JMEPEG (2011) 20:911–917
DOI: 10.1007/s11665-010-9712-3

1059-9495/$19.00

Study on the Technology of Explosive Welding Incoloy800-SS304

Hui Zhao, Pingcang Li, Yinggang Zhou, Zhanghong Huang, and Hunian Wang

(Submitted September 15, 2009; in revised form May 24, 2010)

In this article, Incoloy800 and SS304 (304 stainless steel) were cladded by explosive welding. Accordingly, micro-hardness, tensile strength, shearing strength, bending properties, and SEM microstructure of cladding plate were examined in detail. The bonding interface of the plate showed a wavy morphology. Whereas, a different colorful area was observed at the wave ridge of the base layer either in optical or SEM pictures. Magnetic inspection showed that the colorful area was austenitic steel. Thus, the occurrence of the colorful areas seemed to be the result from the high deformation/cold working of the grains. EDX spectrum analysis and line scanning indicated that the diffusion through the bonding interface was not observed under the EDX and line scanning detection limitation. Micro-hardness, tensile, shearing, and bending testing results showed that the bonding strength was acceptable according to ASTM specification.

Keywords 304 stainless steel (SS304) plate, cladding plate, explosive welding, Incoloy800 alloy plate

1. Introduction

Incoloy800 alloy is a widely used material of construction for equipment because of its high strength, high resistance of oxidation, carburization, and other harmful effects during high-temperature exposure. It is a first choice for an upgrade from the 300 series stainless steels when improved performance or strength at high temperature is required. Thus, these alloys are used for heat-treating equipment, such as baskets, trays, and fixtures. And in chemical and petrochemical processing, these alloys are often used for heat exchangers and other piping systems in nitric acid media especially where resistance to chloride stress-corrosion cracking is required. In nuclear power plants, it is also used for steam-generator tubing. And these alloys are often used in domestic appliances for sheathing of electric heating elements. In petroleum processing, these alloys are used for heat exchangers that air-cool the process stream. The chromium in the alloy imparts resistance to oxidation and corrosion. The high percentage of nickel maintains an austenitic structure so that these alloys are ductile. The content of nickel contributes resistance to scaling, general corrosion, and stress-corrosion cracking (Ref 1-4). However, these alloys bring work-hardening during machining and have higher strength and "gumminess," which is not typical for steels. Heavy duty machining equipment and tooling should be used to minimize chatter or work-hardening of these alloys ahead of the cutting. For the sake of these excellent properties, the price of these alloy are very high (Ref 5, 6). Accordingly, the cost of the equipment used Incoloy800 is high. Therefore, it is necessary to take methods to change the situation. Explosive welding is a method which welds two or more plates with each other by high pressure coming from explosion. It attracts us for joining the dissimilar metal and alloys with varying physical and metallurgical properties. In spite of the occurrence of amount heat during explosive welding, a heat diffusion is not observed from one plate to another due to lack of time (Ref 7-12). So far microstructural characteristics and mechanical properties of explosively welded metals and their alloys have been studied by several investigations (Ref 7-18). However, few works has been conducted on the study of Incoloy800 alloys cladding to stainless steel. In this article, the microstructure and mechanical properties of the explosive welded Incoloy800 and the 304 stainless steel (SS304) are investigated.

Hui Zhao, Pingcang Li, Yinggang Zhou, and **Hunian Wang**, Xi'an Tianli Clad Metal Materials Co., Ltd., Xi'an 710065 Shanxi, China; and **Zhanghong Huang**, Xi'an Western Titanium Technologies Co., Ltd., Xi'an 710016 Shanxi, China. Contact e-mail: huier7921@126.com.

2. Experimental

2.1 Materials and Explosive Cladding Process

In this article, Incoloy800 alloy plate matching ASTM B409 specification was used as the flyer plate. And, the 304 stainless steel (SS304), conforming to ASTM A240 specification, was used as the base plate. The chemical compositions of the materials are shown in Table 1. The dimensions of Incoloy800 alloy and SS304 were $3 \times 300 \times 300$ mm and $21 \times 300 \times 300$ mm, respectively. The surfaces of the base and flyer plates were used as received. The 14-4# (ammonium nitrate about 90%, minimum 7% fuel-oil, and minimum 3% TNT) was chosen as explosive material supplied by Shanxi Hongqi Industrial Explosive Co., Ltd., China. The detonation velocity of the explosive material was 2900-3200 m s^{-1}. The density of explosive was about 0.89 g/cm^{-3}. The parallel setup geometry

Table 1 Chemical composition of materials used

Element	Chemical composition, wt.%										
	Ni	Cr	Mn	P	C	Cu	Si	S	Al	Ti	Fe
Incoloy800	30.2	19.8	0.94	…	0.059	0.03	0.46	<0.005	0.17	0.23	48.2
SS304	10.2	17.2	1.05	0.018	0.059	…	0.71	<0.005	…	…	Bal.

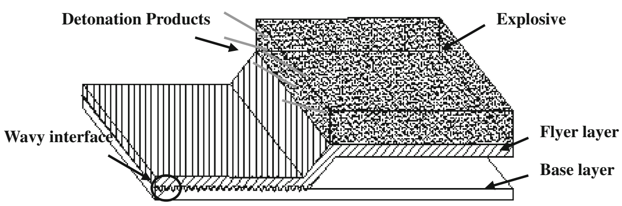

Fig. 1 Sketch of explosive welding (plate/plate): this picture shows the sketch of explosive welding process

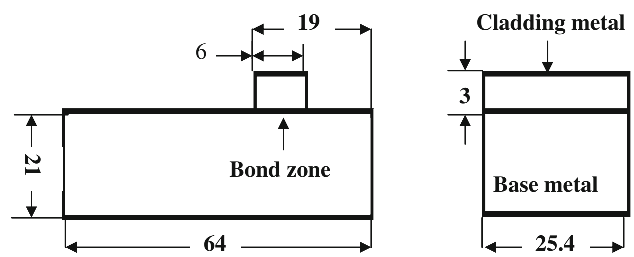

Fig. 2 Shape and size of sample for shearing test: this picture shows the shape and dimension of the shearing samples

Table 2 Ultrasonic testing condition for cladding plate

Material	Instrument	Probe type	Sensitivity	Method	Couplant
Incoloy800/304	MS380	5P/Φ20	80%	Direct contact	Water

was employed. Then the welding assembly was placed on a sand anvil. Detonation started with a magnetic remote system. And the sketch of explosive welding application was shown in Fig. 1.

2.2 Specimen Characterization

Ultrasonic testing (UT) in accordance to ASTM A578 specification was employed to check the cladding plates. All condition parameters were shown in Table 2. Then, the specimens were cut parallel to detonation direction for metallographic study. The cross-sections of specimens were grinded with sandpaper up to No. 2000 and polished. The observation of the microstructure after explosive cladding process was examined by optical microscopy (Olympus GX51) and electron scanning microscopy (SEM,SS550) equipped with the energy-dispersive x-ray spectrometry (EDX).

After explosion, HSB-A digital tesla meter was employed to inspect the magnetic property of Incoloy800 alloys, SS 304, and the cladding plate.

Micro-hardness testing was carried out on Vickers durometer (401MVD) using a 200 g load. Measurement pints were 0, 50, 150, 300, 500, and 800 μm from bonding interface in both sides.

Shear specimens were prepared according to ASTM D3165-05. The shape and size of shearing test sample was shown in Fig. 2 (unit: mm). It needed to remove all cladding layer from base metal, except for the area shown in the picture. And shearing test was also carried out on a DLY-10A instrument in the compression direction. The shearing speed of that machine was 0.3 mm/min.

Tensile test was applied according to ASTM A265-05 and on WAW-1000 testing machine. Samples were cut parallel to the detonation and prepared in accordance with ASTM D3165-05.

Bending test was also performed on WAW-1000 testing instrument. The samples were bended up to 180°. And the samples were bended in face (Incoloy800 alloy inside) and reverse (SS304 inside) ways.

3. Results and Discussion

3.1 Metallographic Studies

Experimental results show that cladding of Incoloy800 to SS304 is achieved by explosive welding technique. After welding, the cladding plate is non-destructively examined by ultrasonic test. The results show that the cladding plate passes the test with no significant defect indications. The optical figures of Incoloy800 and SS304 are shown in Fig. 3. It can be seen from Fig. 3(a) that Incoloy800 alloy consists of the austenite phase with large grain size (about 80-120 μm). The size of austenitic grains is about No. 5 level. And there is no abnormal deposition in the alloy structure. Figure 3(b) illustrates the microstructure of SS304 alloy. This steel contains high nickel content (10.2 wt.%) and keeps the austenitic structure at room temperature. The structure is made up of fully equal-axed grains.

Figure 4 shows the optical views of the cladding interfaces. In general, there are three types of interfaces, straight, smooth and shallow wavy. According to the references (Ref 12, 18), generally, wavy structure is desired in explosively welding process due to bigger interface wave and also higher strength. In this article, the microstructure shows that the interface is wavy. The amplitude of the formed waves (after explosion) is uniform and the size was about 0.64 mm. And the wavelength in the interface is about 1.06 mm. Observation from the optical

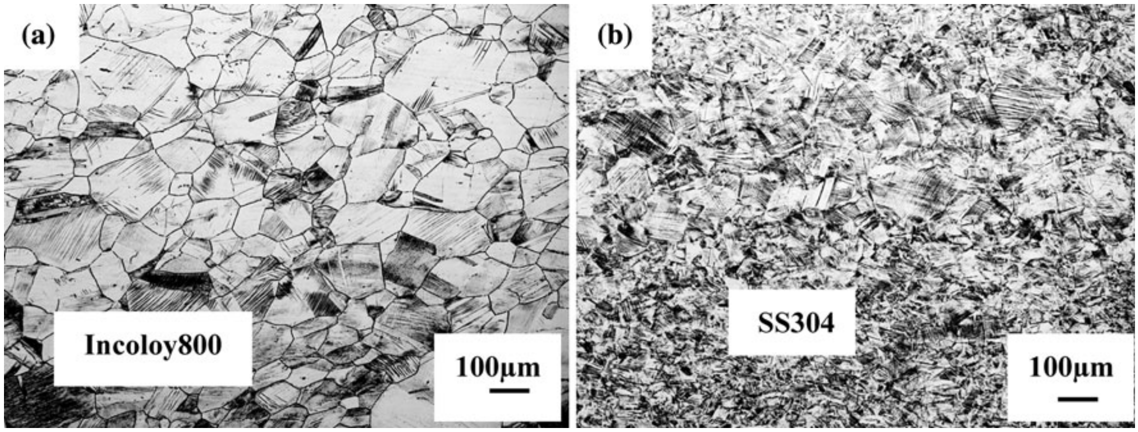

Fig. 3 Microstructures of Incoloy800 and SS304 materials in optical microscope: two pictures show the microstructures of Incoloy800 and SS304, respectively. Incoloy800 (a) shows a microstructure consisting of the matrix austenite phase with large grain size (about 80-120 μm) and (b) illustrates the microstructure of SS304. SS304 keeps the austenitic structure and is made up of fully equal-axed grains

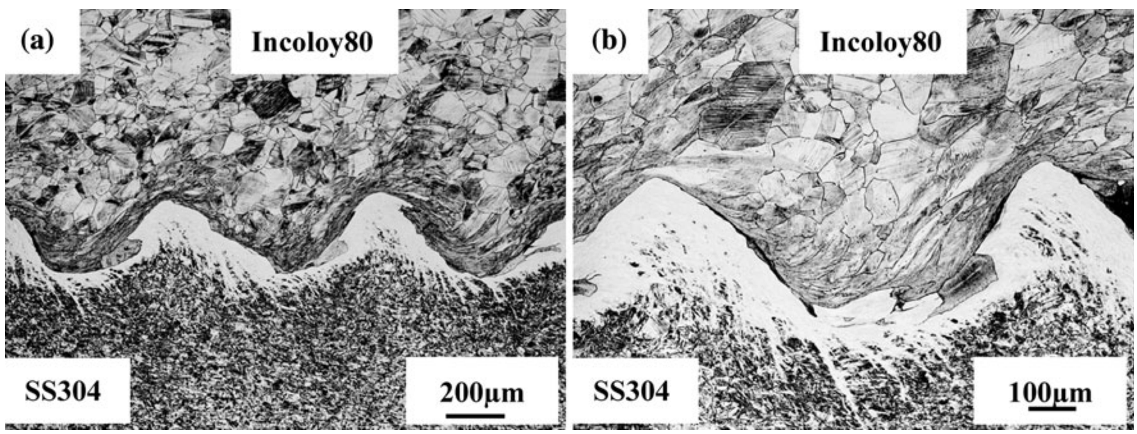

Fig. 4 Cross-sectional microstructure of Incoloy800-SS304 cladding plate (a) and (b) at higher magnification. These pictures show the wavy interface of cladding plate. The amplitude of the formed waves (after explosion) is uniform and it is about 0.64 mm, and the wavelength in the interface is about 1.06 mm

pictures, no melting zone or intermetallic compound is seen in the interface at low magnification. And the grains of flyer layer near to the welded interface are elongated parallel to the direction of the explosion, which basically due to deformation arising from the high velocity impact caused by the explosion. It is consistent with the earlier studies (Ref 13, 14). The morphology of explosively welded joints is similar to the rolling process. In the rolling process, grains are elongated along the rolling direction. Similarly, in explosive welding process, gains in interface are also deformed and prolonged in the direction of explosion. The results are consistent with the earlier reports (Ref 7, 14, 15).

SEM and EDX analysis are used to investigate the microstructures near to the interface and the related figures shown in Fig. 5. It is clearly seen from the Fig. 5(a) that the interface is wavy structure and the shape of interface waves is uniform. It also can be seen at a higher magnification (Fig. 5b) that neither melting void nor intermetallic compound is observed near the interface. However, there is a colorful area at the wave ridge of the base layer with either optical microscope or SEM. Thus, EDX analysis is applied to inspect the typical areas (squares A, B, and C in Fig. 5b). Square A is base layer, square B is colorful zone in the base layer, and square C is the flyer layer. It can be seen from Fig. 5(c), (d), square A and B areas have the same elements: Fe, Ni, Cr, and Si, and furthermore, the contents of each element is similar. No other element that does not belong to SS304 is detected. Tesla meter is used to inspect the magnetic property of raw materials and cladding plate. The results (shown in Table 3) indicate that amounts of the remnant magnetism in 304 SS alloy and the cladding plate are similar. Thus, B area is not the transformation of the 304SS to martensite phase. Both A and B areas are the austenitic steel. And the occurrence of the different colorful areas is the reason that attacking in the explosive welding causes the deformation of the grains near to the interface. After etching, the color of the deformation layer is obviously different from other area in the base layer (Ref 2, 10). Figure 5(e) shows that square C is Incoloy800 alloy.

In order to inspect the diffusion process (Problem), line scanning of Fe, Ni, Cr, and Si elements are carried out away from 500 μm across the interface. The results are shown in

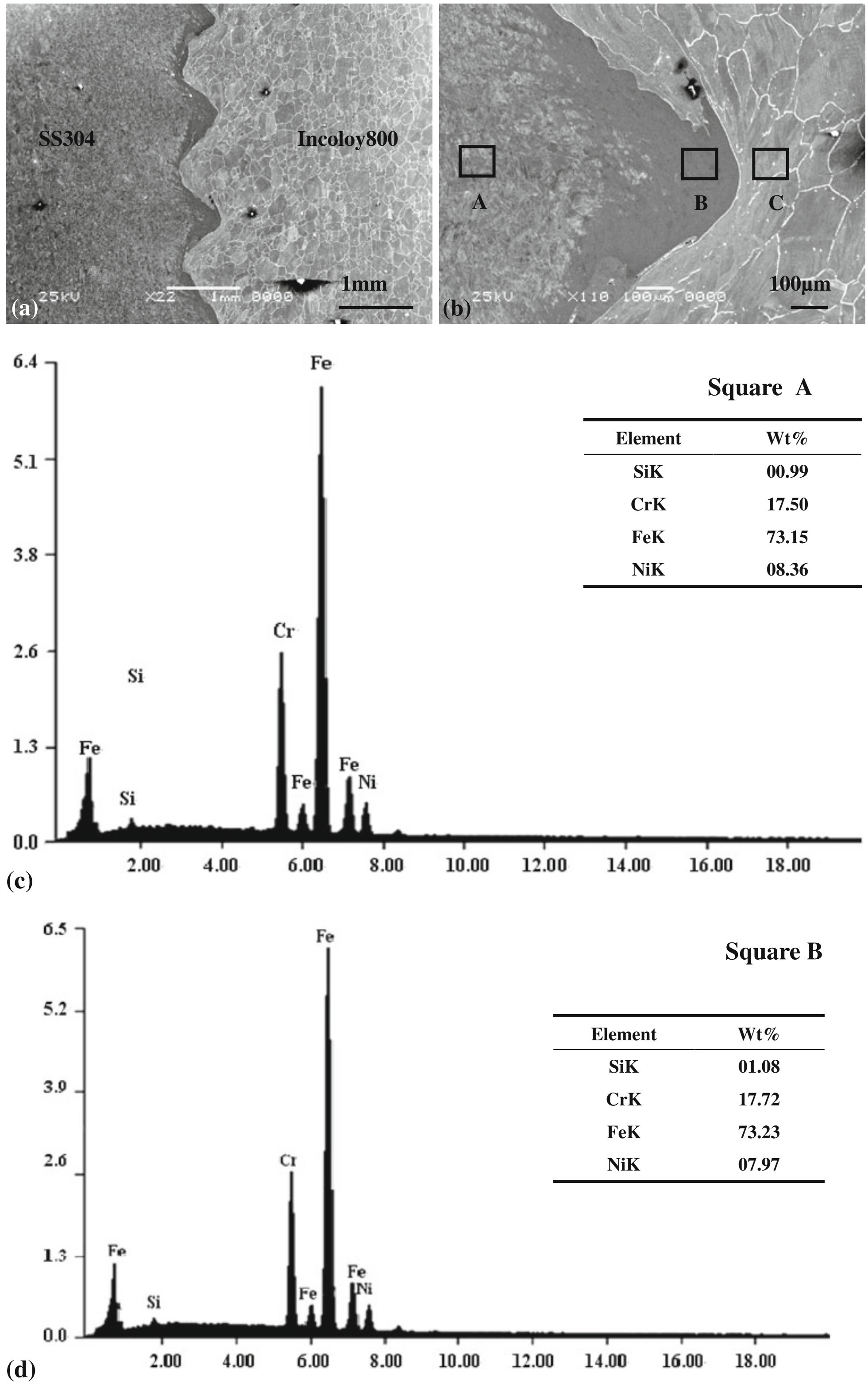

Fig. 5 SEM micrographs (a) and (b) from the cross-section of Incoloy800-SS304 plate and corresponding EDX spectrums (c), (d), and (e): these pictures show the cross-sectional microstructure of cladding plate. In (a, b), a differently colorful zone is observed. EDX analysis method is used to check the components of different zone. In (b), square A represents base layer, square B represents colorful zone at the wave ridge of base layer (B) and square C is flyer layer. And (c), (d), and (e) are corresponding EDX spectrums of above three zones

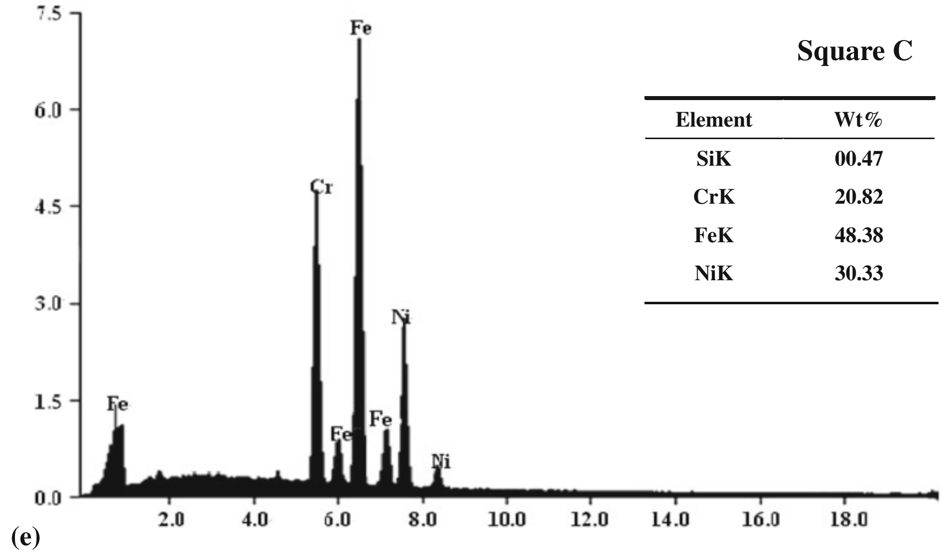

Fig. 5 continued

Table 3 Magnetic property of raw materials and the cladding plate

Material	Magnetization current, A	Remnant magnetism, mT
Incoloy800	100	0.46
SS 304	100	0.68
Cladding plate	100	1.06

Fig. 6. Incoloy800 and SS304 materials contain similar elements, such as Fe, Ni, Cr, and Si, while the contents of Ni, Fe, and Cr elements are distinctly different. And, it can be seen from Fig. 6 that the contents of Fe, Cr, and Ni elements all show sharp transitions at the interface. It indicates that element diffusion during explosive welding process is not observed under the accuracy of line scanning detection. And it is consistent with the above results of EDX analysis. The content of Si element is equivalent in Incoloy800 and SS304 materials.

3.2 Evaluation of Properties of Cladding Plate

Micro-hardness measurement was made across the interface of Incoloy800-SS304 using a load of 200 g. The values on the interface profiles are shown in Fig. 7. Depending on the distance away from interface, the micro-hardness appears various accordingly. As it is seen from Fig. 7, the hardness of base and flyer layers is 234 HV and 275 HV, respectively. And the hardness in the interface reaches approximately 390 HV. The micro-hardness is equivalent in either material over than 300 μm away from the interface. The hardness near the interface increases about 120 for SS304 and 30 for Incoloy800 alloy. The magnetic inspection results (Table 3) indicate that the remnant magnetism of raw materials and cladding plate is similar. Thus, the high hardness of both flyer and base layers near the interface may attribute to the high degree of deformation/cold working of the materials surfaces during the explosive cladding process. These results are consistent with the previous work (Ref 5, 7, 13, 14).

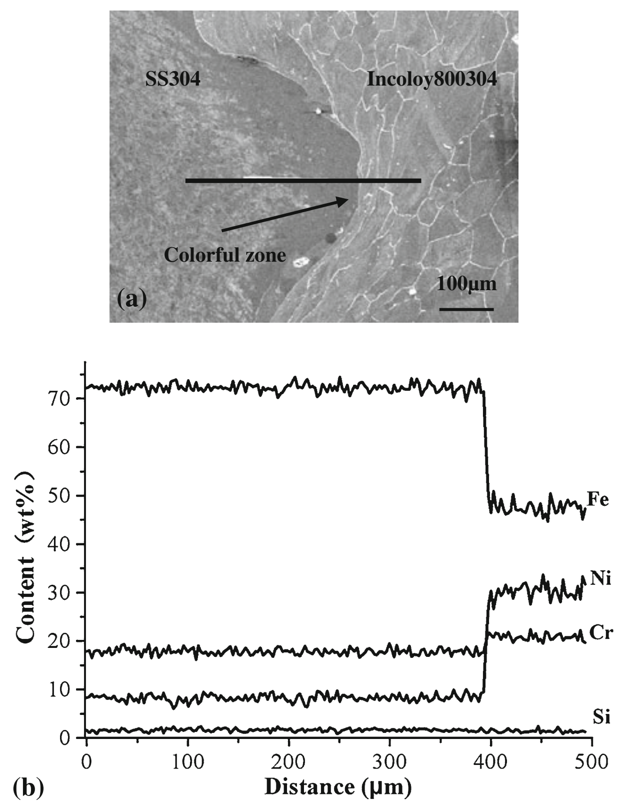

Fig. 6 Line scanning of elements distributed near the interface area: this picture shows the distribution of Ni, Fe, and Cr elements on the cross-section of cladding plates by line scanning. It can check the problem diffusion process during the explosive welding

Tensile testing was carried out at room temperature. The samples after tensile testing are shown in Fig. 8. Yielding strength and tensile strength of Incoloy800-SS304 cladding plate are 545 and 750 MPa, respectively. The results meet the requirements of ASTM A265-05 specification. And it is seen from tensile fracture in the pictures, no separation is observed in the interface.

Shearing test was also employed on the cladding plate. The shearing strength is 578 MPa. It is much higher than that of the requirement of ASTM specification (137 MPa). Figure 9 shows failure views of specimens after shearing test. It can be seen that separation happens at the interface.

Bending test was carried out according to ASTM A265 specification and the views of the bent samples are shown in Fig. 10. The specimen shows excellent bend-ductility within 180°. After bending, no separation, tearing or fracture are observed in all samples (Fig. 10). Base on the investigation, it clearly indicates that Incoloy800-SS304 can be safely applied in service even in bent form.

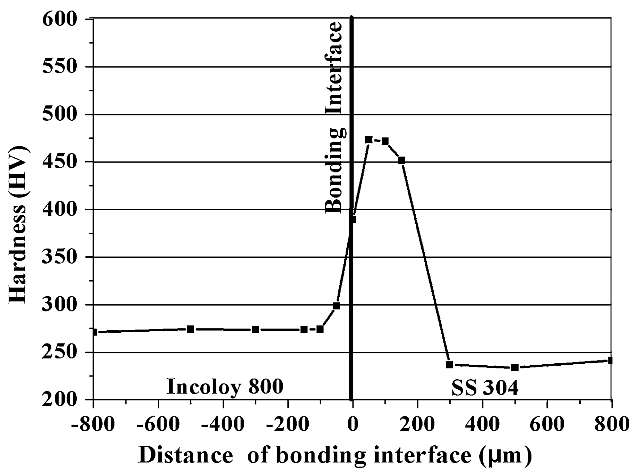

Fig. 7 Hardness variation of the bonded sample: micro-hardness measurements are made across the interface of Incoloy800-SS304 cladding plate. The values of the profiles in the joint are shown in figure. Micro-hardness of base and flyer layers is about 234 HV and 275 HV, respectively. And interface hardness reaches to approximately 390 HV

4. Conclusions

- Incoloy800 cladding onto SS304 is accomplished by the explosive welding.
- After completion of explosion process, a fine wavy structure is observed in the welding interface.
- The magnetic inspection results indicate that the remnant magnetism of raw materials and cladding plate is similar. Thus, the colorful area is not the transformation of the 304SS to martensite phase. Thus, the colorful area is the severe deformation one due to the shock pressure with collision.

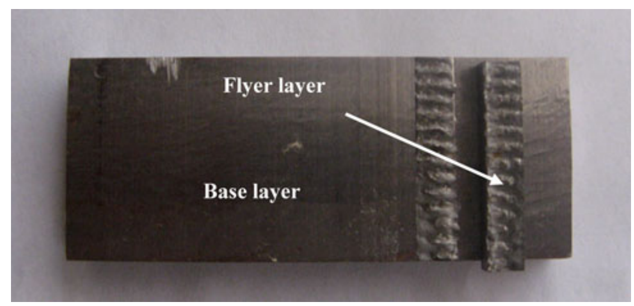

Fig. 9 Failure view due to shear test of explosively welded specimen. The figure shows view of the failure of specimens after shearing test. It can be seen that separation is only observed at the interface

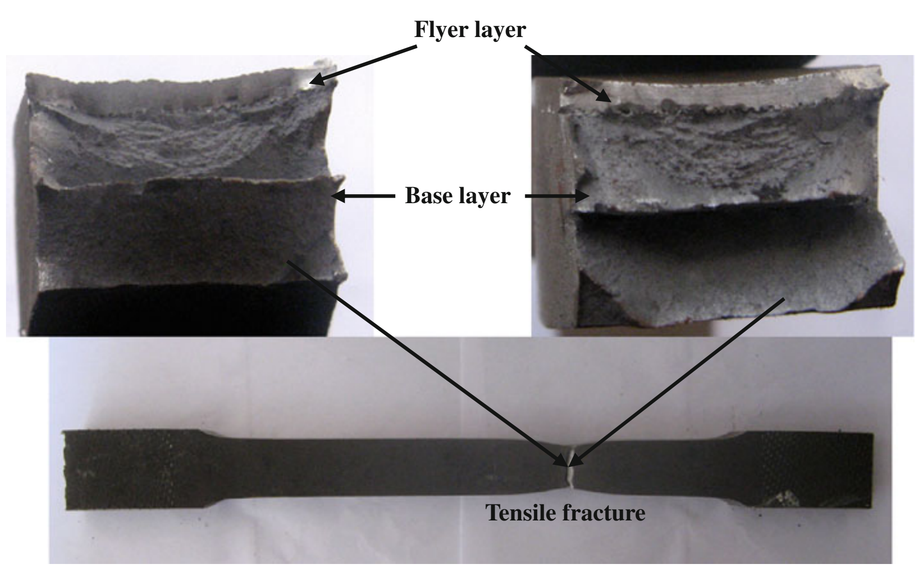

Fig. 8 Views of the samples after tensile tests: this picture shows the tensile sample and its fractures. And it can be seen from the fractures that no departion is observed in the interface of cladding plate

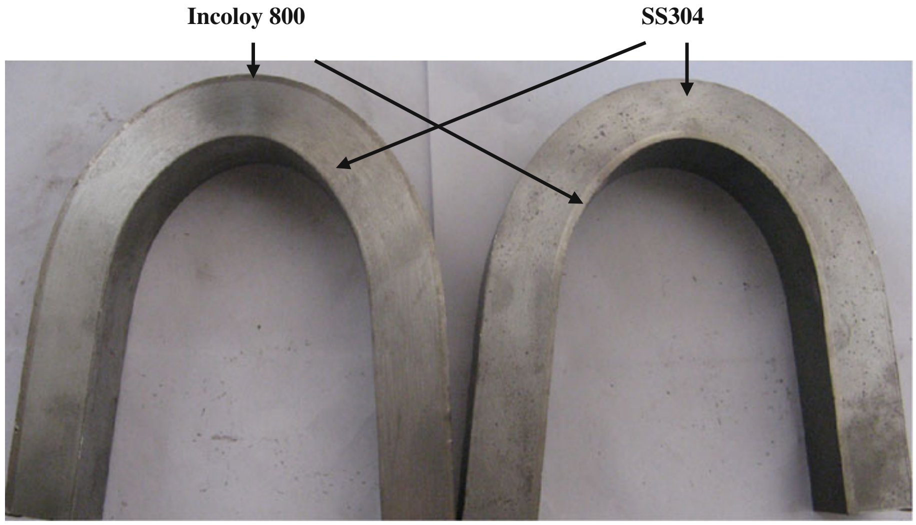

Fig. 10 View of the samples after bending test. The figure shows no separation, tearing, or fracture is observed in the face and reversed-bend specimens within 180° after bending

- The micro-hardness of base and flyer layers is about 234 HV and 275 HV, respectively. The interface hardness reaches to approximately 390 HV.
- Tensile, shear, and bending tested results show that the cladding materials exhibit an acceptable joint strength.

Acknowledgments

All authors acknowledge the support of the National Science and Technology Pillar Program (2007BAE07B02).

References

1. B.S. Yilbas, M. Khaled, M.A. Gondal, M. Ourfelli, Z. Khan, A. Al-Qutub, and B. El-Ali, Nano-Second Pulse Laser Treatment of Incoloy 800HT Alloy-Corrosion Properties, *Opt. Lasers Eng.*, 1999, **32**(2), p 157–172
2. R. Dehmolaei, M. Shamanian, and A. Kermanpur, Microstructural Changes and Mechanical Properties of Incoloy800 After 15 years Service, *Mater. Charact.*, 2009, **60**(3), p 246–250
3. A. Kermanpur, M. Shamanian, and V. Esfahani Yeganeh, Three-Dimensional Thermal Simulation and Experimental Investigation of GTAW Circumferentially Butt-Welded Incoloy 800 Pipes, *J. Mater. Process. Technol.*, 2008, **199**(1–3), p 295–303
4. A.M. Iglesias and M.A.C. Raffo Calderon, Thermal Resistance Contributions of Oxides Growth on Incoloy 800 Steam Generator Tubes, *Nucl. Eng. Des.*, 2003, **219**(1), p 1–10
5. R.C. Yin, Carburization Performance of Incoloy 800HT in CH_4/H_2 Gas Mixtures, *Mater. Sci. Eng. A*, 2004, **380**(1–2), p 281–289
6. M. Fulger, D. Ohai, M. Mihalache, M. Pantiru, and V. Malinovschi, Oxidation Behavior of Incoloy 800 Under Simulated Supercritical Water Conditions, *J. Nucl. Mater.*, 2009, **385**(2), p 288–293
7. R. Kacar and M. Acarer, An Investigation on the Explosive Cladding of 316L Stainless Steel-Din-P355GH Steel, *J. Mater. Process. Technol.*, 2004, **152**(1), p 91–96
8. M.H. Keshavarz, Prediction of Detonation Performance of CHNO and CHNOAl Explosives Through Molecular Structure, *J. Hazard. Mater.*, 2009, **166**(2–3), p 1296–1301
9. J. Yinon, Field Detection and Monitoring of Explosives, *Trends Anal. Chem.*, 2002, **21**(4), p 292–301
10. N. Kahraman and B. Gülenç, Microstructural and Mechanical Properties of Cu-Ti Plates Bonded Through Explosive Welding Process, *J. Mater. Process. Technol.*, 2005, **169**(1), p 67–71
11. S.A.A. Akbari-Mousavi, L.M. Barrett, and S.T.S. Al-Hassani, Explosive Welding of Metal Plates, *J. Mater. Process. Technol.*, 2008, **202**(1–3), p 224–239
12. D.L. Vonne, *Procedure Development and Process Considerations for Explosion Welding*, ASM Handbook, Materials Park, 1993, p 896–900
13. S.A.A. Akbari Mousavi and P. Farhadi Sartangi, Experimental Investigation of Explosive Welding of cp-Titanium/AISI, 304 Stainless Steel, *Mater. Des.*, 2009, **30**(3), p 459–468
14. B. Gulenc, Investigation of Interface Properties and Weldability of Aluminum and Copper Plates by Explosive Welding Method, *Mater. Des.*, 2008, **29**(1), p 275–278
15. M. Acarer and B. Demir, An Investigation of Mechanical and Metallurgical Properties of Explosive Welded Aluminum-Dual Phase Steel, *Mater. Lett.*, 2008, **62**(25), p 4158–4160
16. M.B. Talawar, A.P. Agrawal, M. Anniyappan, D.S. Wani, M.K. Bansode, and G.M. Gore, Primary Explosives: Electrostatic Discharge Initiation, Additive Effect and Its Relation to Thermal and Explosive Characteristics, *J. Hazard. Mater.*, 2006, **137**(2), p 1074–1078
17. A.A. Akbari Mousavi, S.J. Burley, and S.T.S. Al-Hassani, Simulation of Explosive Welding Using the Williamsburg Equation of State to Model Low Detonation Velocity Explosives, *Int. J. Impact Eng.*, 2005, **31**(6), p 719–734
18. A. Durgutlu, B. Gülenç, and F. Findik, Examination of Copper/Stainless Steel Joints Formed by Explosive Welding, *Mater. Des.*, 2005, **26**, p 497–507