



Study on Underwater Explosive Welding of Al-Steel Coaxial Pipes

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Abstract: In order to solve the aluminum surface ablation issue of Al-Steel bimetallic pipes manufactured by the explosive welding technique, a novel explosive welding system has been designed to weld Al-Steel coaxial pipes. The stand-off distance was chosen according to an empirical formula. A special Explosive Cord with an aluminum coating was used as the explosive. Four experiments were performed using Explosive Cords 1, 2, 3 and 4, respectively. In each experiment, three reliable PVDF (Polyvinylidene Fluoride) piezoelectric film sensors were used to sample the impact pressure between the parent pipe and the flyer pipe along the detonation direction. p-t Curves were obtained at different points on the bimetallic pipe manufactured by Explosive Cord 1. In order to observe the inner surface and to judge the bonding interface, specimens were cut along the axial direction. BSE (Backscattering Electron) images of the interfaces were obtained. According to these pictures from all of the specimens cut along the axial direction, the surface ablation phenomenon has disappeared. The bimetallic pipe manufactured by the new welding system using Explosive Cord 3 has an irregular wavy interface, between micro and small wavy interface, which is one of the best bonding forms.

Keywords: metal-matrix composites, explosive welding, surface ablation, microstructures, bonding interface

1 Introduction

Low carbon steel pipe has good mechanical properties and aluminum pipe has good corrosion resistance because of the oxide layer covering the surface. So an Al-Steel bimetallic pipe provides a good combination of mechanical properties with corrosion resistance. It can be widely used in urban construction, petroleum transportation, the chemical industry, nuclear facilities and the aerospace field. However, the physicochemical properties of aluminum and steel differ greatly. It is difficult to join them with traditional techniques. The explosive welding technique has been developed over more than 40 years. It is well known for its capability to directly join a wide variety of both similar and dissimilar combinations of metals that cannot be joined by any other techniques [1]. The bonding is generated by the high velocity oblique collision between the metals to be welded. As the detonation is activated, the flyer metal (plate or pipe) is drastically accelerated by the pressure of detonation and flies with very high velocity towards the parent metal (plate or pipe) as shown in Figure 1. Findik *et al.* reported many relatively complete studies on explosive welding of similar and dissimilar metals in tabulate geometry [2-5]. These studies showed that both similar and dissimilar combinations of metals could be bonded with good quality bonding properties by explosive welding. At the bonding interface, when the explosive ratio and the stand-off distance were increased, the smooth bonding interface transformed to a wavy bonding interface. For a wavy interface, when the explosive loading was increased, the wavy length and amplitude increased. Straight and wavy interfaces have similar strengths and heat treated specimens have more strength than unheated ones. Wang *et al.* obtained Al-Steel bimetallic plates by explosive welding using 2# Rock Explosive and analyzed the bonding interface [6]. The analysis showed that it is difficult to achieve a wavy welded interface between Al and Steel due to their huge differences in density and melting point. The conclusions indicated that a welding window for these two metals exists, but it is too narrow to obtain a nice bonding interface. Some other researchers have done work on Al-Steel plates by explosive welding, but few in a cylindrical geometry [7-10].

Zamani *et al.* presented relatively complete research on explosive welding in a cylindrical geometry [11]. They focused on the explosive welding of a bimetallic pipe, in which the outer and inner pipes were CK22 carbon steel and 316L stainless steel, respectively. However, the melting point of aluminum is 933 K, which is much lower than that of stainless steel (1653 K). If the same manufacturing method is used to weld aluminum and low carbon steel, it may cause serious aluminum surface ablation as shown in Figure 2. In order to

decrease the surface ablation, X. Guo tried changing the detonation velocity of the emulsion explosive, but the surface ablation phenomenon still existed. In addition, the energy utilization efficiency of the traditional method is extremely low, so the noise produced by the explosion can still be very high at a distance of 5000 m. Explosive welding underwater can significantly reduce noise pollution. Some researchers have welded plates underwater using the explosive welding technique [12-17]. Nonetheless there are very few references about underwater explosive welding of cylindrical members.

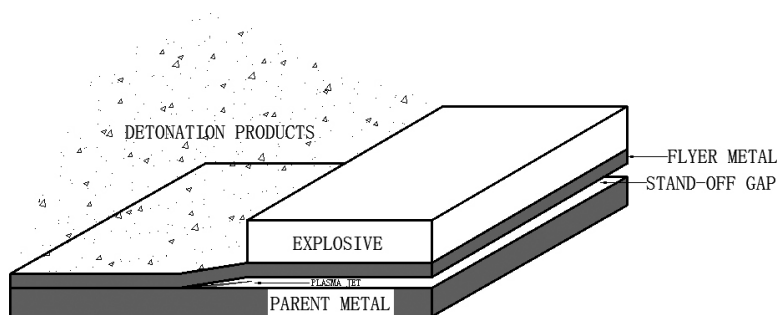


Figure 1. Schematic diagram of explosive welding process in planar geometry



Figure 2. Ablation phenomenon in the surface of Al-Steel pipe by the old explosive welding method

To eliminate the ablation phenomenon of the inner pipe and to reduce the noise pollution of explosive welding in the cylindrical geometry, an explosive

welding system was designed to weld Al-Steel coaxial pipes, and is described in this article. The aim of this study was to try to weld Al-Steel coaxial pipes underwater with a good bonding interface and to investigate the changing impact pressure and the changing interface morphology along the detonation direction. Q235 carbon steel and 1060 aluminum were chosen as the parent and flyer pipes, respectively. The stand-off distance was 1 mm according to the empirical formula. The explosive load was variable. Four experiments were performed under different explosive loads. In each experiment, three reliable PVDF (Polyvinylidene Fluoride) piezoelectric film sensors were used to sample the impact pressure between the parent and flyer pipes along the detonation direction. In order to observe the inner surface and to judge the bonding interface, specimens were cut along the axial direction. BSE (Backscattering Electron) images of the interfaces were obtained.

2 Materials and Methods

2.1 Aluminum coated explosive cord and pipes

Tubes are axisymmetric, stable and economic structures. Aluminum Coated Explosive Cords were made from aluminum tubes of cylindrical geometry filled with RDX (hexogen) and some passivators such as paraffin and inorganic salts. This assembly can ensure the uniformity of explosive density and be suitable for industrial production, long term storage and long distance transportation. It is a special columnar explosive with aluminum coating as shown in Figure 3 (this coating is not only confined to aluminum; it can also be used for other metals such as lead, silver and some other soft materials). In our experiments the Aluminum Coated Explosive Cords were comprised of RDX and K_2SO_4 (85 wt.% and 15 wt.%, respectively). The aluminum coating guarantees that the explosive has good water proofness, which is very important for our explosive welding system. Although the Explosive Cords used in our experiments had different linear densities, their detonation velocities were close to 6900 m/s, with specifications given in Table 1.

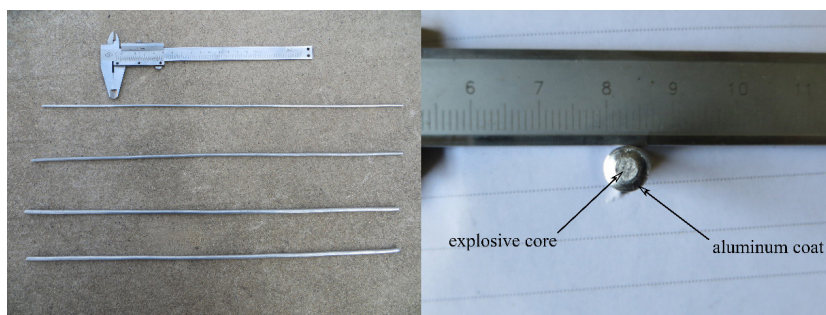


Figure 3. Aluminum Coated Explosive Cord

Table 1. Specifications of the Explosive Cord

Explosive Cord	Outside diameter [mm]	Linear density [$\text{g}\cdot\text{m}^{-1}$]	Detonation velocity [$\text{m}\cdot\text{s}^{-1}$]	Mass fraction of components [%]	
				RDX	K_2SO_4
1	3.0	4.0	6960	85	15
2	4.0	9.3	6900		
3	5.0	14.7	6870		
4	6.0	19.8	6830		

Table 2. Dimensions of the pipes

Materials	Length [mm]	Inside diameter [mm]	Outside diameter [mm]	Wall thickness [mm]
Steel of Q235	500	32.0	38.0	3.0
Aluminum of 1060	550	28.0	30.0	1.0

Table 3. Main properties of the pipes

Materials	P [$\text{kg}\cdot\text{m}^{-3}$]	σ_s [MPa]	σ_b [MPa]	δ [%]	$\mu/1$	E [GPa]	Melting point [K]
Steel of Q235	7850	225	420	25	0.26	206	1766
Aluminum of 1060	2710	75	124	25	0.33	68.9	933

The parent pipe was Q235 carbon steel and the flyer pipe was 1060 aluminum. Their dimensions and main properties were shown in Tables 2 and 3, respectively.

1.2 Interior explosive welding system

The welding system (shown in Figure 4a) was composed of water, parent pipe, flyer pipe, Explosive Cord, detonator and locating plate. The dimensions of the pipes made the stand-off distance to be 1 mm. The Explosive Cord was detonated by the detonator. The detonation wave propagates in the explosive. When it passes through the interface of the Explosive Cord and water, a strong shock wave is created in the water. The space occupied by the Explosive Cord is now full of high pressure detonation products. The shock wave impacts upon the flyer pipe and accelerates it. Simultaneously, the expansion of the high-pressure detonation products accelerates the flyer pipe by driving water. The flyer pipe then collides with the parent pipe at a relatively high velocity. A schematic diagram of the system is shown in Figure 4b.

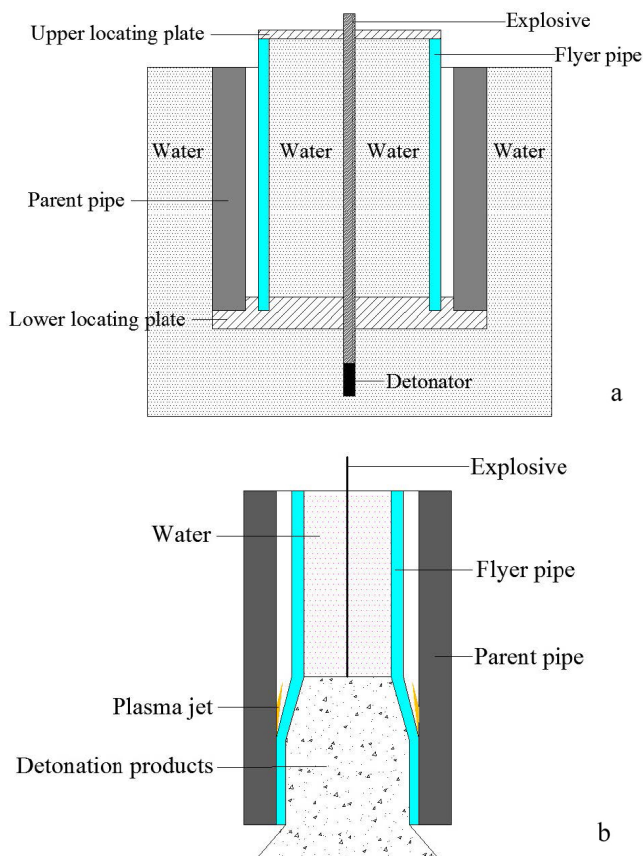


Figure 4. (a) Diagram of the welding system, (b) Schematic diagram of explosive welding process in cylindrical

Hokamoto *et al.* used a high explosive SEP (Asahi Chemical Industry, Japan), with a detonation velocity and density of $7000 \text{ m}\cdot\text{s}^{-1}$ and $1.3 \text{ g}\cdot\text{cm}^{-3}$ respectively, on Al/ZrO₂ underwater explosive welding [12]. In view of this, four kinds of explosives with a mean detonation velocity of $6890 \text{ m}\cdot\text{s}^{-1}$ were adopted in our experiments. The flyer pipe and the parent pipe were coaxial. The stand-off distance is determined by Equation 1, in which S represents the stand-off distance and δ_1 is the thickness of the flyer pipe.

$$S = (0.5\sim 1)\delta_1 \quad (1)$$

In our experiments, the thickness of the flyer pipe was 1mm and the stand-off distance was 1 mm. The explosive load was variable. Because this is a new welding system and there is almost no relevant literature, four kinds of explosives were used to weld Al-Steel coaxial pipes. In each experiment, three reliable PVDF piezoelectric film sensors were used to sample the impact pressure between the parent and flyer pipes. We stipulate that “Specimen 1” means a specimen cut from the bimetallic pipe manufactured by Explosive Cord 1 and that “Specimen 2” means a specimen cut from the bimetallic pipe manufactured by Explosive Cord 2, and so on. In order to observe the interfaces, the specimens were cut along the axial direction. BSE (Backscattering Electron) images of the interfaces were obtained.

3 Results and Discussion

3.1 Impact pressure test

The p-t curves (Figure 5) were obtained at different points on the bimetallic pipe manufactured by Explosive Cord 1. The calculated mean peak pressure was 502.06 MPa. According to the relationship between the impact velocity and the impact pressure in explosive welding, the impact velocity was $49.53 \text{ m}\cdot\text{s}^{-1}$, obtained by Equation 2 for the case of the known impact pressure. In Equation 2, ρ_1 and ρ_2 are the densities, and v_{s1} and v_{s2} are the sound velocity in the flyer and parent pipes, respectively.

$$v_p = \frac{p \left(1 + \frac{\rho_1 v_{s1}}{\rho_2 v_{s2}} \right)}{\rho_1 v_{s1}} \quad (2)$$

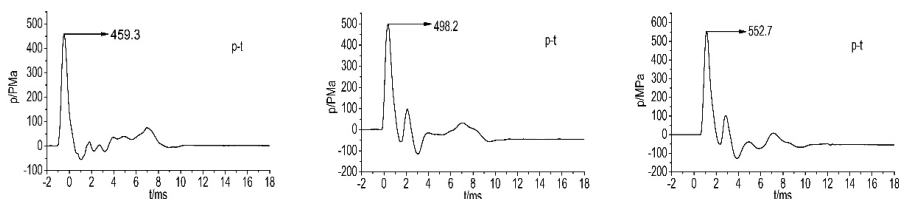


Figure 5. p-t Curves in three effective points along the detonation direction

However, this is not high enough to attain the welding velocity of Al-Steel. It is speculated that the bonding is mechanical bonding. One of the main reasons is that the explosive content in Explosive Cord 1 is not high enough. The PVDF piezoelectric film sensors did not produce any data in the other three experiments. A possible reason for this was that the sensors were damaged by the plasma jet before the flyer pipe impacted the parent pipe. On the other hand, it means that the metallurgical bonding may be formed in the other three bimetallic pipes. The p-t curves also showed that the impact pressure increased along the detonation direction. The main reason for this is that the conical underwater shock waves strike the pipe and form reflected shock waves. The reflected shock waves then strike the pipe after this point as incident shock waves and reflect again. A schematic diagram of the shock waves in the tube internal reflection is shown in Figure 6. GH is the Explosive Cord and GA is the reaction zone. When the detonation waves propagate to point A , conical underwater shock waves form with A as the vertex. The detailed reflection process: AB and AC are the incident wave fronts. As they reach the inner wall, they will strike and be reflected at point B and C , respectively. As the detonation wave propagates along AH , the conical underwater shock waves will pass A_1 , A_2 and A_3 in turn. Actually, the incident wave (AB) casts along AB_3 which is perpendicular to AB . The reflected wave (B_1D_1) casts along BF_3 which is perpendicular to B_1D_1 and it is easy to see that the movement direction of B_1D_1 is the same as that of AC . So, the B_1D_1 will strike the inner wall as an incident wave and be reflected again. In the same way, the incident wave (AC) can be analyzed. The strike will weaken during every reflection, but the inner wall will be struck more and more along the detonation direction.

3.2 Observations on the specimens

The specimens cut along the axial direction are shown in Figures 7, 8 and 10. We can see that the inner surfaces of all of the specimens are smooth. The ablation phenomenon has not occurred, which means that the new welding system can effectively solve the ablation problem. The main reason for this is that when the

explosive detonates in the air it can produce a temperature of 2000–4000 K which may damage the flyer pipe; when it is detonated underwater the temperature increase of the water is not significant, because water is incompressible compared to air.

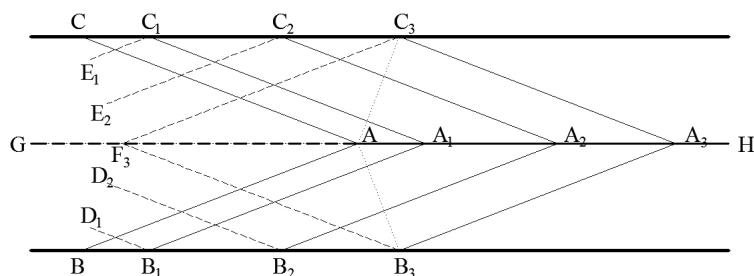


Figure 6. Schematic diagram of the shock wave in the tube internal reflection

In Specimen 1 (Figure 7), the flyer pipe breaks away from the parent pipe. Cutting the specimen along the axial direction releases circumferential stress, which indicates the bonding between aluminum and steel is mechanical bonding. The main reason for this is that the explosive content is too small to accelerate the flyer pipe sufficiently.

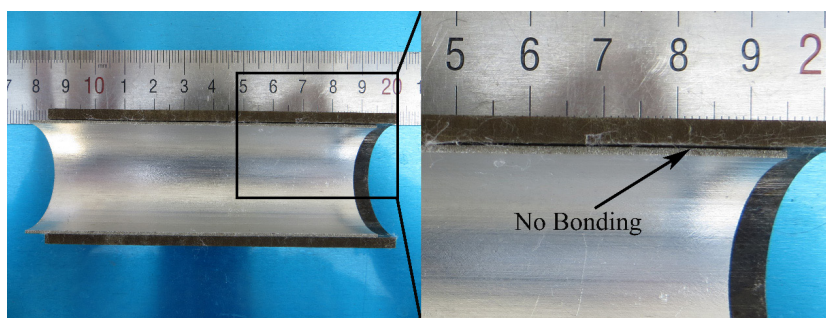


Figure 7. Picture of Specimen 1 cut along the axial direction

In Specimen 2 (Figure 8), the flyer pipe has bonded to the parent pipe in most areas except the end of the specimen. BSE observation (Figure 9) shows the wavy interface has been formed in some areas of the bonding interface, but there are some longitudinal microscopic cracks formed in the parent pipe near the bonding interface. This kind of bonding is not good enough for the explosive welding of bimetallic pipes, although it is difficult to achieve a good bonding interface between aluminum and steel due to their huge differences in density

and melting point. The main reason for this is again that the explosive content is not large enough. Releasing circumferential stress produces macroscopic cracks, and because of the stress concentration phenomenon microscopic cracks form at the interface.

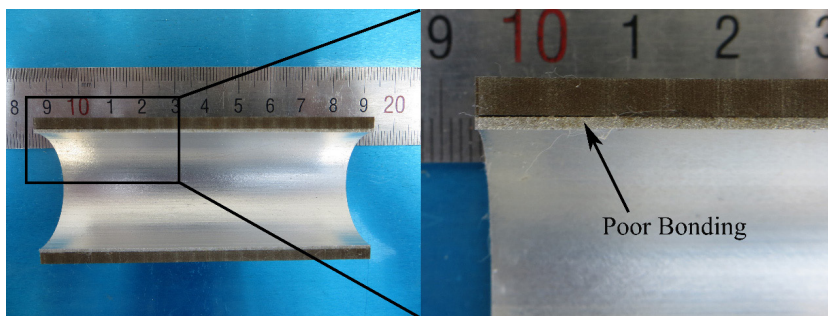


Figure 8. Picture of Specimen 2 cut along the axial direction

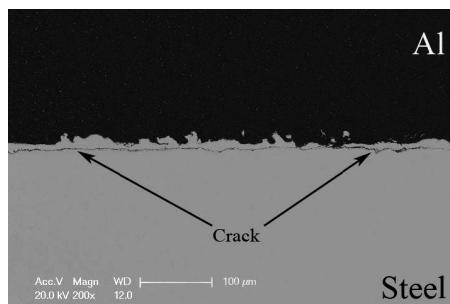


Figure 9. BSE micrograph of Specimen 2

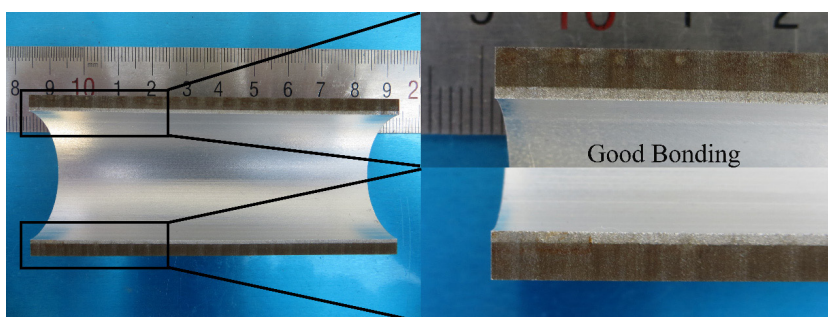


Figure 10. Picture of Specimen 3 cut along the axial direction

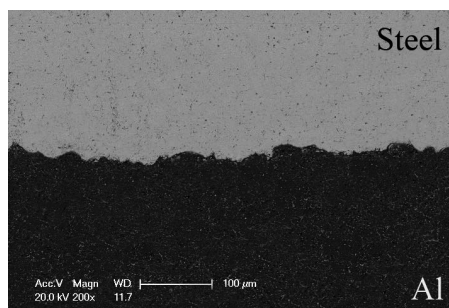


Figure 11. BSE micrograph of Specimen 3

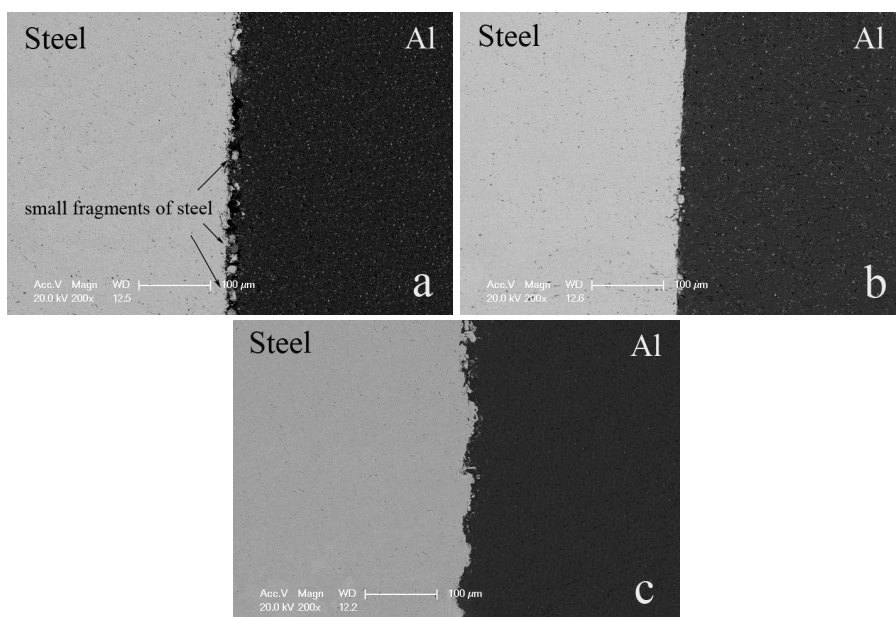


Figure 12. BSE micrograph of the interfaces of different parts of the bimetallic pipe manufactured by Explosive Cord 3: (a) the head; (b) the middle (c) the end

In Specimen 3 (Figure 10), there is no gap between the parent and flyer pipes to the naked eye. However, this is not a reliable judgement that the bonding is good. To study how good the join is, BSE images (Figure 11) of the interface were obtained. Figure 11 shows that an irregular wavy interface has been formed. This bond has generally good strength because of the large and wavy contact surface, although a straight interface can be at least equally strong as the one exhibiting

a wavy interface [2, 18]. It is generally recognized that there are three wavy interfaces [19]: big wavy (the wavelength is generally around 300 μm , the height of wave being generally around 100 μm and 150 μm), small wavy (the wavelength is generally around 50 μm and 200 μm , the height of the wave being generally around 50 μm), micro wavy (the wavelength is generally around 100 μm , the height of wave being generally around 20 μm) [20]. The interface of the Al-Steel bimetallic pipe in Specimen 3 is an irregular wavy contact. Judged from the wavelength and wave height it belongs to a wavy interface between micro wavy and small wavy. Compared with the bonding interface of big and small wavy, this kind of wavy interface has a higher bonding strength [21]. Another three specimens along the detonation direction were taken from the head, middle and end of the bimetallic pipe manufactured by Explosive Cord 3. BSE images (Figure 12) of the interfaces of these three specimens were obtained. The BSE micrograph of the head specimen shows that there are some small fragments of steel in the microscopic crack of the interface (Figure 12a). The main reason for this is that the unstable detonation of the Explosive Cord cannot provide sufficient energy. When the detonation approaches a stable situation, the small fragments decrease and the interface becomes straight (Figure 12b). The BSE micrograph of the end specimen (Figure 12c) shows that a continuous micro wavy interface has formed. This is because of fluidization and intensive deformation under high pressure and high-strain-rate phenomena in the interfacial area. Acarer *et al.* [2] concluded that the bonding interface changed from a straight to a wavy structure when the explosive loading and stand-off distance were increased. In the present experiments, the stand-off was constant and the explosive loading was uniform along the detonation direction. So the interface transformation from straight to wavy is evidence of increasing impact pressure along the detonation direction on the one hand, and on the other hand it indicates that the welding window of these two metals is too narrow, because of different bonding interfaces in the same bimetallic pipe were obtained. The increasing impact pressure phenomenon is the most important character of explosive welding in the cylindrical geometry. The study of this phenomenon will contribute to improving the charge structure of explosives and to saving explosives.

In the experiment using Explosive Cord 4, a bimetallic pipe with a large longitudinal opening was obtained as shown in Figure 13. The reason for this is that water outside the parent pipe cannot provide enough resistance under the explosive content of Explosive Cord 4, which is a weakness of the welding system. Although a strong constraint such as a backer anvil could be applied outside the parent pipe, the water constraint is very simple and economic for large-scale industrial manufacturing.



Figure 13. Picture of Specimen 4 with a big longitudinal opening

4 Conclusions

In this study, underwater explosive welding of aluminum 1060 and carbon steel Q235 was carried out with different explosive loads. The impact pressures between the parent and flyer pipes were tried being got in different experiments. To study the bonding interfaces the micro-structural features of the interfaces were investigated. The following conclusions can be drawn:

- a) All of the bimetallic pipes manufactured have a smooth inner surface, which means the new welding system can successfully eliminate the ablation phenomenon in aluminum pipes.
- a) The impact pressure between the parent and flyer pipes increases along the detonation direction.
- b) The explosive welding window of the Al-Steel combination is too narrow to obtain different bonding interfaces in the same experiment.
- c) The backscattering electron images show the bimetallic pipe manufactured using Explosive Cord 2 has a poor bonding interface, whereas the one using Explosive Cord 3 has an irregular wavy interface, between a micro and small wavy interface, which is one of the best bonding forms with high bonding strength.

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