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Effect of interface morphology on the mechanical properties of titanium clad steel plates

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Abstract: Interface morphology has important influence on the bond quality of titanium clad steel plates. The mechanical properties of titanium clad steel plates with wavy and straight interfaces were investigated by tensile-shear tests and bending tests. The interface morphology of the plates was examined by optical microscopy (OM) and scanning electron microscopy (SEM). The experimental results show that the shear strength of a wavy interface is higher than that of a straight interface. A wavy interface is the guarantee for obtaining high shear strength to provide a greater shear resistance. During the macrobending process, cracks appear in the swirl of the wave tip and ferrotitanium intermetallics. For *in-situ* observing the bending process by SEM, the wave tip of a wavy interface and the massive ferrotitanium intermetallics of a straight interface are places where cracks initiate and propagate. The results are the same as those observed in the macrobending process. Because of high hardness, the wave tip and the massive ferrotitanium intermetallics are hard in terms of compatible deformation.

Keywords: clad metals; cladding; titanium; low carbon steel; interfaces; morphology; mechanical properties

1. Introduction

Titanium (hereafter, Ti) shows excellent corrosion resistance and high strength-to-weight ratio. In order to take advantage of the outstanding corrosion resistance of Ti and the splendid strength of steel, Ti clad steel is proposed. Due to its great mechanical properties and low fabrication cost, Ti clad steel is universally used in pressure vessels, flue gas desulfurization (FGD) engineering in a power plant, and the anticorrosion of chemical equipment [1].

The main obstacle of manufacturing Ti clad steel is how to make Ti and steel join together. Explosive cladding, as a solid state metal-joining process, creates a metallurgical bond between two metal components by explosive force [2-3]. This process could effectively minimize the area of heat affected zones and decrease brittle intermetallic layers. The morphology of a typical explosion bond interface is a wavy bond zone, which exhibits high bond strength. The interface region of the dissimilar explosive cladding joints of Ti to steel was examined by hierarchical structure levels, such as macroscopic, mesoscopic, microscopic, and nanoscale [4-7]. There was a reaction layer of about 100-300 nm thick consisting of nanosized grains formed along the entire bonding interface.

Large area and thin cladding metal is hard to produce by the explosive cladding process. An advanced method, explode-rolled [8], by which blanks are made first by exploding, and subsequently rolled into thin clad plate has been invented. The interface of an explode-rolled titanium clad steel plate is straight. Interface morphology plays an important role in the interfacial bond strength of titanium clad steel plates. Thus, this paper aims to study the effect of wavy interfaces and straight interfaces on shear and bending properties and to analyze crack initiation and extending on interfaces based on *in-situ* observation results during the bending process.

2. Experimental procedure

Commercial purity Ti (CP-Ti) plates and low carbon steel sheets were joined by explosive cladding and explode-rolled cladding. CP-Ti was chosen to act as an overlay plate, while low carbon steel was performed as the base plate. Their

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chemical composition is given in Table 1. The thickness of the explosive Ti clad steel plate was 4 mm CP-Ti + 36 mm low carbon steel, and the thickness of the explode-rolled titanium clad steel plate was 1.2 mm CP-Ti + 10 mm low carbon steel.

Table 1. Chemical composition of the materials **wt%**

Materials	C	Mn	P	Si	S	N	H	O	Fe	Ti
CP-Ti	0.009	—	—	—	—	0.012	0.002	0.06	0.031	Bal.
Low carbon steel	0.17	0.51	0.018	0.17	0.011	—	—	—	Bal.	—

Samples for microstructural observation were extracted from the central part of the clad on a plane parallel to the detonation. All specimens were ground to 1 μm thick and further polished. The base plate was etched in a 4vol% nitric acid solution. The microstructure of the samples was observed by optical microscopy (OM ZEISS AX10) and scanning electron microscopy (SEM, ZEISS ULTRA 55).

Tensile shear strength was measured by tensile-shear tests, and the samples and tests were cut and carried out according to GB/T 8546—2006 (titanium clad steel plates) and GB/T6396—2008 (clad steel plates-mechanical and technological test), respectively. Despite the influence of thickness on strength, all shear strength was replaced by tensile shear strength uniformly in the tests. Fig. 1 shows the specifications of a tensile-shear specimen.

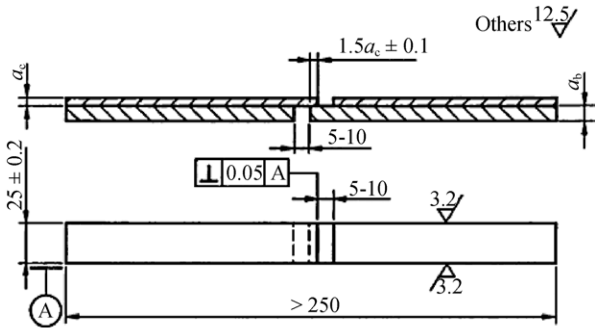

Fig. 1. Specifications of a tensile-shear specimen (unit: mm). a_b—thickness of the overlay plate; a_c—thickness of the base plate.

An internal bend test was used to measure the bending properties of titanium clad steel plates. A JSM-5800 electron microscope and a DEBEN test bed were applied to observe the *in-situ* bending process of the clad plates (the largest load of the DEBEN test bed was 5000 N, and the maximum length for bending was 10 mm). The size of the sample was 1 mm×1 mm×50 mm. The thickness of CP-Ti was the same as that of low carbon steel. Fig. 2 shows the bending process of the three-point test.

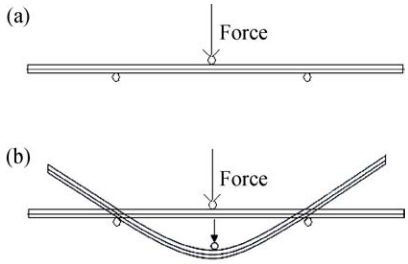

Fig. 2. Bending process of a three-point test for the specimen: (a) before loading; (b) loading.

3. Results and discussion

3.1. Microstructure

Fig. 3 shows the microstructures of titanium clad steel plates under an optical microscope. The typical morphology of the explosive clad plate with a wavy interface is presented in Fig. 3(a); the length and height of the wave are 0.8 and 0.2 mm, respectively. The interface is outlined by a characteristic sharp transition between Ti and the steel. The rheological microstructure with plastic deformation near the interface of the steel can clearly be seen in Fig. 3(a). The formation of a wave crest along the boundary of Ti and the steel indicates that the most severe deformation occurs; and the farther away from the wave crest, the less plastic deformation occurs. Metal frit appears at the wave tip. The microstructure of the steel consists of ferrite and pearlite. However, the straight interface of the explode-rolled clad plate is demonstrated by Fig. 3(b); moreover, lots of polygon or elongated white hard lumps are distributed inhomogeneously in the steel. In addition, the microstructure of the matrix steel is partly recrystallized.

3.2. Tensile-shear test and analysis

Specimens from the two Ti clad steel plates were prepared for the tensile-shear test. The effect of interfaces on the tensile-shear process was taken into consideration while ignoring the influence of the clad plate thickness. The width of the bonding part during the tension-shear test is 1.5 times thick of the clad plate. The results are listed in Table 2.

Table 2 shows that shear strength of the explosive clad plate is up to 40 MPa higher than that of the explode-rolled clad plate. It also shows that a wavy interface results in a higher shear strength than a straight interface. The fracto-

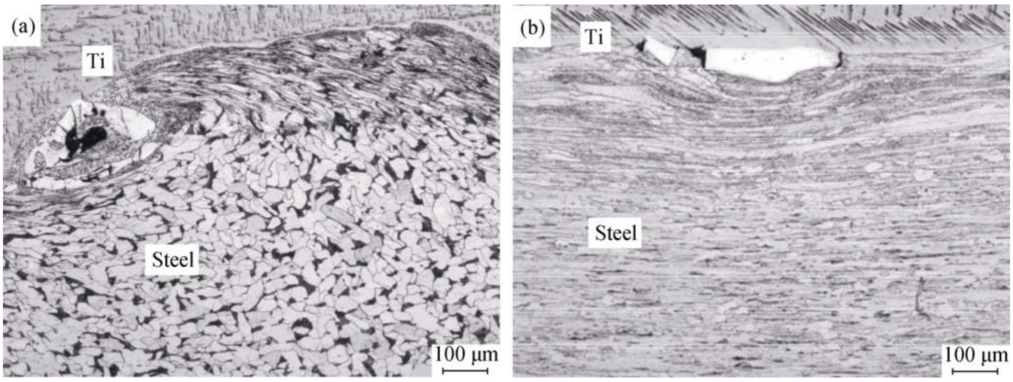

Fig. 3. Microstructures of titanium clad steel plates: (a) wavy interface; (b) straight interface.

Table 2. Shear strength of the two titanium clad steel plates

Materials	Average shear strength / MPa
Explosive titanium clad steel plate	205
Explode-rolled titanium clad steel plate	168

graphs of both the plates were investigated to clarify the fracture mechanism of the plates.

Fig. 4 presents the fracture surface of the explosive clad plate after the tensile-shear test. The wavy microstructure of the low carbon steel interface splits and fractures with a wave crest partly sliced off during the tension-shear process. In addition, fractures at the wave crest differed significantly from that at half of the wave and trough, as tiny grains appeared on the interface of the wave crest. The mark of splitting is clearly demonstrated on the interface of the trough, and the interface is relatively smooth. The interface of CP-Ti is similar to that of low carbon steel, except the weakened wave character in which the wave crest is shorter.

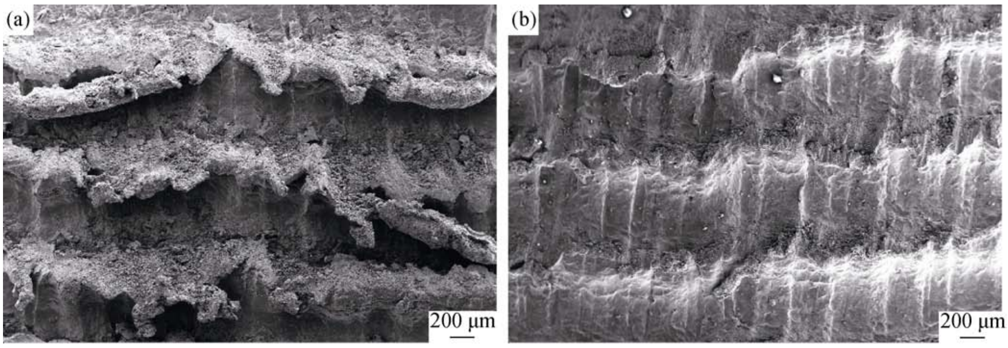

Fig. 4. SEM micrographs of the fracture surface of the explosive clad plate: (a) low carbon steel; (b) CP-Ti.

The interface wave deforms irregularly under the tension-shear force, which leads to fracture. Under the tension-shear force, the wave rolls and shears, and the wave tip is the initial position where rolling and shearing occur. By analyzing the interface at different positions, it seems that the split marks are mainly detected at the trough, while tiny grains are segregated at the wave crest, all of which verify the analysis discussed above.

The surface fracture of the explode-rolled titanium clad steel plate illustrated in Fig. 5 is relatively smooth. By analyzing the interface of low carbon steel, it is concluded that the wavy interface was damaged during rolling. Along with the development of relative slipping between CP-Ti and low carbon steel, the continuous (connecting) wavy interface was fragmented, and intermetallics in the form of lumps was retained and distributed randomly on the bonding interface.

According to the aforesaid analysis, it is clear that during the tension-shear process of the two clad plates, the resistance of the wavy interface to shear is larger than that of the straight interface, indicating that the interface morphology has huge effect on shear strength.

3.3. Bending process test and analysis

According to GBT6396—2008 (clad steel plates-Mechanical and technological test), the explosive clad plate sample of 25 mm thick and the explode-rolled plate sample of 11.2 mm

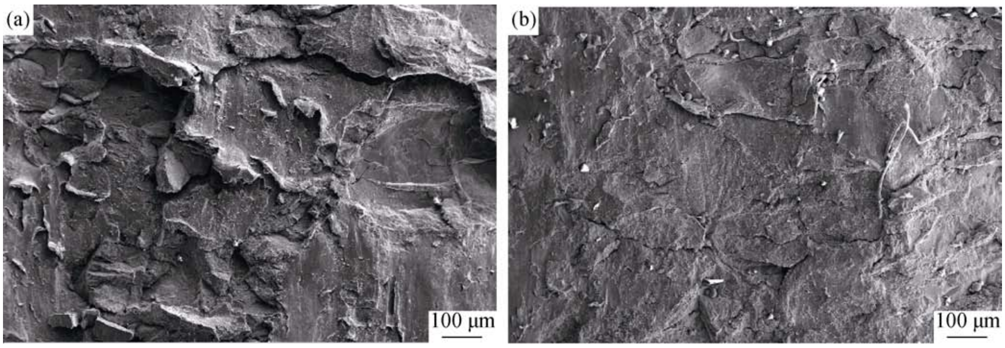

Fig. 5. SEM micrographs of the fracture surface of the explode-rolled clad plate: (a) low carbon steel; (b) CP-Ti.

thick were prepared. During the bending process, CP-Ti is inside, while low carbon steel is outside. The plastic deformation behavior of the titanium clad steel plate and the impact characteristics of interfaces on the plastic deformation were investigated.

When the bending angles of the explosive clad plate and the explode-rolled clad plate are 180°, the interfacial bonding is in a sound condition without separation, and no fracture formed within the cladding metal and the base metal. Fig. 6 shows the metallographic maps of the titanium clad steel plate after bending, and it can be seen that cracks appear in the shape of a swirl at the wave tip of the explosive clad plate; and intermetallics on the interface of the explode-rolled clad plate is broken. By the internal bend test, it is found that the adjacent area of interface bonding is mainly under pressure, and the pressure is centered in the swirl of the wave tip and ferrotitanium intermetallics where cracks exist.

By *in-situ* observation during the bending process, the initiation position and propagation path of cracks on the clad plate interface were analyzed. With the load increasing, both low carbon steel and CP-Ti deformed and coordinated at spots in the adjacent of interfaces. Facture formed at the center of stress if the deformation failed to be coordinated. Moreover, cracks propagated under the imposed load with further loading.

Fig. 7 shows that during the *in-situ* bending process, cracks initiate at the wave tip and then extend with the bending angle increasing. The position where cracks initi-

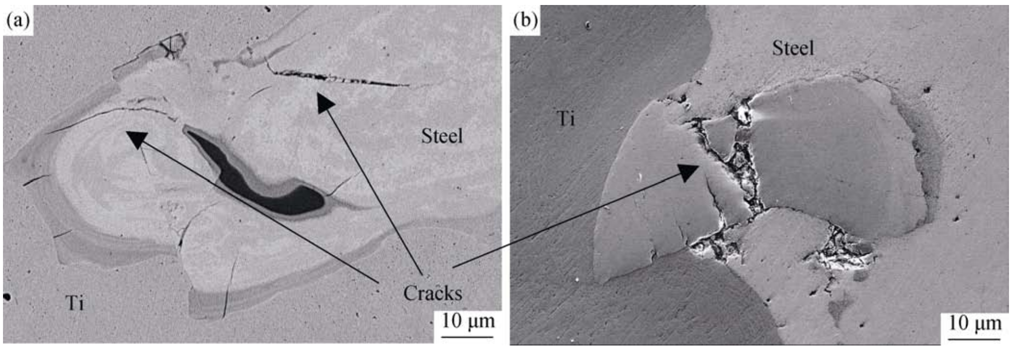

Fig. 6. SEM micrographs of the titanium clad steel plate after bending: (a) explosive clad plate; (b) explode-rolled clad plate.

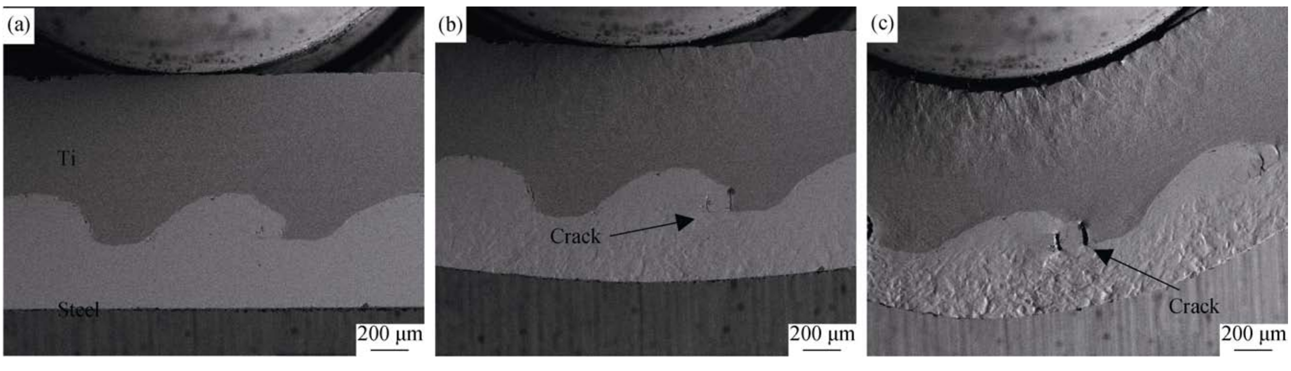

Fig. 7. SEM micrographs of the *in-situ* bending process of the explosive titanium clad steel plate: (a) before the bending process; (b) crack initiation; (c) crack propagation.

ated indicates that it is the center of stress. The deformation fails to coordinate during the plastic deformation if the hardness of low carbon steel and CP-Ti varies greatly, thus cracks generate. As for the wave tip, cracking happens here because the hardness of intermetallics at the wave tip is higher than that of low carbon steel and CP-Ti. The observation results are compatible with the ones analyzed on crack formation and propagation in an explosive titanium clad steel plate by other research methods in Refs. [2-5], namely, the wave tip is one of the positions where cracks form easily.

Fig. 8 shows that during the *in-situ* bending process of the exploded-rolled clad plate, cracks initiate at intermetallics on the interface. Since the intermetallics have a higher hardness than CP-Ti and low carbon steel, it is likely to become the center of stress. During the loading process, the intermetallics also fractures to release stress, and CP-Ti and low carbon steel can coordinate better.

The results indicate that cracks initiate at the wave tip during the tension-shear process. Then, cracks extend due to the interface separation of the clad plate under shearing. Intermetallics along the interfaces provide more resistance to hinder crack propagation during interfacial movement.

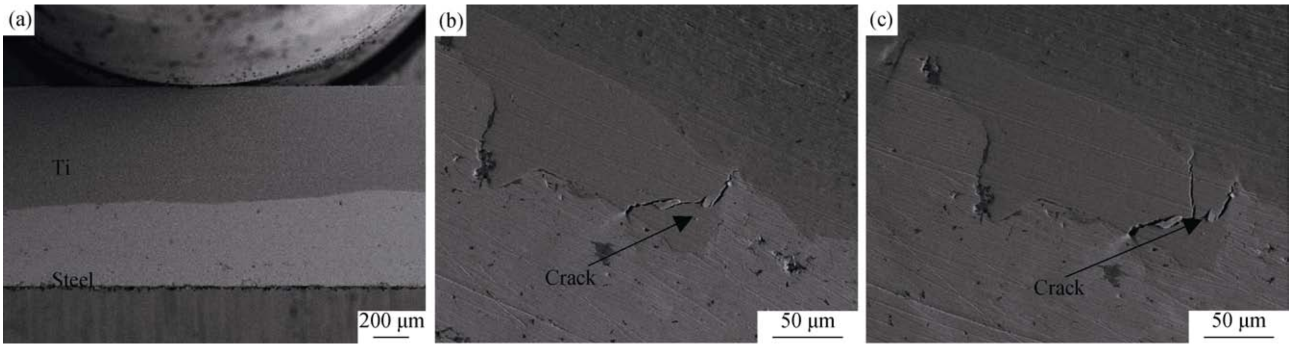

Fig. 8. SEM micrographs of the *in-situ* bending process of the explode-rolled titanium clad steel plate: (a) before the bending process; (b) crack initiation; (c) cracks propagation.

4. Conclusions

(1) The explosive titanium clad steel plate contains a wave interface caused by plastic deformation within the steel, while the explode-rolled titanium clad steel plate comprises of a straight interface along with intermetallics.

(2) The tensile-shear strength of a wavy interface is higher than that of a straight interface. A wavy interface is the guarantee for obtaining high shear strength to provide a greater shear resistance, and massive ferrotitanium intermetallics on the straight interface are favorable for improving the shear strength.

(3) For the clad plate with a wavy interface, cracks exist at the wave tip during the bending process. Moreover, for the clad plate with a straight interface during the bending process, cracks exist in intermetallics.

(4) For the *in-situ* observation of the bending process, the wave tip on the wavy interface and the massive ferrotitanium intermetallics on the straight interface are places where cracks initiate and propagate. The result is in line with observations in the macrobending process.

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