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A study on the critical wall thickness of the inner tube for magnetic pulse welding of tubular Al–Fe parts

Junjia Cui[a,b], Guangyong Sun[a,b], Junrui Xu[c], Zhidan Xu[d], Xiaodong Huang[e], Guangyao Li[a,b,*]

[a] *State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China*
[b] *Joint Center for Intelligent New Energy Vehicle, Shanghai 200092, China*
[c] *School of Mechanical Engineering, Xiangtan University, Xiangtan 411105, China*
[d] *SAIC GM Wuling Automobile Co., Ltd, Liuzhou 545000, China*
[e] *School of Civil, Environmental and Chemical Engineering, RMIT University, GPO Box 2476, Melbourne 3001, Australia*

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ABSTRACT

Microstructure and mechanical properties of the welding zone highly depend on the thickness of inner tube for jointing two tubes using magnetic pulse welding (MPW). In this study, the critical thickness of inner 20Fe tube for the Al–Fe welding tubes is investigated by combining the theoretical calculation and experiments. Theoretical analysis demonstrates that plastic deformation zone of the inner tube expands from its inner surface to its outer surface. With equilibrium equations and modified Tresca yield criterion, the critical thicknesses of inner tube under various collision velocities are derived so as to assure the high quality of the welding. The results show that the critical thickness of inner tube increases linearly with the discharge voltage. With the discharge voltage increases by every 2 kV, the critical thickness increases by 0.5 mm accordingly. The theoretical predictions agree well experiments with an error of less than 2.5%. Furthermore, effects of thickness of inner tube on the mechanical properties of welding zone are also investigated.

1. Introduction

Light-weight aluminum is suitable for application in aerospace structure, railway and cars. Steel with high strength is an ideal material for load-carrying structures. Tailor welded Al-to-Fe structures, which take advantage of the good characteristics of both materials and can be used for the weight reduction of automobiles to improve fuel efficiency and reduce air pollution, have attracted extensive attention in recent years as reported by Kore et al. (2008). While, it is difficult to weld such dissimilar materials using conventional, thermal welding processes because of their differences in melting point, density, thermal conductivity and expansion coefficient as reported by Schubert et al. (2001).

Several welding technologies such as braze welding, friction welding and explosive welding have been developed to overcome this problem. Lin et al. (2010) found that 5A06 aluminum alloy and SUS321 stainless steel can be welded by braze welding using Al–Cu_6 filler metal and non-corrosive flux. According to Coelho et al. (2012), Al–Fe joint without any defects could be produced using friction stir welding, meanwhile the joint efficiency depended foremost on the mechanical properties of the thermo-mechanical affected zone. Explosive welding is an effective tool to weld dissimilar material. Han et al. (2003) made AA1050 aluminum alloy plate and SS41 steel plate welded by explosive welding. In the interfacial zone, they found an intermetallic compound, $FeAl_3$. The same or dissimilar material such as Cu–Cu, Al–Fe and Cu–Al could be welded by means of optimizing process and welding structural parameters including distance and explosive ratio, etc. However, the welding process usually produces local high-temperature zones, resulting in intermetallics. The high hardness, brittleness and different lattice structures of such compounds may cause the welding zones to crack easily as reported by Fukumoto et al. (2000).

Alternative welding approach for Al–Fe structures is magnetic pulse welding (MPW), which is based on the high-speed electromagnetic forming at room temperature as stated by Psyk et al. (2011). As the solid phase welding, electromagnetic welding and explosive welding share a similar theory. Zhang et al. (2011) systematically explored the magnetic pulse welding and explosive welding, and identified that the explosive welding is more

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[*] Corresponding author at: State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha 410082, China.
E-mail address: gyli@hnu.edu.cn (G. Li).

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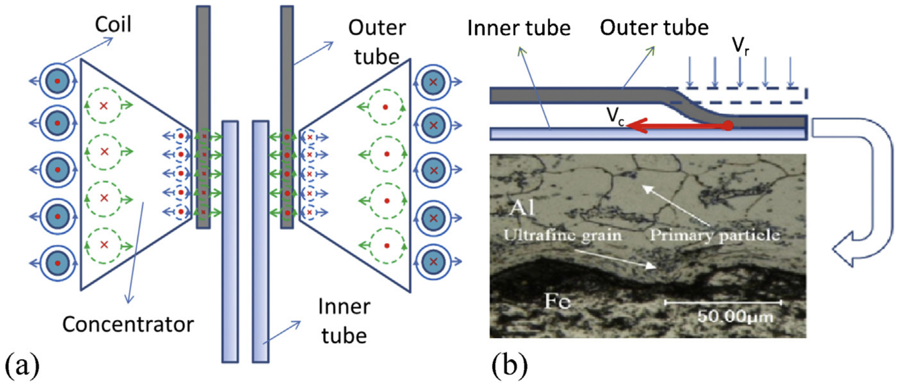

Fig. 1. The production of magnetic pulse welding: (a) schematic of the current in MPW; (b) a successful welding structure with a transition zone.

suitable for large-size item welding. Meanwhile, the impact speed in explosive welding can be up to 900 m/s, resulting in intermetallic compound easily, which is usually acted as a crack source.

The theory of MPW is based on the fundamental principle of magnetism that similar poles repel each other as reported by Tomokatsu et al. (2013). To fulfill the welding of two tubes, their ends are placed slightly overlap with one tube inside the other but do not touch as shown in Fig. 1. During the electromagnetic impulse welding process, a capacitor bank is instantaneously discharged to generate high-frequency current in the main coil. A magnetic field shaper used to concentrate the magnetic field line around the weld zone of the tubes is placed between the outer tube and the electromagnetic coil. The current in the main coil will induce secondary current in the field shaper. This secondary current will flow through the shaper's outer surface to its inner surface, thus inducing another secondary current in the adjacent flyer tube.

The magnetic forces created by eddy currents applied to work-piece are much like uniform, but in real applications, some regions of a work-piece have to be more deformed and therefore a much greater pressure has to be applied to these regions. The task of the field shaper is to concentrate the magnetic forces to some desired regions. Zhang et al. (2004) proved that the field shaper structure would improve the welding efficiency of MPW under given experimental conditions for 6061Al–1010Steel structures. The intense magnetic fields between the field shaper and flyer tube create high electromagnetic pressure between them. This magnetic pressure drives the flyer tube in high velocity toward the target tube so as to create a weld as reported by Cui et al. (2014).

Xu et al. (2013) reported that when the impact velocity (Vr as shown in Fig. 1) between the outer tube (3A21) and the inner tube (20Fe) is larger than 355 m/s, the velocity of the impact point (V_C) could reach to 8000 m/s and a successful welding structure with a transition zone would be achieved under tremendously pressure as shown in Fig. 1(b).

Dissimilar material welded tubes are mainly used for line transporting of liquid and gas in industrial production. The heavy weight of tubes will certainly increase the manufacturing and operational cost. However, according to the principles and characteristics of magnetic pulse welding, the surface of the inner tube should be smooth to make the welding effect perfect when the two tubes impact. According to Demir et al. (2010), the interface of the tubular structure will wrinkle when the tube is subjected to extreme pressure. In MPW, once the wrinkle appears, it will hinder the full contact of two tubes and makes the welding effect poor. Thus, the inner tube has a critical thickness in the MPW process to ensure the high quality of the welding joint.

Tamaki and Kojima (1988) studied the stiffness of the inner tube in MPW. In their study, a tubular core with a flange for the ease of setting up the tube coaxially was used as the inner tube. The outer diameter, thickness and length of the outer tube, D, t_1 and L, was 29 mm, 1 mm and 30 mm, respectively. The clearance between tube and tubular core, C was 1.5 mm. The thickness of tubular core, t_2 was varied to study the stiffness of the inner tube in MPW. They evaluated $R=(l/l_0)\times 100(\%)$ as the feasibility of welding. Where, R is the welded length ratio; l_0 is the total circumference at the tube-core interface after welding; l is the length of welded portion along the circumference of the interface. Through the study, they found that plastic deformation happens when the thickness of the tube is smaller than a certain value. In this condition, the weld length ratio R is less than 100%, which is judged to be a failure welding. The weld length ratio R increases with an increasing thickness of core and reaches about 100% with it larger than 6 mm at 4.2 kV.

The studies mentioned above are mainly focused on the mechanical properties of welding joint and the impact behavior between the two metal tubes. The effects of structural parameters on mechanical properties, especially the thickness of the tube, have not been fully investigated. In the existing researches, the inner tube critical thicknesses are normally obtained by experiments conducted under a particular energy condition without revealing of the impacting factors. In addition, the critical thickness values determined by experiment are just the outcomes of trial-and-error method, which are less supported by relevant theories.

In the present study, both theoretical analysis and experiments are performed to investigate the critical thickness of the inner tube in MPW. Firstly, the equilibrium equations are used to obtain the displacement components of the inner tubes under the magnetic load. Based on Lame's equations and modified Tresca yield criterion, the pressure under different impact velocities for the inner tubes is derived, and thus the critical wall thickness is obtained. The resulting theoretical values are then verified by experiments with the discharge voltages of 10 kV, 12 kV and 14 kV. Finally, the effects of the inner tube thickness on mechanical properties for Al–Fe joint are investigated and discussed.

2. Materials and methods

In this study, 3A21 aluminum alloy with a thickness of 1.0 mm is used for the outer tube, and 20Fe is selected as the material of the inner tube. The chemical compositions of these materials are shown in Tables 1 and 2, respectively.

The 20 kJ electromagnetic forming machine with a capacitance of 100 μF and a maximum charging voltage of 20 kV is used