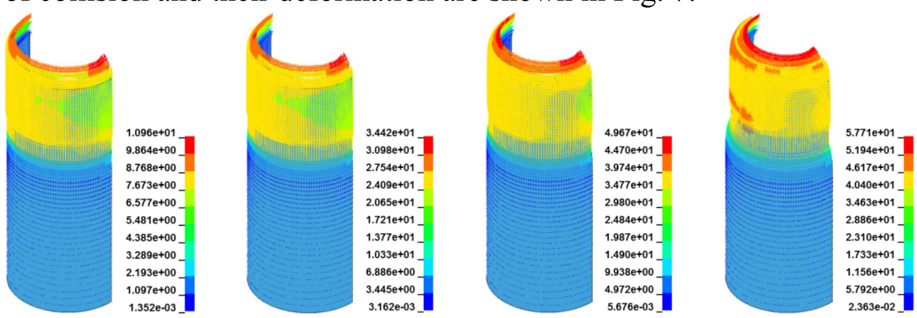


***Figure 5**: Flow chart of the acquisition of critical thickness of inner tube*

4 Results and Discussion

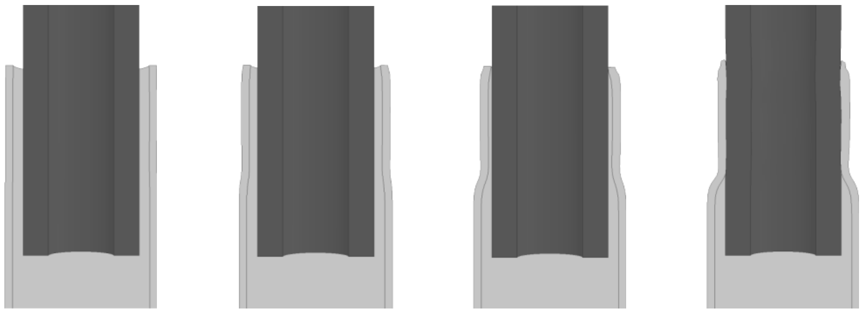
4.1 Distribution of Magnetic Field and Deformation of the Outer Tube

Due to the reason that magnetic force is proportion to magnetic field strength, the distribution of magnetic field of the outer tube in this period was studied in the simulation. Fig. 6 shows the distribution of magnetic field under a discharge voltage of 14 kV. It could be see that the magnetic field was mainly focused in the area closed to the field shaper, which means that the maximum magnetic force occurs at the end face of the outer tube. The process of collision and their deformation are shown in Fig. 7.



(a) 6 μs *(b) 10 μs* *(c) 13 μs* *(d) 16 μs*

***Figure 6**: Magnetic field distribution of inner tube*



(a) 10 µs *(b) 13 µs* *(c) 16 µs* *(d) 18 µs*

***Figure** 7: The impact process at a discharge voltage of 14 kV*

4.2 Impact Speed of Outer Tube

Impact velocity is a very important process parameter in MPW. A numerical simulation was employed here to study the impact velocities under various discharge voltages. Regardless of the slightly uneven velocities caused by the slot in the field shaper, the simulated velocities of end face of outer tubes under different discharge voltages is shown in Fig. 8.

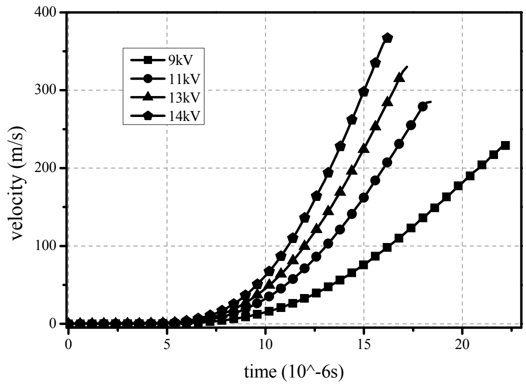


***Figure 8**: Simulated velocities of outer tubes under different discharge voltages*

The FASTCAM SA5 1000 K-M2 system was employed to measure the movement of the out tube and detailed information was shown by Xu et al. (2013). The impact velocity obtained through experiment and simulation is shown in Table 2.

Voltage (kV)	$v_{experiment}$ (m/s)	$v_{simulation}$ (m/s)
9	226	229
11	278	285
13	322	330
14	355	367

***Table 2:** Impact velocity of outer tube obtained thorough experiments and simulation*

Where $V_{\text{experiment}}$ represents experimental impact velocity and $V_{\text{simulation}}$ represents simulated impact velocity. It can be see that the simulated velocities agree well with experimental results and the maximum relative error is less than 4%.

4.3 Study on the Critical Thickness of Inner Tube

When the inner tube suffers higher pressure, thicker tube is needed to resist the plastic deformation. As demonstrated by Johnson (1972), the impact pressure is proportional to the impact velocity. The maximum stress in inner tube which had the critical thickness was regarded as the modified yield stress. Since von mises yield criterion was used in the simulation, the modified dynamic yield criterion could be expressed as below:

$$f = \sqrt{1/2[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} - N(v)\sigma_s \tag{1}$$

Where $\sigma_1, \sigma_2, \sigma_3$ represent the principal stresses, σ_s is the yield strength of inner tube, $N(v)$ is the dynamic factor and v is the impact velocity. When $f \geq 0$, material yields.

The maximum stress of inner tube in the whole impact process was obtained through simulation and Fig. 9 shows the stress distribution under the voltage of 11 kV while the thickness of inner tube was 2.4 mm. The maximum stress occurred in the inner surface of the tube, which means that the plastic deformation was first happened in the inner surface, and plastic deformation zoon would propagate from the inner surface to the outer surface.

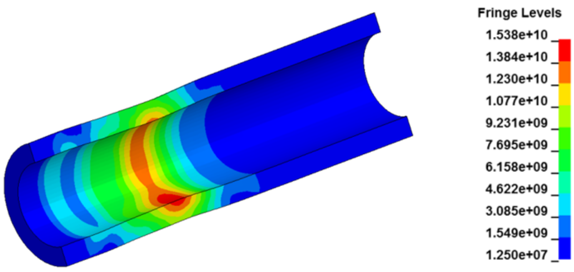


***Figure 9**: The stress distribution in the inner tube under voltage of 11 kV*

Four discharge voltages were used to obtain the relationship of dynamic factor $N(v)$ and impact velocity v and the data through simulation are listed in table 3.

Voltage (kV)	$v_{\text{simulation}}$ (m/s)	N(v)
9	229	44.6
11	285	59.6
13	330	70.5
14	367	81.0

***Table 3**: Dynamic factors under various voltages*

Based on the given data, the relationship of $N(v)$ and v was established as below:

$$N(v) = 0.2615v - 15.24 \tag{2}$$

Fig. 10 shows the comparison of the fitting curve with experimental value, the fitting curve shown a well linear relationship of dynamic factor and impact velocity.

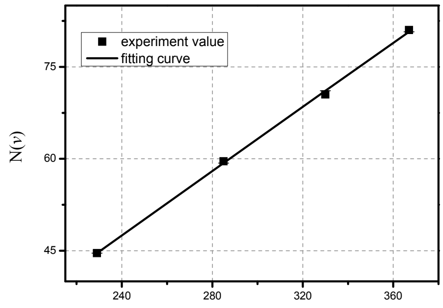


***Figure 10**: Relationship of dynamic factor $N(v)$ and impact velocity v*

In order to verify the model, the predicted dynamic yield stress under the voltage of 10 kV and 12 kV were used in the simulation. Fig. 11 shows the plastic strain distribution of inner tube under different discharge voltages. The maximum plastic strains in the two pictures are less than 0.12%, which means that model can predict the deformation of inner tube accurately.

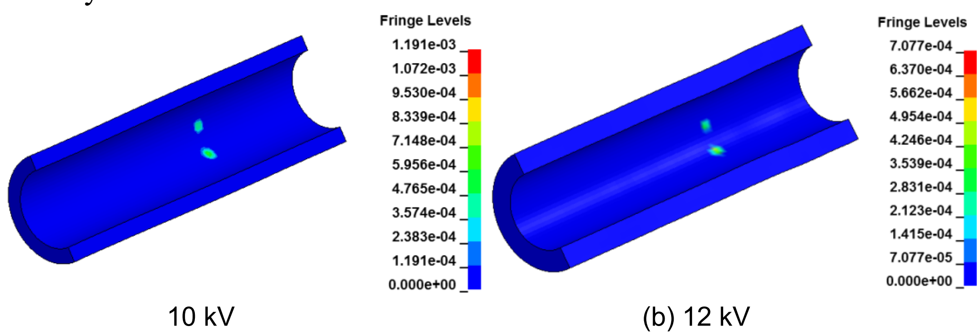


***Figure 11:** Plastic strain distribution of inner tube under different voltages*

The results show that the value of N related to impact velocity was suitable to the material 3A21 in our investigation. It is not fully considered whether it is valid in general. Further study considering this question is recommended.

5 Conclusions

In this study, both experiments and simulation were used to explore the critical thickness of inner tube in MPW process. The conclusions can be summarized as follows:

(1) A combined FEM-BEM method was used to investigate the electromagnetic process of MPW. The simulated impact velocity under various discharge voltages agreed

well with the experiment values. The error of simulated impact velocity increased with the increasing of discharge voltages while the maximum relative error was less than 4%. Maximum impact velocity occurred at the end surface of the outer tube.

(2) End surface of the outer tube suffered the maximum magnetic force, and the impact velocity also achieved the peak value in this area. Higher impact velocity caused larger impact pressure in the interface. As a consequence, deformation of inner tube was first occurred in area closed to the end surface of outer tube, then transferred to the free end.

(3) An inverse method was proposed to find the dynamic yield stress of the inner tube, and the predicted yield stress was then employed to obtain the critical thickness. The plastic deformation of inner tubes with critical thickness was less than 0.12%.

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