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Experimental and Interfacial Waveform investigation on Aluminum/Stainless Steel Composite Tube by Explosive Welding

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Abstract –The welding experiments of Aluminum/stainless steel composite tubes were carried out by the internal explosive welding method. Aluminum/stainless steel composite tube interfacial zone was analyzed by scanning electron microscope, and the interfacial shape appears wave and the wave amplitude is small. Unlike composite plate interfacial wave, which has good periodic variation rule, composite tube interfacial wave has not good rule of periodic variation. The major reasons, which cause the difference, were that diameter of flyer tube is enlarging when the process of explosive welding of composite tube, and the time that detonation products inside the tube affect to the flyer tube is longer than that of flyer plate. Besides, compression, bending and flattening test of the composite tube mechanical properties were carried out, and no separation happened when the tests were carried. It is indicated that the composite tube has excellent properties and can endure large plastic deformation. And the quality of composite tube interface satisfies the using requirement.

Keywords –Explosive welding; Al/stainless steel composite tube; Interfacial wave; Combination quality

1. Introduction

Bi-metal explosive welding composite tube is made of two metal tubes which have different materials and properties through explosive welding method [1,2]. It has broad application prospects and is widely used in industries because of the advantages both of the base tube and the flyer tube. For example aluminum/stainless steel composite tube has widely application in the field of nuclear energy facilities, for its aluminum complex tube can generate α-Al_2O_3 ceramic layer[3]. It is the acceptable solution to anti-nuclear radiation penetration in the piping of nuclear power equipment [4].

It is known that interfacial bonding morphology is one of the important parameters to measure the quality of explosive welding, and also has an important effect on the subsequent machining processing of the material. Zhang Y et al. carried out an experimental research on explosive welding of titanium/steel clad plate in 2012[5]. Zareie H.R., et al. analyzed the effect of explosive welding parameters on metallurgical and mechanical interfacial features of Inconel 625/plain carbon steel bimetal plate in 2012 [6]. Bataev I. A. et al. analyzed the structural and mechanical properties of metallic–intermetallic laminate composites produced by explosive welding and annealing in 2012[7]. Nizamettin K et al. analyzed microstructural and mechanical properties of Cu–Ti plates bonded through explosive welding process in 2005[8]. Mustafa A et al. carried out investigation on explosive welding parameters and their effects on microhardness and shear strength in 2003[9]. Compared to research on the composite panel interface combined wave, research on the composite tube combined interface wave is little [10].

This paper analyzed the variation discipline of the composite tube bonding waveform and the main reason to affect the combined wave morphology based on the experimental of explosive welding Al/Stainless steel composite tube. Section 2 determines the technology design of the composite tube explosive welding feasibility. Section 3 evaluates its bonding interface performance. Section 4 investigates the capacity to undergo plastic deformation by the composite tube mechanical properties testing, provided a preliminary study for the plastic forming of more complex shape composite tube latter. And the conclusion is given in Section 5.

2. First-order headings

2.1. Second-order headings

In the experiment, the material of base tube is stainless steel (316L), and flyer tube is commercial purity aluminum (1060). Chemical compositions of 316L and 1060 substrate material are given in Table 1. And the basic performance parameters of Al tube and stainless steel tube are list in Table 2.

Table 1. Chemical compositions of 316L and 1060 substrate material (mass%)

Material	Mn	Si	C	Ni	Cr	S	Mo	P
1060	0.03	0.25	-	-	-	-	-	-
316L	1.85	0.5	0.03	12.55	17.8	0.014	2.46	0.03

Table 2. Basic performance parameters of Al tube and stainless steel tube

Material	ρ ($g.cm^{-3}$)	$\sigma_{0.2}$ (MPa)	σ_b (MPa)	Diameter (mm)	Thickness (mm)
1060	2.71	35	75	10	1
316L	7.98	175	480	14	2

2.2. Experimental method

Internal explosive method (IEM) is introduced in welding experimental method. The principle of the technology is that flyer tube is placed in the base tube inner hole and explosive is filled in flyer inner hole. Flyer tube with high-speed collide with the base tube by the explosive load, and then combined together when explosive welding happened. To prevent damage to the base tube deformation, the base tube should be placed in the mold because of powerful impaction generated by the explosive.

There were two issues should be considered in the design of the mold. Firstly, the steel strength of the mold can reliably constrain the deformation of the base tube. Secondly, explosive welding composite tube can easily separate from the mold. For these reasons, the mold structure is design two divided parts, including the outer die part and the inner die part. The material of internal model is tool steel, and 45 # steel is for outer mold. Figure 1 shows the schematic of entire assembling structure of the composite tube explosive welding system.

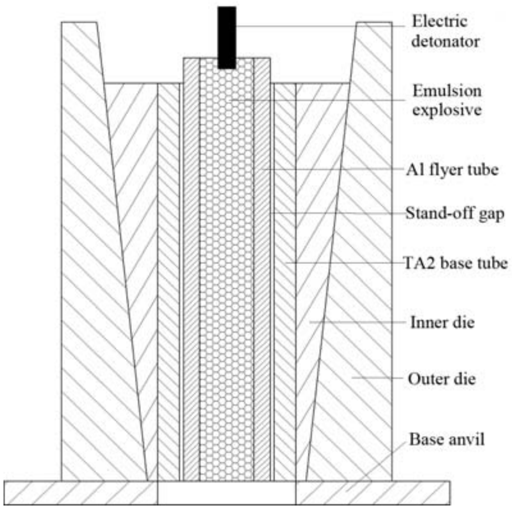

Figure 1. The schematic of explosive welding system

According to the thickness of flyer tube wall, distance-off gap between the flyer tube and base tube is 1mm. The inner and outer surfaces of the aluminum tubes and stainless steel tubes are cleaned by ultrasonic method, and then cleaned with acetone before the assembly of flyer tube and base tube. In order to ensure the quality of the combination of composite pipe and prevent flyer tube inner surface to erosion, experiment used a low detonation velocity (about 2000 m/s) mixed powdery emulsion explosive (PEE).

3. Interfacial waveform analyze

3.1. Experimental results

Figure 2 shows a group of Al/316L composite tubes obtained from the explosive welding experiment. There are no obvious defects on the appearance of Al/316L composite tubes. Through measuring the outer diameter of the composite tube, it is found that the outer diameter of the composite tube almost no changed because of reliable constraint of the steel mold.

Figure 2 composite tubes of Al/stainless steel

3.2. SEM morphology of the interface wave

The random experimental Al/316L composite tube is chosen to investigate the changes of the morphology of Al/316L explosive welding composite tube combination interface wave. It is known that the combination quality of the end of explosive welding composite tube is not good, because of the principle of explosive welding. The samples are cut off 10mm in length on both two ends at first. And then electron microscopy scanning (SEM) is carried out to the combination of the interfacial of the forepart, middle-part and end-part along the explosive direction of the composite tube samples. Figure 3 shows the SEM morphology of Al/316L composite tube.

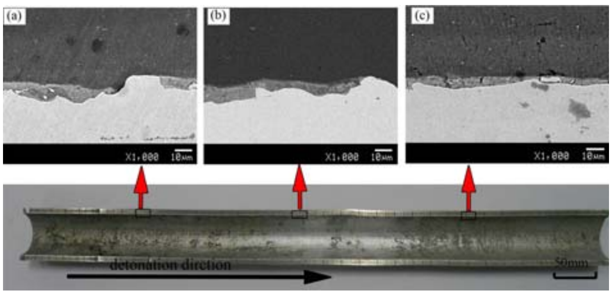

Figure 3 SEM Morphology of Al/316L composite tube. **a**. forepart interface. **b**. middle-part interface. **c**. end-part interface.

The binding interface characteristics of Al/316L explosive welding composite tube can be achieved from Figure 3. There is a small amount of unequal thickness of the molten layer on the interface, which is about 10μm in forepart near detonation point, and approximately 3μm in end-part. The wave morphology of combination interface can be regarded as a microwave-like combination [11]. The wavelength is about 40μm in the near detonation point of forepart of composite tube, and about 30μm in the end-part of composite tube. And the wave height decreases from 15μm to 5μm approximately. There is no periodic rule to the waveform interface.

In order to compare waveform law of the composite plate interface, interfacial waveform of the forepart, middle-part and end-part along the explosive direction of the T10/ Q235 composite plate by microscope also was analyzed. Based on the reference [12], Specific process parameters of T10/ Q235 composite plate experiment were as follows that the material of flyer plate is T10 tool steel with size is 300mmx200mmx7mm, and the material of base plate is Q235 carbon steel with size is 300mmx200mmx20mm; The gap between the flyer plate and base plate is 6mm. Buffer layer is the oil blankets. Rock ammonium nitrate 2# is the explosive, which is 40mm thickness in with density of 0.8g/cm3. Figure 4 shows the morphology of T10/Q235 composite plate.

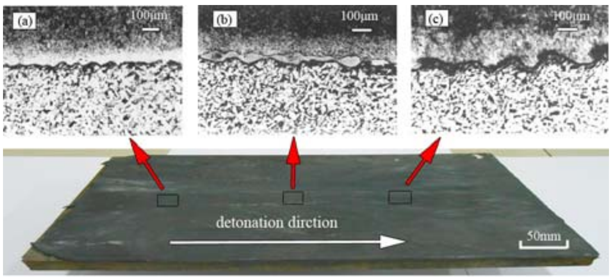

Figure 4 Morphology of T10/Q235 composite plate. **a.** forepart interface. **b.** middle-part interface. **c.** end-part interface.

It can be seen the binding interface characteristics of T10/Q235 explosive welding composite plate. The regular periodic waveform is formed on the binding interface; the wavelength is about 100μm in the near detonation point of forepart of composite plate, and increase to 300μm in the end-part of composite plate. The wave height increases from 20μm to 100μm approximately. There is about 100μm thickness of the molten layer generating on the interface. Weld interface is microwave-like waveforms combination to the basically stable small wave-like waveforms combination, even large wave-like waveforms combination from composite plate detonation point to the end-part.

It can be supposed that the composite plate combination wave have such universality variation, because other explosive welding composite plates, such as Copper/stainless steel[13]、Aluminum/dual phase steel[14]、Titanium/steel[15] composite plates interface, have similar waveforms. It can be found that the thickness of the molten layer on the interface of is thinner and the rule of the interfacial waveform is not periodic, comparing with the combination interfacial features and wave morphology of explosive welding composite plate.

3.3. Discussion

According to the crafts of explosive welding composite tube and the loading process of explosive, it can be concluded that the thickness of the molten layer on the interface of explosive welding composite tube is thinner and the rule of the interfacial waveform is not periodic. The reasons for the phenomenon are as follows.

The outside diameter size of flyer tube should be expended as the same as the inner diameter size of base tube before the collision welding happened by the power of detonation load in the process of tube explosive welding. It means that the outside diameter of Al tube should be expend to the 14mm, which is the size of the inner diameter of stainless steel tube. Supposing flyer tube diameter expanded in the theory of equal thickness expanded. The wall thickness size of Aluminum tube would be from 1mm to 0.836mm before Aluminum tube collide to base tube based on the principle of constant quality. It is known that the reason for expanded composite tube diameter is caused by the peak pressure of the detonation wave. Expanded flyer tube diameter would consume a part of the detonation energy, and the peak pressure of the detonation would be reduced when flyer tube colliding base tube in the process of tube explosive welding. So the amplitude of Al/316L composite tube interfacial combination wave also decreased at the same time.

Excluded the detonation products from dynamite explosion in time or not has a great influence to the process of explosion welding [16]. The detonation products from tube explosion welding explosion is not like that of plate, which can disseminate to the air in time because of bare assembly explosives. The time of high pressure products from tube explosion welding press the flyer tube is longer than the plate, and the interfacial wavelength and wave-height of Al/316L composite tube could become diminish because of the long time pressure of high pressure products. The ultimate morphology shows flat interfacial wave.

In addition, detonation products were increasing and accumulating over time because of excluding the detonation products from dynamite explosion not timely in this relatively airtight tube. Pressure from detonation load in the direction of the axis of the composite tube would increase, but would decrease near the end of process of explosive welding. It is because that excluding the detonation products from tube port in time. According to the relation of interfacial waveform and explosion load [2], the change that the interfacial wavelength and wave-height of composite tube increased along the detonation propagation direction and decreased in the end of process would be made.

4. Mechanical properties test

To verify the bonding interface from the SEM images of Al/316L composite tube meet the requirements of the binding strength, test of the mechanical properties is carried out to the composite tube combination of interface. The radial flattening capability, axial compression capability and bending capability are all tested.

The test results can be shown in Figure 5, Figure 6 and Figure 7. Figure 5 illustrates the appearance of the flattening test results of the composite tube samples. The cracking phenomenon of combination of interface does not appear when the distance of flattening H (the distance of up and down of inner wall) from 10mm to 3mm in the radial load.

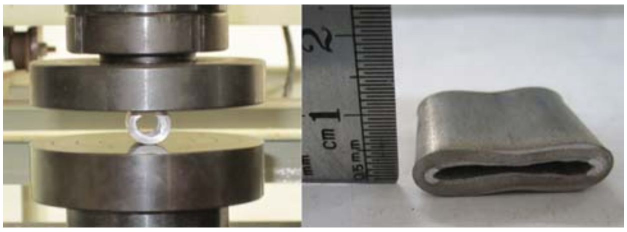

Figure 5 Composite tube of Al/316L mechanical properties flattening test

Figure 6 shows the appearance of the axial compression test results of the composite tube samples. The cracking phenomenon of combination of interface does not appear when the distance of axial compression from 10mm to 5.35mm(53.5%) in the axial load.

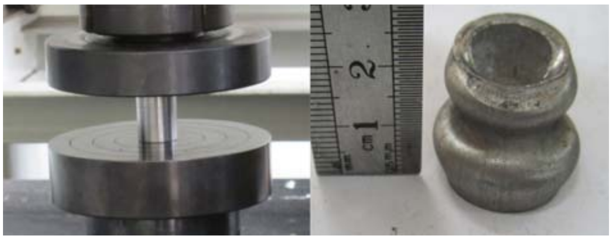

Figure 6 Composite tube of Al/316L mechanical properties compression test

In order to execute the bending test of the composite tube samples, the strip specimens with length of 40mm and a width of 5mm were manufactured by the wire cutting machine, and then were flattened. The specimens were divided into two groups, one group stamped from inside and another group stamped from outside. The bending properties test of specimens were carried by the SANS computer-controlled electronic universal tensile machine. The appearance of the bending test results of the composite tube samples are shown in Figure 7. The cracking phenomenon of combination of interface does not appear when the bending angle of two groups is 60°.

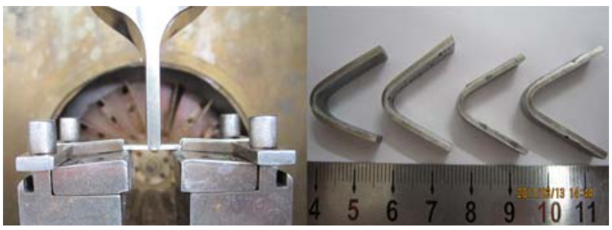

Figure 7 Composite tube of Al/316L mechanical properties bending test

The mechanical properties of the test results show that the binding interface mechanical properties of Al/316L composite tube, in accordance with the determined process of the explosive welding, fully meet the requirements of engineering.

5. Conclusions

(1) A number of Al/316L explosive welding composite tubes were obtained using the internal explosive welding method.

(2) Al/316L explosive welding composite tube interfacial zone was analyzed by SEM, comparing with the combination interfacial features and wave morphology of composite plate. The amplitude of the Al/316L explosive welding composite tube combined interface is little change and the rule of the interfacial waveform is not periodic.

(3) It could be considered that there are two reasons for the difference. First, the outside diameter size of flyer tube should be expended, and second the detonation products from dynamite explosion can not excluded in time.

(4) The obtained Al/316L composite tube in experiment has thinner thickness of the molten layer on the interface than composite plate. The combination of interface does not appear phenomenon of cracking and abruption by the test of radial flattening capability, axial compression capability and bending capability.

(5) The mechanical properties of the test results show that the binding interface mechanical properties of Al/316L composite tube fully meet the requirements of engineering.

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