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ORIGINAL ARTICLE

Interface and performance of CLAM steel/aluminum clad tube prepared by explosive bonding method

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Abstract China low activation martensitic steel/aluminum clad tubes were prepared by explosive bonding method in order to study its microstructure characteristics at the interface and to evaluate its performance. The interface morphology of the different parts of the clad tube was characterized by scanning electron microscope and energy dispersive spectroscopy. Then, the performance of the clad tube, including its bonding strength and formability, was investigated. Microstructural results showed that existence of an under-fusion area at the head of the clad tube, diffusion of elements, and the metallurgical bonding was observed in the middle part while cracks and crushing particles appeared at the end of the clad tube. No separation after the cold extruding and hydroforming process showed that the middle part of the clad tube had excellent bonding properties and could endure the second plastic deformation.

Keywords Clad tube · Explosive cladding

1 Introduction

China low activation martensitic steel (CLAM steel) is a kind of reduced activation ferritic martensitic (RAFM) steel developed by Fusion Design Study (FDS) of the Institute of Plasma Physics of Chinese Academy of Sciences in collaboration with research institutes both at home and abroad, under the national supports for related key projects. CLAM steel has excellent properties, such as good impact toughness and tensile strength [1]. It has been chosen as the primary structural material candidate in the designs of FDS series PbLi blankets for fusion reactors [2], dual function lithium lead test blanket module (TBM) [3], as well as for ITER and for China's fusion engineering test reactor "blanket" [4]. With the further development in recent years, CLAM steel displayed its excellent properties. Compared to other RAFM steels such as EUROFER97 and JLF21, impurities in CLAM steel are kept to the minimum or eliminated, and some chemicals, such as Cr or W, are added to achieve better properties [5]. CLAM steel has good low-temperature impact toughness among all RAFM steels [6].

In nuclear fusion engineering applications coating of CLAM steel parts with alumina ceramics can effectively improve electric insulation, corrosion resistance, and protect form tritium penetration [7]. Many methods, including plasma spray [8], hot dip aluminizing and oxidation process [9], chemical compaction [10], and double glow plasma deposition [11], were applied to prepare alumina ceramic coating. However, the difficulty in preparation of compact alumina coating on internal surface of complex parts severely limits its practical application in nuclear fusion materials. In recent studies, a new preparation method was developed: Steel/aluminum clad tube [12] was prepared through explosive cladding with pure aluminum being the inner layer. Then, the tube fittings of complex shape were manufactured by plastic deformation of the clad tube. At last, the pure aluminum layer on the internal surface of the clad tube fittings was converted into the alumina layer through an in situ oxidation process.

In this paper, the method briefly described above was used to prepare a CLAM steel/aluminum clad tube with metallurgical bonding on its interface through explosive cladding. The interface bonding characteristics of the head, the middle part,

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Table 1 Chemical composition of CLAM base tube (wt%)

Element	Fe	Cr	C	Mn	P	S	N	W	Ta
Content	Bal.	9	0.1	0.45	0.003	0.002	0.02	1.5	0.07
Element	Si	Ti	V	Ni	Co	Cu	Nb	O	
Content	0.01	<0.006	0.2	0.02	<0.005	<0.005	<0.001	<0.002	

and the tail end of CLAM steel/aluminum clad tube were investigated. Also, formability of the CLAM steel/aluminum clad tube was studied in order to evaluate the feasibility of manufacturing of complex-shaped parts.

2 Materials and method of the explosive cladding experiment

2.1 Materials of the experiment

A 1060 pure aluminum tube was used as the flyer tube for explosive cladding with the dimensions of Φ 21 mm×1 mm×400 mm. A CLAM steel seamless tube with dimensions Φ 27 mm×2.1 mm×400 mm was used as the base tube. The chemical composition of the base tube is shown in Table 1. It was found that the roughness of the internal surface of the base tube and the external surface of the flyer tube is Ra 0.16.

2.2 Method of the explosive experiment

Before the explosive cladding experiment, the flyer tube and the base tube were concentrically assembled. At first, the pure aluminum flyer tube was fixed into the base tube, and 0.5–1 mm clearance was kept between the flyer tube and the base tube by a fixing apparatus. Then, the emulsion explosives, including the density modifier (used to slow down the explosion speed) and sensitizer (used to stabilize the explosion speed), were filled into the aluminum tube. The base tube with coated lubricating oil on the external surface was placed into the internal mold. Subsequently, the internal mold with the tube blank was installed into the external mold. The space between the internal and the external molds was also coated with lubricating oil to prevent the cold welding effect. The tapered internal mold was designed to ensure the mold removal after the cladding experiment. Finally, the CLAM steel/aluminum clad tube was obtained after an explosion triggered by an electric detonator.

3 Results and discussion

3.1 Macroscopic results for CLAM steel/aluminum clad tube

A macroscopic picture of the CLAM steel/aluminum clad tube prepared by the explosive cladding method is shown in Fig. 1. The external diameter of the clad tube from the detonation end to the tail end is quite smooth, because of the radial constraint of the deformation caused by the rigid mold in the explosive cladding experiment [13]. The rigid mold also ensures excellent external surface quality of the base tube and prevents excessive deformation or even cracks of the clad tube. In the explosive cladding process, the radial deformation of the base tube is prevented by the circular restraint provided by rigid mold. Therefore, the explosion energy is mainly spent on the bulging of the inner tube and for the formation of the interface due to collision of the flyer tube with the base tube. High temperature and high pressure are easily generated at the interface between the flyer tube and the base tube. In the experiment, plastic deformation, fusion, and even diffusion of the flyer tube and the internal wall of the base tube were induced by the huge collision energy. Consequently, the flyer layer is welded onto the base layer.

Fig. 1 CLAM steel/aluminum bimetal tube prepared by explosive welding

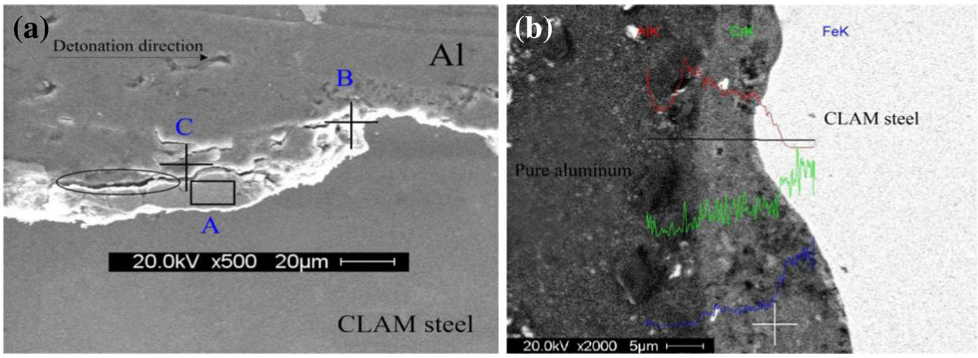

Fig. 2 Interface appearance and element area: **a** detonation end and **b** middle part

3.2 Interface morphology and the element distribution of the clad tube

The sample of the CLAM steel/aluminum tube included the detonation end, the middle part, and the tail end. The interface morphology and the element distribution in different samples were characterized by scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS), respectively. Morphology of the detonation end and of the middle part of the aluminum-CLAM steel explosive clad bimetallic tube is shown in Fig. 2.

It is obvious that the aluminum clad is poorly bonded to the CLAM steel base, and some un-bonded areas exist between the aluminum layer and the steel layer. During explosive cladding, long cracks are produced in the aluminum layer and in the interfacial layer. These cracks are predominantly formed along the explosion direction. Results of the element analysis of the different areas are shown in Table 2. Aluminum is absent in area A, indicating that this part belongs to the steel base layer where aluminum has not penetrated. However, an interface exists between a fragment of area A and the base. It indicates that this part is crushed by a cracked particle, formed during the intensive collision of explosive cladding. Area B is a transition layer where elements of Al and Fe are found, indicating mutual diffusion. Area C is composed of pure Al, indicating that this is a part of the aluminum tube.

Table 2 Distribution of elements on the interfacial transition layer

Content of area element wt%	Al	Cr	Fe	W
A	–	8.44	89.29	2.27
B	5.65	10.10	79.66	4.59
C	100	–	–	–

Morphology and element line scanning of the interfacial area in the middle of the aluminum-CLAM steel explosive clad bimetallic tube are displayed in Fig. 2b. An obvious wave-like interface is generated between the CLAM steel base and the pure aluminum clad. In detail, a large wave and a small wave can be distinguished at the interface. Plaksin et al. attributed the wave formation mechanism to the regular instabilities that are induced by oscillating detonation waves that are transmitted through the interface of the impact materials. The waveform is an irreversible plastic deformation of metallic material under an applied load [14]. It was found that the velocity of the explosion product is one fourth of detonation wave's velocity, which means that the detonation wave and the explosion product are not propagating synchronously. The detonation wave has certain shape and parameters (wavelength, amplitude, and frequency), and its front is infinitely steep. It is the sudden energy change, caused by the wave propagation, which forms the waveform on the metal interface.

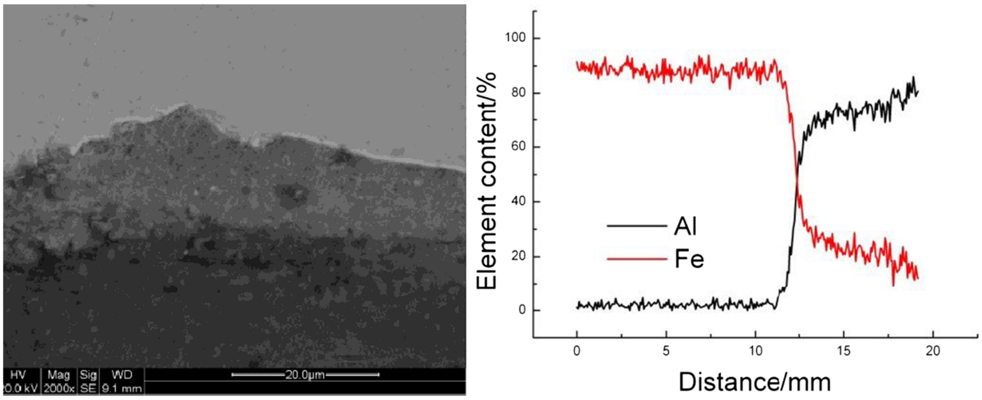

Fig. 3 The tail end interface appearance and the element distribution of aluminum-CLAM steel clad tube

Table 3 Distribution of elements at interface transition layer

Element content	Wt%	At%
Al	78.9	88.46
Cr	2.72	1.58
Fe	18.38	9.96

There are no cracks, holes, or crushed particle in direction perpendicular to the detonation direction. According to the element distribution curve, Al, Fe, and Cr exhibit gradient distribution, demonstrating mutual diffusion among several main elements at the interface. Figure 3 also shows the element distribution in a qualitative way since it is a backscattered electron image. A transition layer with the width from 5 to 15 μm is formed between the CLAM steel base and the aluminum base. As for the CLAM steel base, narrow transition layers are mostly located at the wave peak and the wide transition layers are mainly formed. The element analysis of the transition layer is shown in Table 3.

The SEM image of the interface of the aluminum-CLAM steel clad tube at the tail end is shown in Fig. 3. A diffusion layer is formed between the base tube and the flyer tube. The maximum thickness of the diffusion layer is 20 μm.

3.3 Interface bonding performance

Interface bonding strength of a bimetal is an important parameter to evaluate the quality of a clad tube. The bonding strength determines the subsequent plastic forming. Since the detonation end, the middle part and the tail end differ in the explosion speeds, causing the bonding strengths at these areas to differ from each other. The segments of 12.5 % of the total length at the two ends are defined as the detonation end and the tail end, respectively. The middle part, constituting 75 % of the total length, is defined as the middle segment. At least three samples are cut from each part of the tube (the specific quantity shall be based on the validity of practical test data). The bimetallic ring is 2 mm thick. The interface bonding performance was measured by a shear test. The testing unit is comprised of a base, a punch, and a guide sleeve as shown in Fig. 4. The shear force supplied by the punch should only act on the internal aluminum layer. The guide sleeve was designed to control the accurate punch position and the contact stability. In the shear test, the bimetallic ring-shaped sample was placed into the groove on the top of the base. Then, the base was covered by the guide sleeve. The guide sleeve helps to prevent the plastic deformation of the base layer and restricts the movement of the punch onto the inner layer. At last, the testing unit was installed onto the electronic mechanical test platform for the shear test. The experiment was completed when the inner aluminum layer was separated from the CLAM base tube.

According to the results shown in Table 4, the sample in the middle segment of the clad tube possesses higher average shear strength, 73.8 MPa, approaching to 75 MPa, the shear strength of pure aluminum. Shear strength in middle segment of the clad tube is higher than that at the detonation end and at the tail end. These results are consistent with the observation of the abovementioned interfacial morphology.

3.4 Formability of the CLAM steel/aluminum clad tube

In order to further evaluate the plastic forming performance of the CLAM steel/aluminum clad tube, tube blanks that were cut out of the middle segment of the clad tubes were subjected to the reducer cold extrusion and hydroforming at room temperature. The surface of the tube blank was lubricated before cold forming. The punch extruded at the speed of 2 mm/s. During forming, the tail end experiences compression stress along axial and circular directions. Therefore, the base tube and the clad tube got remarkably thicker after deformation, and the obtained wall thickness was uniform. The manufactured reducer is shown in Fig. 5a. Apparently, the pure aluminum layer and the CLAM steel base layer are in good interface bonding, they are free from any delamination, forming parts are of good quality, and there are no cracks and wrinkles.

CLAM/Al clad T-branches are widely used in liquid Li–Pb loops in nuclear fusion engineering. After being further oxidized of the aluminum layer, which brings great value in improving electric insulation of pipeline system, promoting corrosion resistance of liquid Li–Pb toward base tubes, and reducing tritium penetration. In this study, the CLAM steel/aluminum clad tube was hydraulically bulged into the T-branch. During the hydroforming process, deformations of all parts vary greatly, causing easy delamination on the side wall of the branch tube and at the ends of the main tube. Figure 5b demonstrates hydroformed clad T-branch. The

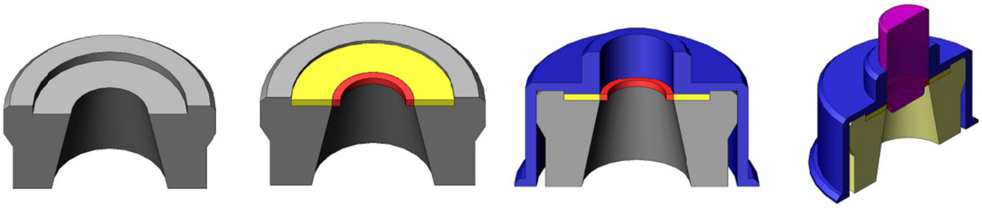

Fig. 4 Apparatus for the shear testing of the clad tube bonding strength

Table 4 Results of the shear test for the CLAM steel/aluminum bimetallic clad tube

Sampling position	Average shear strength/MPa	Fracture position and test effectiveness
Detonation end	62.7	Interface, effective
Tail end	73.0	Interface, effective
Middle segment	73.8	Interface, effective

CLAM steel/aluminum bimetallic T-branch had high accuracy and strong mold contact capability after the hydroforming process. Moreover, from the SEM image (Fig. 6), we know that there is no microcracks at the interface of the clad tube, the ends of the main tube, and the side wall of the branch tube are free from any delamination.

4 Conclusions

1. The interface of the CLAM steel/aluminum bimetal tube, prepared by explosive cladding, is wave-like and the width of the transition layer varies from 5 to 20 μm. There are no cracks, holes, or crushed particles in the direction perpendicular to the detonation direction.
2. The aluminum layer was not welded to the steel layer at the detonation end of the CLAM steel/aluminum bimetallic tube. Metallurgical bonding was formed both in the middle segment and at the tail end. Shear strength in the middle segment of the clad tube was higher than that at the detonation end and the tail end.
3. The CLAM steel/aluminum bimetal tube prepared through explosive cladding has the capability to withstand huge plastic deformation and could be further processed into tube fittings of more complex shapes to meet practical application requirements of the nuclear fusion engineering.

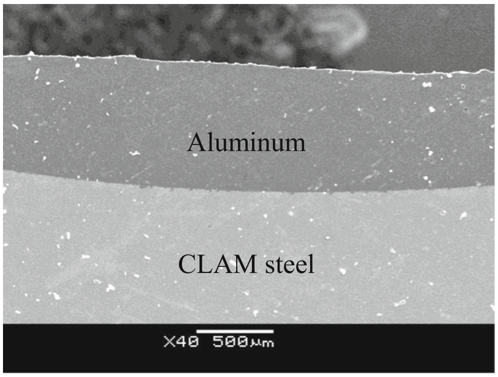

Fig. 6 Microimage of the clad T-branch end

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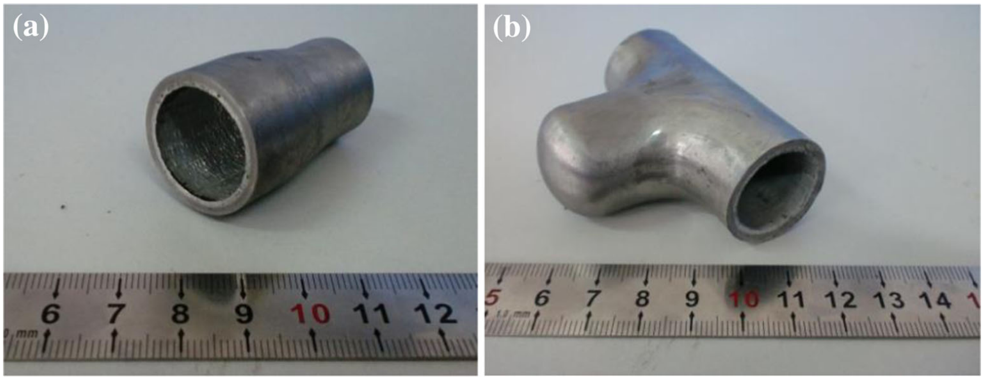
Fig. 5 Cold extrusion and hydroforming of the bimetallic tube: **a** reducer and **b** T-branch



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