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Evaluation of Microstructure and Mechanical Properties of Explosive-Welded HSLA/304L Steel Bimetallic Plates

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High strength low alloy (HSLA) steel 10CrNi3MoV and stainless steel 304L (SS304L) were used to manufacture bimetallic plates by explosive welding. The quality and overall performance of the bimetallic plates were evaluated in terms of microstructure and mechanical properties. Its microstructure, elemental distribution, and phase analysis of the bonding interface were investigated by means of OM, SEM, EDS, and XRD. The mechanical properties of the bimetallic plates were studied by experimental measurements, including tensile tests, shear tests, Charpy impact tests, hardness tests, and then evaluated based on the standards. Experimental evaluation showed out that HSLA 10CrNi3MoV steel and SS304L could be cladded with a good quality of bonding properties by explosive welding. The base material 10CrNi3MoV steel still maintained its inherent excellent mechanical performance, even after undergoing explosive welding process. The functional flyer layer SS304L maintained its corrosion resistance even after undergoing a process of post-weld heat treatment at high temperature 645 °C for 240 min. Shear strength of the bimetallic plates was about 432 MPa more than twice the value required by the standard. The maximum hardness value was obtained near the joint on the side of SS304L, and the minimum one appeared in the middle of the explosive welding interface.

Keywords cladding, explosive welding, mechanical properties, microstructure, weld interface

1. Introduction

Bimetallic composite plates can fully combine the respective advantages of the two materials that are used for a flyer layer and a parent base plate, thereby achieving a comprehensive performance that a single metal is hard to reach under normal conditions (Ref 1, 2). The bimetallic composite plate is demanded in chemical, ship manufacturing, and nuclear power industries due to its good corrosion resistance and mechanical properties (Ref 3). Especially in the structural design of new ships with small nuclear reactors to be installed in China, designers are faced with complex material selection issues. These issues include the need to simultaneously satisfy a sound structure, minimum weight, maximum strength and toughness, and resistance to marine corrosion within a reasonable high budget. Unfortunately, no single structure material can satisfy all the requirements simultaneously. Therefore, the bimetallic plates with excellent performance could be employed in the extreme service environment for the small-sized mobile nuclear reactors on the sea.

Explosive welding is one of the most widely used methods for manufacturing bimetallic composite plates to join two discrete materials with completely various physical and mechanical features. Explosive welding can form a metallurgical wave-like interface between two metals, and its mechanical strength is comparable to or better than the parent metal. The explosive welding of two different kinds of metallic plates is achieved by the exhaustive deformation owing to high temperature and high pressure created at the interface zone through bombardment of explosives in very short time. Explosive selection and detonation velocity are critical for obtaining the good weld (Ref 4-6). There are two basic geometric configurations of the explosive welding process that are commonly employed: angle bonding and parallel-plate bonding (Ref 7). Currently, hundreds of combinations of similar and dissimilar metals and also fiber-reinforced composite materials have achieved successfully by explosive welding. In particular, several scholars have studied the microstructural characteristics, mechanical properties, and failure mechanisms of explosive welding components of various metals. Guo et al. (Ref 8) studied the explosive bonding between aluminum and 316L stainless steel and did a more in depth study on the bonding interface. Linear and wavy bonding interface coexisted and intermetallic phases were present in the local interfacial zone. Gulenc (Ref 9) conducted an investigation on the weld ability of aluminum sheet to copper sheet by explosive welding and the effect of explosive ratio on the joint interface. The joint interface was transformed from linear to wavy appearance by increasing explosive ratio. On the wavy interface, wavelength and amplitude of waves were increased with explosive loads. The grains near the interface were elongated along the explosive direction. Durgutlu et al. (Ref 10) had experimentally researched copper/stainless steel joints formed by explosive welding and demonstrated that the interface could be bonded with good quality properties. Kaya et al. (Ref 11) investigated the explosive welding of Grade A ship steel and duplex stainless steel composites plates. The highest hardness was obtained at

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the bonding interface, followed by the outer surface of the plates. As the distance from the explosion zone increased, hardness also increased due to the increasing deformation hardening.

The welding interface of the bimetallic plate is the weakest part, which is one of the main causes of failure. The experimental parameters of flyer thickness, loading ratio, angle of inclination, and standoff are very critical for the sake of acquiring a high-quality explosive-welded bond. The selection of the process parameters is based on the mechanical properties, density, size, and shear wave velocity of each component reported by Mendes, Gholam Hossien Liaghat et al. (Ref 12, 13). Akbari Mousavi et al. (Ref 14) performed a series of explosive welding trails to assess how process variables affect the strength of the bond. In most cases, there was very little difference in the shear strength of the two directions of parallel and perpendicular to the detonation direction. The bond strength increased slightly with increasing standoff distance. The results also showed that the maximum and minimum interfacial fracture toughness values were obtained from a straight and vortex-shaped interfaces, respectively. The finite element simulation was used to numerically analyze the welding process of the two plates and was properly verified based on the explosion welding data. The influential physical parameters that affect the explosive bonding could be defined as effective strain and shear stress. The simulations confirmed some previous results from the explosive welding process (Ref 15). Ma et al. (Ref 16) carried out a computational combined experimental study of explosive welding for 316L(N)/CuCrZr hollow structural member. The results indicated that the samples with the post-heat treatments exhibited a ductile fracture with dimple features after tensile test. After the aging heat treatment, the strength of the specimens increased significantly. Proper heat treatment through post-explosive welding could improve the mechanical properties of the joining interface with great enhancement of elements diffusion (Ref 17). Moreover, the straight and wavy interfaces had similar strength based on the tensile shear tests. The untreated specimens exhibited cracks in the bending zone.

Hence, in this current study, high strength low alloy (HSLA) steel 10CrNi3MoV and austenitic stainless steel 304L (SS304L) were bonded to form bimetallic plates through explosive welding. Explosive welding method can not only achieve effective metallurgical bonding between metals, but also produce large-area laminates, which has important technical significance. 10CrNi3MoV steel is a class of HSLA steels, mainly used as the structural material of Chinese ships. The corrosion protection of 10CrNi3MoV steel is achieved by applying anti-corrosion paint on the surface, and the coated surface needs regular maintenance. SS304L has a wide range of applications in industry, which is attributed to its good corrosion resistance and formability. Furthermore, SS304L has many years of experience in nuclear power service as a spent fuel pool structural material and is resistant to radiation. The bimetallic plates of 10CrNi3MoV steel and SS304L can combine the respective advantages of the two to form a composite structural material, which provide a new material selection for engineering structure design. SS304L as a corrosion protection layer instead of coating can avoid maintenance for decades in severe radiation service environment.

The HSLA steel 10CrNi3MoV/SS304L bimetallic plates have both excellent mechanical properties and corrosion resistance, which would be used to manufacture structural component of suppression pool in the small-sized mobile nuclear reactors on the sea. Under the condition of a hypothetical marine accident, the bimetallic plates of the structural material in the pressure suppression pool will be affected by the harsh environment of various conditions such as corrosion, nuclear radiation, stress, instantaneous high temperature and high pressure. Its functional design is to achieve suppression and protection of nuclear reactor core.

However, there are few reports of data on the HSLA steel 10CrNi3MoV/SS304L bimetallic plates. In order to supplement the data and improve the safety design of structural component in nuclear industry, it is necessary to carry out new experimental research for comprehensively evaluating the performance of the HSLA steel 10CrNi3MoV/SS304L bimetallic plates. The data obtained in the present research assist the designers for designing the structural component and estimating its reliability. The mechanical properties of strength and toughness in bimetallic plates are very crucial for choosing dimension in thickness to ensure a safety of the structure servicing for at least 40 years (nuclear power design life). The results from metallurgical microstructure of the bimetallic plates and corrosion resistance functional design would be beneficial for failure analysis.

On that account, the present study deals with the evaluation of microstructure and mechanical properties of HSLA steel 10CrNi3MoV/SS304L bimetallic plates prepared by explosive welding. The microstructure, phase composition and element distribution of the explosive welding interface were studied by characterization of the wavy zone and vortices using an optical microscope (OM), scanning electron microscope (SEM) with energy-dispersive X-ray spectrometry (EDS), and X-ray diffraction (XRD) technology. The influence of explosive welding process on the tensile properties, shear strength, impact toughness, and microhardness was further investigated. Moreover, the intergranular corrosion resistance of the SS304L after explosive welding and undergoing a post-weld heat treatment at 645 °C for 240 min was studied to evaluate the functional flyer layer performance.

2. Materials and Methods

2.1 Materials and Explosive Welding Conditions

The functional surface flyer layer and base plates were made of SS304L and HSLA steel 10CrNi3MoV, respectively. The chemical compositions of the jointed plates are given in Table 1. The dimensions of the flyer layer and base plates were 5000 mm × 1000 mm × 4 mm and 5000 mm × 1000 mm × 32 mm, respectively. The explosive material was an ammonium nitrate expanded with inert additives mixture. The gap between the two plates was approximately 9 mm maintained by several support blocks. The base plate HSLA steel 10CrNi3-MoV was located at the sand bottom and the explosive material was laid on the top of the flyer layer SS304L. Fuel oil coated on the surface of the SS304L to protect the welding quality. The experimental setup for explosive welding process is shown in Fig. 1. The final thickness of the explosively bonded HSLA steel 10CrNi3MoV/SS304L was approximately 34 mm caused by explosive thinning. After explosive welding, the bimetallic plate needs to be heat-treated and leveled to release the residual

Table 1 Chemical composition of HSLA steel 10CrNi3MoV and SS304L (wt.%)

Material	C	Cr	Si	Mn	Ni	N	S	P	Co	Mo	V	Fe
SS304L	0.028	19.06	0.540	1.78	9.28	0.055	< 0.0050	0.026	0.041	…	…	Balance
10CrNi3MoV	0.076	0.918	0.240	0.465	2.89	–	< 0.0050	0.0045	0.0082	0.212	0.061	Balance

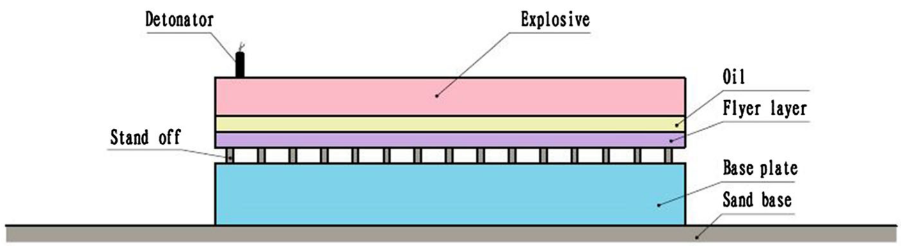


Fig. 1 Experimental setup for explosive welding process

stress of the explosive welding and then restore the performance of the raw materials before explosive welding. Heat treatment at 645 °C for 240 min, then air cooling. Leveling was accomplished on a large rolling leveler.

Ultrasonic inspections were carried out for the explosively bonded HSLA steel 10CrNi3MoV/SS304L bimetallic plates, and the results showed that the welding quality met the BI grade requirements of GB/T 8165-2008 (Ref 18).

2.2 Microstructure and Chemical Composition Analyses

For microstructure investigation, the cross section of the HSLA steel 10CrNi3MoV/SS304L bimetallic plates was extracted from the central parts of the clad plates and followed by mechanical polishing and etching. Two kinds of etchants employed for the bimetallic plates samples. One etchant consisted of 4 ml nitrate and 96 ml alcohol, and another one was aqua regia for HSLA steel 10CrNi3MoV and SS304L, respectively. OLYMPUS GX71-type optical microscope was used for the microscopic studies. Higher-resolution examination of the specimens was carried out using Quanta600 scanning electron microscope (SEM). Energy-dispersive X-ray spectrometry (EDS) analysis was used to characterize the alloy elements distribution across the weld interface of HSLA steel 10CrNi3MoV/SS304L.

2.3 Phase Analysis in Macro-scale

The X-ray diffraction (XRD) measurements, aimed at interfacial phase analysis, were taken using the D8 ADVANCE-type X-ray diffractometer system with LynxEye solid-state detector (radiation copper target with voltage 40 kV and beam current 40 mA) made by German BRUKER Company. The specimen of dimensions 3 mm × 4 mm × 25 mm was prepared from the separated shear test specimen with fresh interface included the flyer layer material.

2.4 Testing Mechanical Properties

2.4.1 Tensile Tests. Tensile tests at room temperature were done based on the China standard GB/T228.1-2010 (Ref 19). Round tensile specimens with 10 mm in diameter, 60 mm in gauge length and 100 mm in total length were prepared as shown in Fig. 2a. The tensile specimens were extracted from the 1/4 width parts of the plates in transverse direction. Considering that SS304L is an anticorrosive functional layer and the strength is mainly realized by HSLA steel 10CrNi3-MoV in the engineering design, the tensile specimens were only made of HSLA steel with the flyer layer removed. Tensile properties of the cladded steels have been investigated before and after explosive welding.

2.4.2 Shear Tests. The specimens for shear tests were prepared parallel to the explosion direction from the HSLA steel 10CrNi3MoV/SS304L bimetallic plates according to GB/T 6396-2008 (Ref 18). The specimen dimensions are shown in Fig. 2b. Three shear specimens tested at room temperature were prepared to evaluate the mechanical properties of the joint and calculate the average value. The shear test was carried out on universal testing machine in the compression direction with a shearing speed of 2 mm/min.

2.4.3 Charpy Impact Tests. In order to investigate the toughness of the cladded metals, Charpy impact tests were retained. Standard Charpy V-Notch specimens were employed with a section of 10 mm × 10 mm and a length was 55 mm, a central 45° V-notch of 2 mm depth. Considering the same that the SS304L is an anticorrosive functional layer, the investigation on toughness of the cladded metals only took the base material HSLA steel 10CrNi3MoV with the layer SS304L removed. The toughness of HSLA steel 10CrNi3MoV was evaluated by Charpy V-notch impact tests at − 20 °C before and after explosive welding.

2.4.4 Hardness Tests. Vickers hardness measurements were taken in the HSLA steel 10CrNi3MoV/SS304L section to estimate the changes in the hardening across the explosive-welded interface. The test was carried out on the finely polished longitudinal interfacial section. The measurements were taken with a load of 0.98 N (100 g) with a dwell time of 10 s.

2.5 Intergranular Corrosion Tests

The specimens experienced sensitization heat treatment at 675 °C for 1 h before the experiments. Intergranular corrosion test was done by holding the 80 mm × 20 mm × 2.5 mm flyer layer SS304L specimens in boiling sulfuric acid–copper

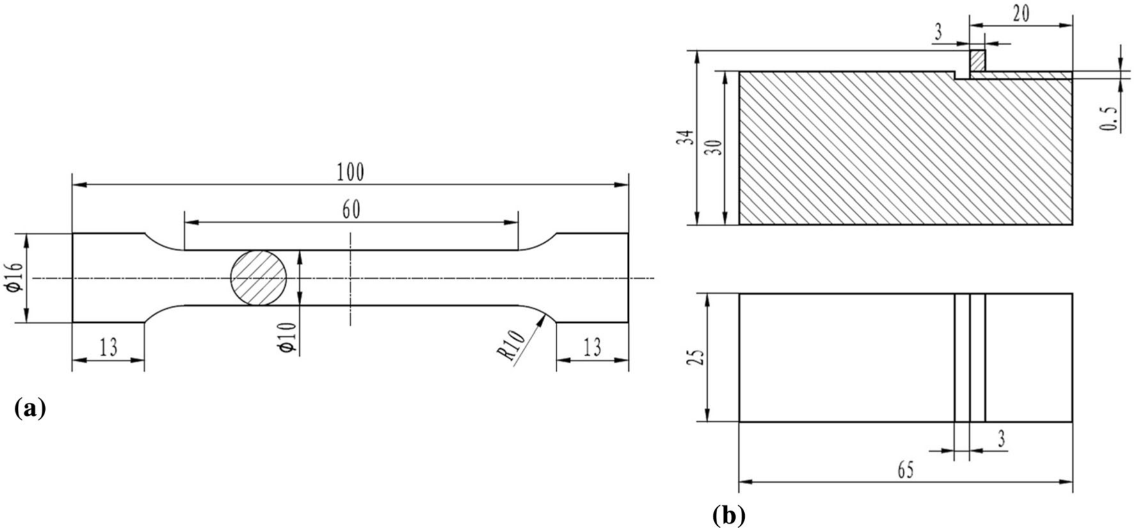


Fig. 2 The dimensions of test specimen (unit: mm): (a) tensile test specimen; (b) shear test specimen

sulfate solution for 16 h based on ASTM A262. Then, the specimens were bent to 180º for checking the fissures to determine whether SS304L was susceptible to grain boundary corrosion before and after explosive welding experienced heat treatment.

2.6 Nondestructive Inspection

One of the application conditions of bimetallic plates is as a nuclear power structural material that suppresses pressure and resists corrosion. The quality of the bimetallic plates should be strictly controlled to ensure the safety of the service performance of the equipment. According to the requirements of China special standard GB/T 8165-2008, ultrasonic examination was carried out for the explosively bonded HSLA steel 10CrNi3MoV/SS304L bimetallic plates, and the results showed that the welding quality met the BI grade requirements. The area combination rate of the bimetallic plates was 100%. The length of single unbounded zone near the supporting point was not more than 25 mm, which was far less than the requirement in GB/T 8165-2008 standard ($\leq$ 50 mm).

3. Results and Discussion

3.1 Metallographic Characterization of the Explosive Welding Interface

The optical images are given in Fig. 3 and Fig. 4 for the HSLA steel 10CrNi3MoV/SS304L explosive welding joints. Metallographic studies showed that the metallurgical bonding of HSLA steel 10CrNi3MoV and SS304L was achieved by explosive welding, and the bonding interface had a wavy morphology as shown in Fig. 3 and 4. The final average flyer layer thickness was about 3.1 mm (base SS304L plate was 4 mm in thickness) experienced the process of explosive thinning. The wavy length and the amplitude of HSLA steel 10CrNi3MoV/SS304L interface were approximately 0.83 mm and 0.28 mm, respectively. This is an ideal feature of explosive welding due to the realization of a larger interface bonding area and higher shear strength (Ref 1). The quality and morphology of the weld interface depend on the gap, the angle of collision, the impact velocity, and the properties of the materials. The previous study (Ref 12) also indicates that the morphology of the wavy weld interfaces (mainly the amplitude and length of the waves) is affected both by the impact velocity and the type and particle size of the explosive sensitizers. The gap between the two plates directly affects the impact velocity, and the explosive sensitizers are related to the properties of the materials. The morphology of the interface indicated that the process of explosive welding used in this study provided enough explosives and explosive loading to effectively obtain a uniform wavy interface. Increased the explosives ratio or explosive load then changed the interface from straight to wavy interface. The interface between the two metals was well bonded with the typical vortices morphology formed during the explosion. The similar findings were also reported in the literatures (Ref 20-22).

Figure 3 shows the HSLA steel 10CrNi3MoV microstructure of the cross section of the bimetallic plates etched by the etchant of 4 ml nitrate and 96 ml alcohol mixture. Figure 3a shows that the explosive-welded interface with a characteristic of sharp transition between the two metals, and the appearance of local vortices with island-like were also formed in the front or back slope of the interface waves. The similar result was reported in titanium/low-alloy steel plates (Ref 3). Formation of the local vortices zones was attributed to the fluctuation of the high pressure caused the fluctuation of jet metal, which resulted in the liquid metal being captured periodically by both the flyer layer and the base plate into the vortices, and finally formed the structure of the vortices as stated by Han (Ref 23). Furthermore, the vortices usually existed in the wavy interface with a good performance; only the size of the vortices was different. From Fig. 3(c)–(e), it can be seen that the width of the localized vortices was approximately 60 μm. The metallographic structure of the base metal far away from the interface was tempered sorbite according to metal microstructure inspection method standard of GB/T 13298-2015 (Ref 24) as shown in Fig. 3b.

Two different materials used in explosive welding need to use different etchants. Figure 4 shows the SS304L microstructure of the cross section of the bimetallic plates etched by aqua regia. The metallographic structure of the flyer layer metal

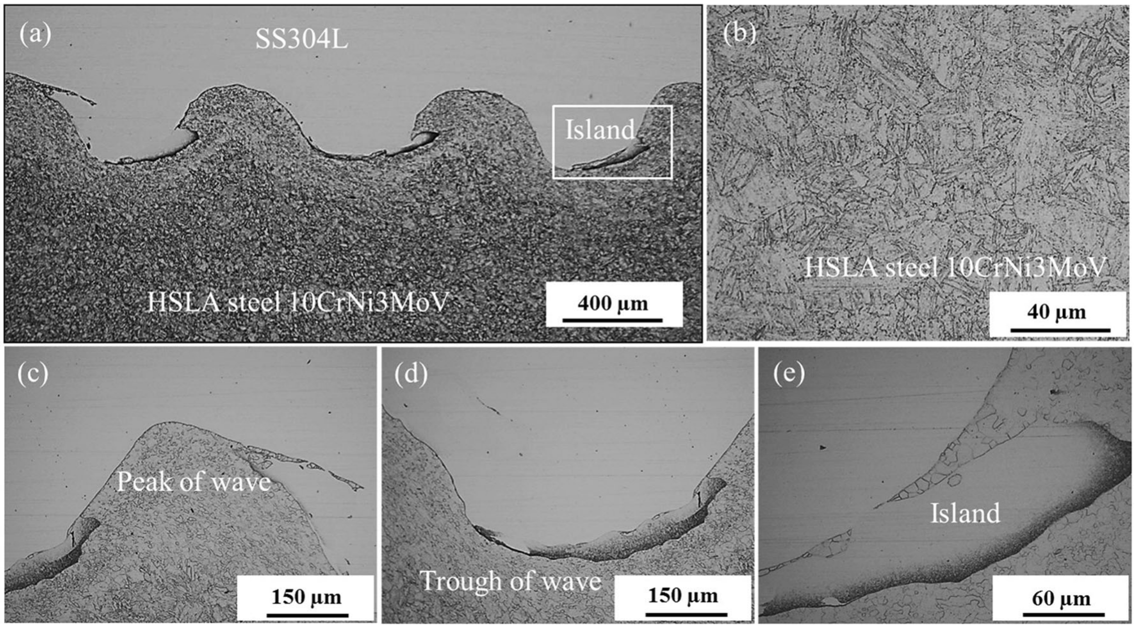


Fig. 3 Optical microscopy images etched for HSLA steel of the interface in explosively bonded HSLA steel 10CrNi3MoV/SS304L bimetallic plates: (a) wavy interface, (b) base material HSLA steel 10CrNi3MoV, (c) peak of the wave, (d) trough of the wave, and (e) vortex island on the side

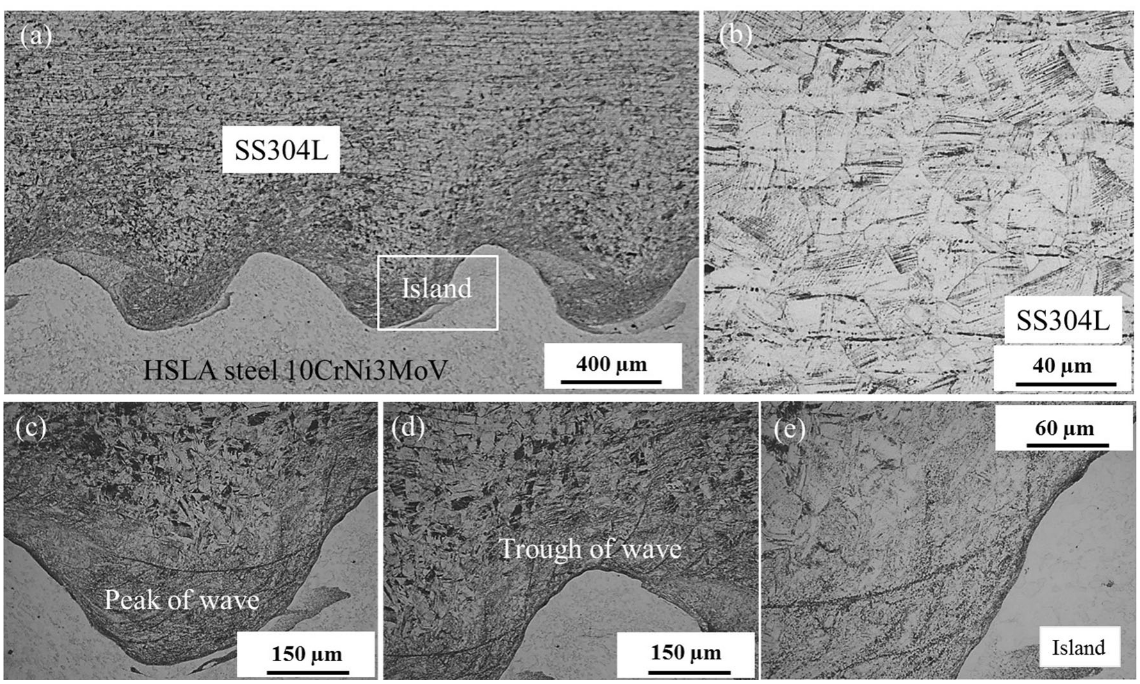


Fig. 4 Optical microscopy images etched for SS304L of the interface in explosively bonded HSLA steel 10CrNi3MoV/SS304L bimetallic plates: (a) wavy interface, (b) flyer layer material SS304L, (c) peak of the wave, (d) trough of the wave, and (e) vortex island on the side

SS304L was twin austenite and ferrite as shown in Fig. 4b, and a large number of slip lines were observed in austenite grains according to metal microstructure inspection method standard of GB/T 13298-2015 (Ref 24). During the bonding process of explosive welding between the plates, the flyer layer austenite grains were twined under the external force, which resulted in the formation of twins. The characteristics and the morphology of the interface structure of the bimetallic plates (Fig. 4a, c–e) were consistent with Fig. 3(a), (c)–(e).

The aforementioned analysis reveals a highly intact interface cladded between the dissimilar metals by explosive welding. The presence of the local vortices could be distributed more evenly along the interface with stable form as shown in Fig. 3(a) and 4(a).

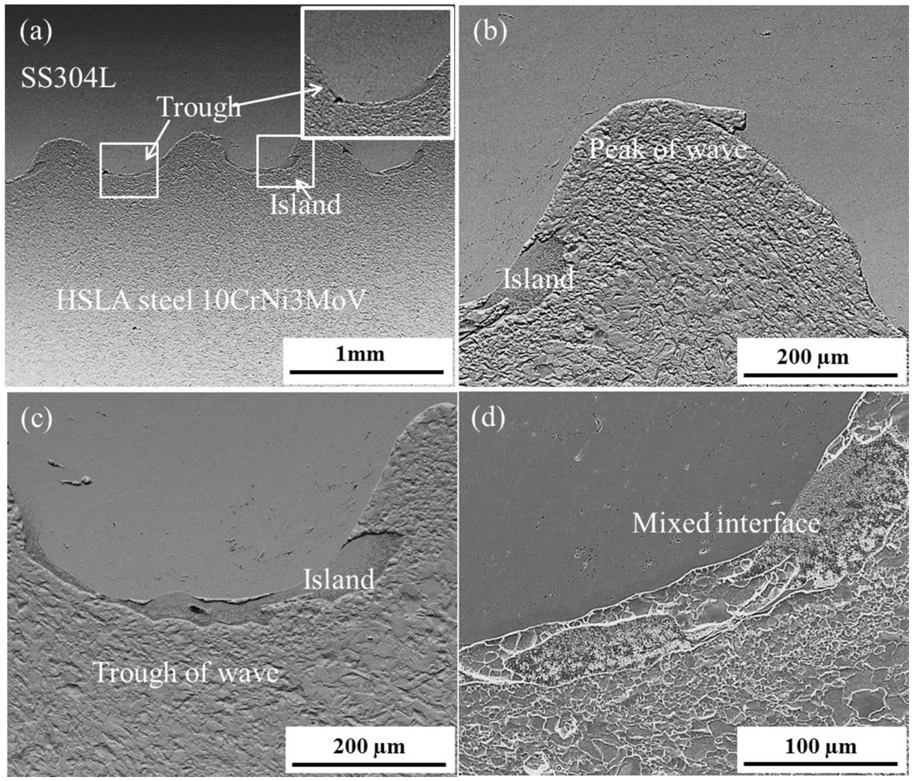


Fig. 5 SEM images of the interface in explosively bonded HSLA steel 10CrNi3MoV/SS304L bimetallic plates: (a) wavy interface, (b) peak of the wave, (c) trough of the wave, and (d) mixed interface on the side

3.2 SEM Observation of the Explosive Welding Interface

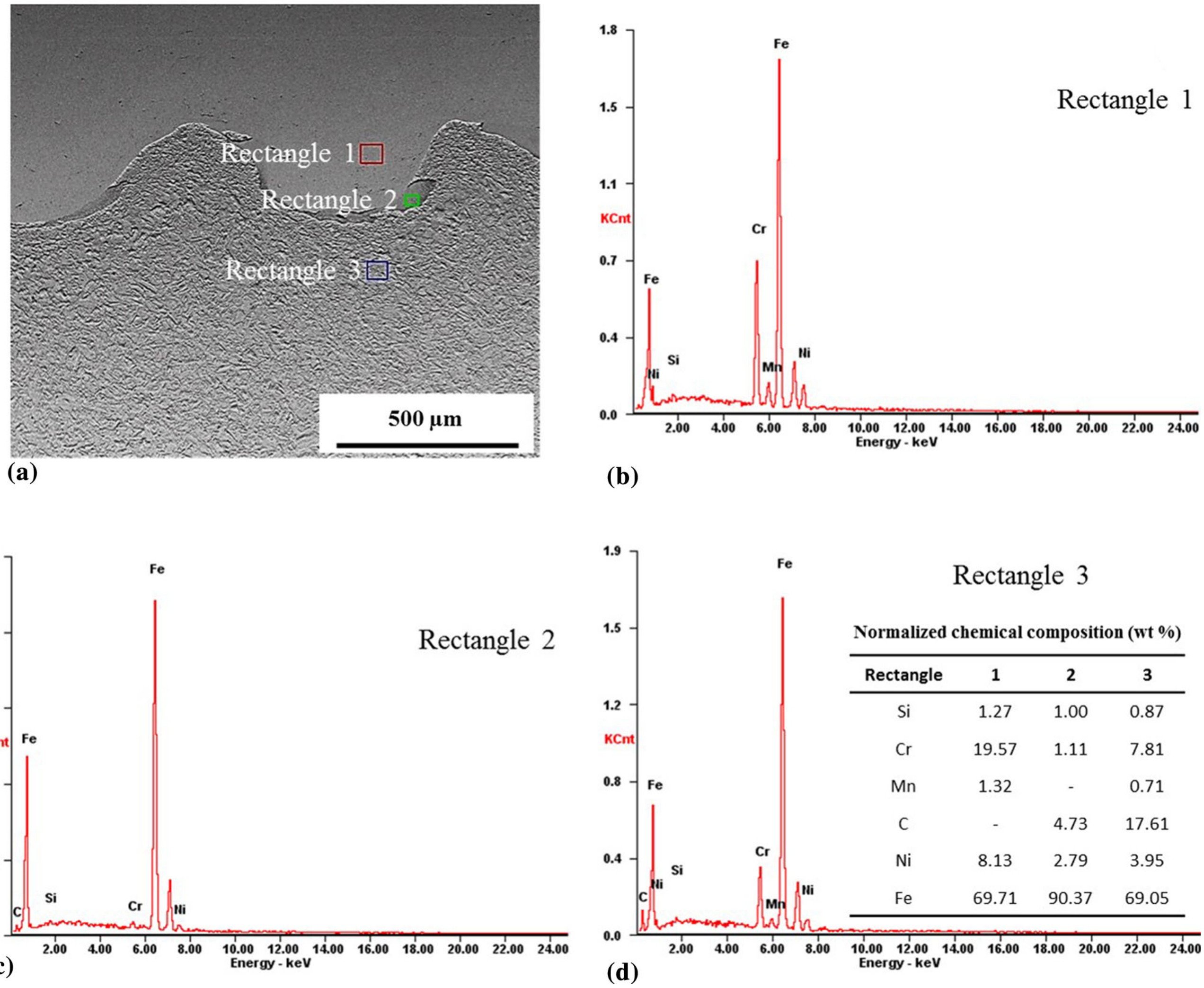
Figure 5 shows the SEM observation results of the morphologies around the wavy interface. Under the action of detonation wave, the flyer layer plate impacted the base plate at high speed, and the contact interface between two plates has undergone severe plastic deformation under the action of periodic stress (Fig. 5a). The interface presented wavy structure with stable waveform. With the further distance from the bonding boundary, the deformation degree of the structure of base plate and the flyer layer decreased gradually until the morphology before explosive welding was restored. Three typical positions, peak of wave, trough of wave and the vortices island-like, were observed, as shown in Fig. 5b–d. Figure 5(b), (c) shows a clear demarcation between the two metals near the slope edges of the wavy interface. A mixed interface region adjacent to the vortices was formed, and a fine cast microstructure region distributed in the interior of the vortices, most likely because the molten metal formed by cooling occurred in this zone, as shown in Fig. 5(d).

The tempered sorbite phase in the HSLA steel 10CrNi3MoV zone near the interface was fine equiaxed structure which could be attributed to the subsequent heat treatment recrystallization recovery process. No elongated structure was observed in the two metals adjacent to the explosive welding interface, but an obviously deformation had occurred on both sides of the interface and formed a microstructure of fine grains. The results of this study were different from those reported in the literature (Ref 25) that the grains of the base steel and flyer (2205 duplex stainless steel) plates near to the interface were elongated parallel to the impact direction because of high impact velocity. The high impact velocity of the flyer layer on the base plate caused deformation of the grains near the interface resulted in strain hardening and high residual stress at the explosive welding interface. The subsequent heat treatment could effectively eliminate the explosive welding interface stress and restore to recrystallize the elongated grains. No heat treatment technology was employed in (Ref 25), but our work was done with adequate heat treatment process at 645 °C for 240 min.

3.3 Distribution of Alloy Elements Across the Explosive Welding Interface

Figure 6 shows EDS analysis on the three positions near the explosive welding interface. Results showed that chemical elements composition of melted vortices zone consists of SS304L and HSLA steel with complex distribution on the basis of the comparison of the chemical composition before and after explosive welding (Table 1 and Fig. 6d). This was due to high-temperature melting and mixing of both flyer layer and base steel plate (Fig. 6c). The high carbon content up to 4.73 wt.% (0.028 wt.% in SS304L and 0.076 wt.% in 10CrNi3MoV steel as shown in Table 1) in the local vortices zone also indicated that the pollutant or carbide existed in this location, which was formed during the explosive welding process of high temperature and high pressure.

Figure 7 shows electron probe linear scanning analysis near the interface, the significant fluctuations in Cr, Ni, and Fe contents near the interface. High Cr content in the SS304L side near the explosive welding interface melted region, whereas the HSLA steel 10CrNi3MoV side had a lower Cr content. A significant change in Ni content in the interface near the peak and trough resulted in complex diffusion condition. Overall, the



Normalized chemical composition (wt %)

Rectangle	1	2	3
Si	1.27	1.00	0.87
Cr	19.57	1.11	7.81
Mn	1.32	-	0.71
C	-	4.73	17.61
Ni	8.13	2.79	3.95
Fe	69.71	90.37	69.05

Fig. 6 EDS analysis results of local interface zone: (a) wavy interface, (b) results for rectangle 1 in (a), (b) results for rectangle 2 in (a), (c) results for rectangle 3 in (a)

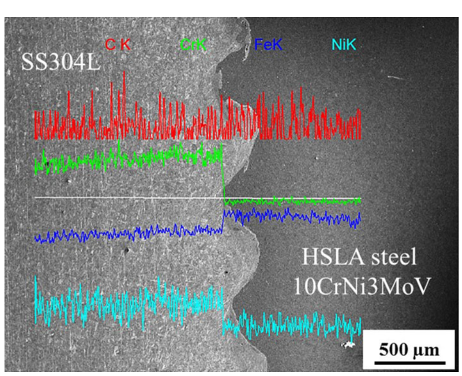


Fig. 7 Distribution of elements across the HSLA steel 10CrNi3MoV/SS304L interface

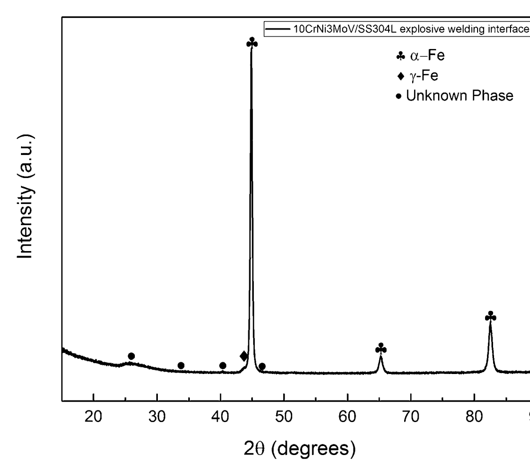


Fig. 8 XRD phase's analysis of the interface in explosively bonded HSLA steel 10CrNi3MoV/SS304L bimetallic plates

diffusion layer of alloying elements near the interface was very thin in several microns.

3.4 XRD Analyses of the Explosive Welding Interface

The analysis in phase composition of the interface in explosively bonded HSLA steel 10CrNi3MoV/SS304L bimetallic plates is presented in Fig. 8. The XRD examination result indicated that there were two phases in the explosive welding interface. The main phase was ferrite (α-Fe) and a little austenite (γ-Fe). Combining microstructure and element analysis, the phase composition of the weld interface included both the base metal steel 10CrNi3MoV (tempered sorbite, mainly α-Fe ferrite with carbide) and the flyer layer SS304L (mainly γ-Fe). There was also an unknown phase on the interface, which was considered to be an intermetallic phase formed under high temperature and high pressure during the explosion welding process. Because the amount of unknown phase was small or difficult to form, the pick information was not obvious.

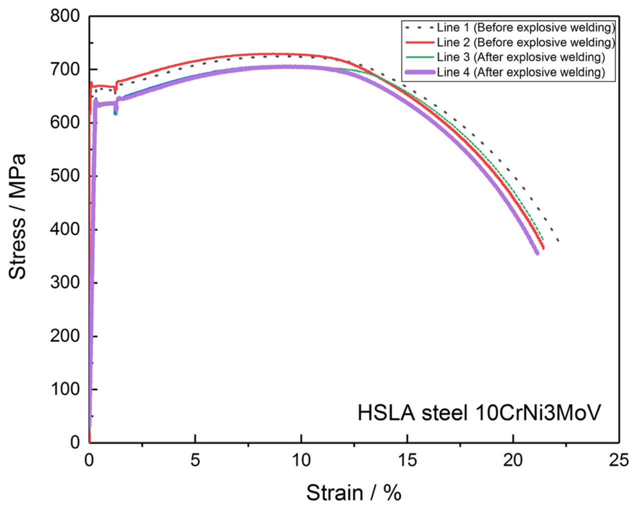


Fig. 9 Stress–strain curves of tensile tests for base material HSLA steel 10CrNi3MoV before and after explosive welding

3.5 Mechanical Properties

3.5.1 Tensile Properties of the HSLA Steel. It is worth noting that the tensile properties of HSLA steel 10CrNi3MoV experienced explosive welding are crucial to the service performance when structural components are subjected to tensile loading. Reliability of the tensile strength test data would guarantee structural stability within the design life.

In this paper, the tensile behaviors of the base metal HSLA steel 10CrNi3MoV before explosive welding and bimetallic plates removed the flayer layer SS304L were studied. Two experiments were conducted for each condition. The obtained stress–strain curves are shown in Fig. 9. The results indicated that the tensile strength of the material experienced explosive welding was slightly lower than that of the material before explosive welding. The plasticity of the material undergone explosive welding was changed little which can be ignored. The specific test data from explosive welding specimens showed that the ultimate tensile strength (UTS) and the yield

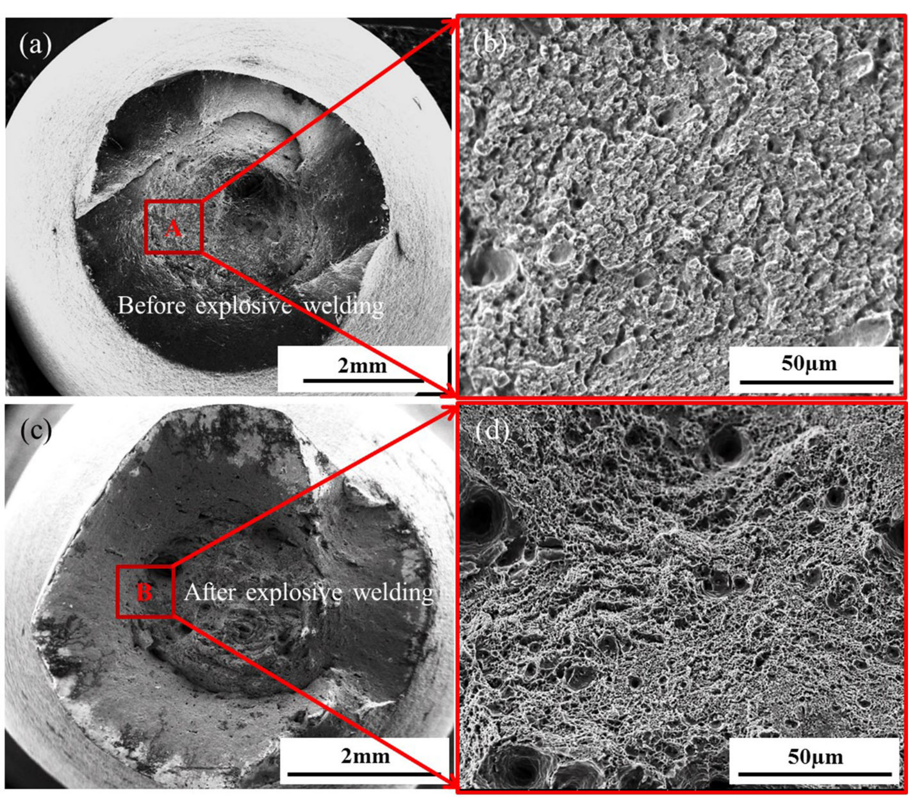


Fig. 10 Fractography of the base material HSLA steel 10CrNi3MoV after the tensile tests, (a) macro-fractography of the material before explosive welding, (b) high-resolution fractography of position A, (c) macro-fractography of the base material after explosive welding, (d) high-resolution fractography of position B

stress (YS) of the base metal HSLA steel 10CrNi3MoV decreased from about 727 to 705 MPa and 666 to 637 MPa in average values, respectively. The change in tensile properties of the HSLA steel was mainly due to severe deformation and harden in explosive welding. Even after subsequent heat treatment and leveling, the mechanical properties of the bimetallic plates cannot be restored to the original state as before the explosion welding. However, based on an overall assessment of acceptable data deviations, the tensile properties of base metal HSLA steel can be considered relatively stable. It demonstrated that a reasonable manufacturing process was employed. In addition, after undergoing similar explosive welding, the stability of the base metal 10CrNi3MoV obtained from the stress–strain curve was better than the experimental results of the X65 steel reported in the literature (Ref 26). After explosive welding, the X65 base metal obtained much higher tensile strength and lower in plasticity by more than half, which could be explained by no effective post-weld heat treatment process was used. Simply selecting an appropriate heat treatment process at 645 °C for 240 min in our work, the HSLA steel can reduce the harmful effect of explosive welding. It has also been reported in the literature (Ref 27) that the tensile properties and Charpy impact energy of the base plate (HSLA steel) were lowered due to hot rolling and then increased substantially due to heat treatment.

In order to study the fracture behavior of the HSLA steel 10CrNi3MoV before and after explosive welding, fractography observation was carried out on the surface of the tested specimens as shown in Fig. 10. Figure 10 reveals typical ductile fracture characteristic features including lots of dimples for the material HSLA steel 10CrNi3MoV from two states before and after explosive welding. Comparing the high fractography resolution in positions A and B, it can evidence that the broken surfaces of base material experienced explosive welding show spherical dimples with a few large-scale defective dimples in good agreement with the results reported (Ref 26). It is important to note that the fractured surfaces of the base metal before explosive welding consist of a certain amount of uniform small scale dimples as shown in Fig. 10b, which is correlated with the excellent plasticity and strength upon the material. Large-scale defective dimples could cause mechanical performance to be disturbed.

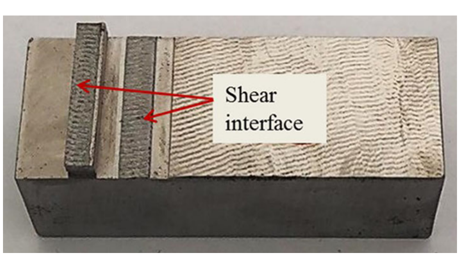


Fig. 11 Fractured shear test specimen of the bimetallic plates

3.5.2 Shear Characterization of the Explosive Welding Composite Plates. According to the provisions of the standard GB/T 6396-2008, the shear tests of the bimetallic plates were carried out at room temperature. Figure 11 shows the shear test specimen was conducted. The shear tests results are given in Table 2. The average shear fracture strength for the three specimens was about 432 MPa, which was much higher than the standard requirement of GB/T 8165-2008 210 MPa. The shear strength was twice the standard required value, which was related to the selection of appropriate explosive welding parameters and effective heat treatment process in the experiment. The heat-treated specimen had higher shear strength than the one without heat treatment. The heat treatment process could improve the interface bonding strength (Ref 17). Too high shear strength with explosive distortion stress is harmful to the quality of the bimetallic composite plates because of the potential stress cracking. Effective high-temperature heat treatment process can reduce the shear strength and improve the performance reliability of the bimetallic explosive-welded plates, which may be due to the effects of eliminating the welding interface stress and promoting the recrystallization growth of the deformed grains.

The shear test demonstrated that HSLA steel 10CrNi3MoV/SS304L bimetallic plates had good shear strength, implying that the composite plates could be safely used. Fractography of shear test fracture was the dimple morphology with ductile characteristic as shown in Fig. 12. Figure 12a shows the macro-morphology of the shear test fracture, and Fig. 12b shows the high-resolution microscopic morphology near the center of the shear fracture. The EDS analysis revealed that the element content of Cr, Mn in the rectangle 1 was approximately 1.27%, 0.78%, respectively (Fig. 13b). Near a periodic wavelength area rectangle 2 relative to position rectangle 1, Cr content was about 3.73% (Fig. 13c). The EDS analysis results confirmed once again that the metal in the shear fracture interface was a mixture of two materials and the metallurgical bonding of the weld interface was realized. The distribution of the elements measured by EDS also showed that the mainly shear fracture occurred near the base metal HSLA steel 10CrNi3MoV, which could be explained by lower hardness in the base metal that was prone to fracture measured in Fig. 15.

3.5.3 Impact Toughness Behavior of the HSLA Steel. The Charpy V-notch impact tests at − 20 °C were carried out to evaluate the toughness of HSLA steel 10CrNi3MoV before and after explosive welding. The results of impact tests are given in Table 3. The specimens were not completely broken due to the bending connection of some materials (Fig. 14), which was a characteristic of toughness and avoided brittle fracture (Ref 2).

The impact energy of the base material after explosive welding was about 258 J (standard deviation ± 11 J), which

Table 2 Shear tests results of the HSLA steel 10CrNi3MoV/SS304L explosive welding joints

Materials	Shear strength, MPa			Average values
HSLA steel 10CrNi3MoV/SS304L explosive welding joints	435	446	416	432
Standard requirement of GB/T 8165-2008	≥ 210			

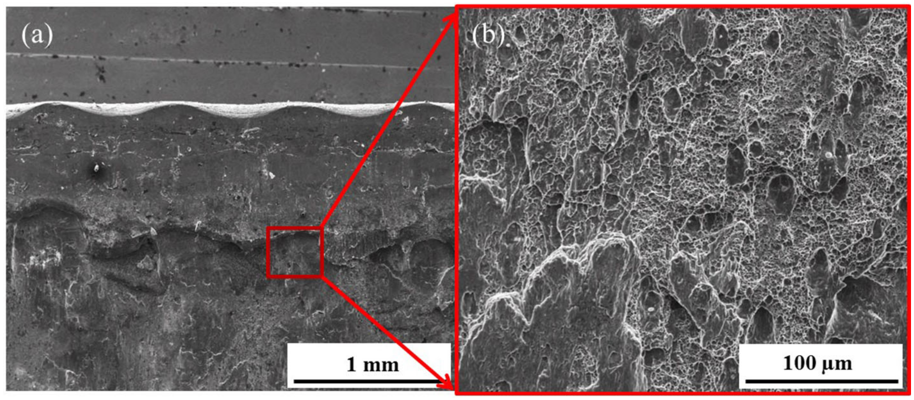


Fig. 12 Fractography of shear test fracture: (a) macro-fracture; (b) high-resolution fractography of the surface in (a)

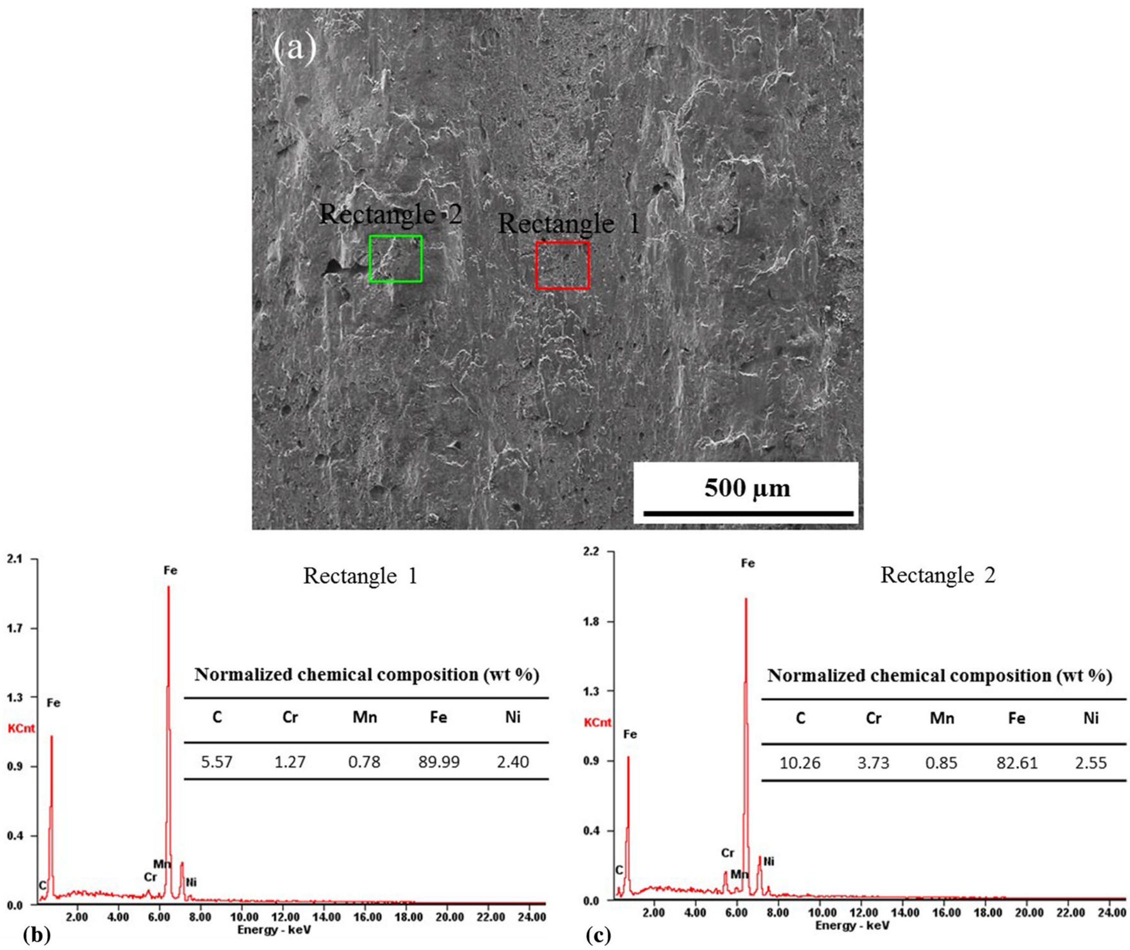


Fig. 13 Target areas of EDS analysis: (a) shear test fracture; (b) results for rectangle 1 in (a); and (c) results for rectangle 2 in (a)

Table 3 Impact tests results of the HSLA steel 10CrNi3MoV before and after explosive welding

Materials	Impact energy (J) tested at − 20 °C			Average values
10CrNi3MoV before explosive welding	247	213	204	221
10CrNi3MoV after explosive welding	251	252	271	258

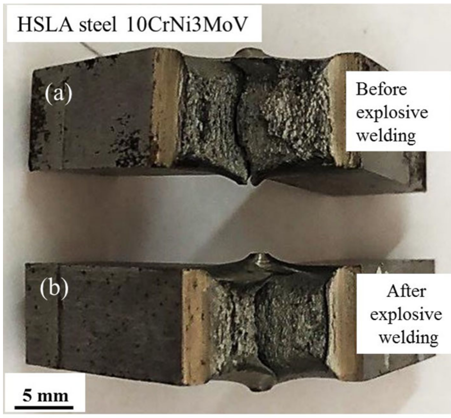


Fig. 14 Charpy impact tests specimens of HSLA steel 10CrNi3MoV after tests at − 20 °C: (a) the base material before explosive welding and (b) after explosive welding

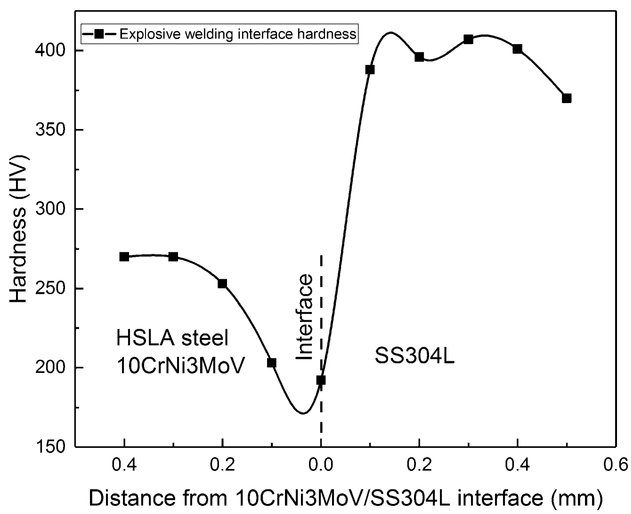


Fig. 15 Vickers hardness values of the HSLA steel 10CrNi3MoV/SS304L interface

was higher than that from the material before explosive welding 221 J (standard deviation ± 23 J). The increase in ductility of the HSLA steel 10CrNi3MoV with the decrease in standard deviation after explosive welding process demonstrated that a good recovery of the base metal properties was obtained. Thus, the toughness reduction caused by explosion hardening was avoided. The stable impact toughness maintained was mainly attributed to effective post-weld heat treatment process by releasing explosive stress in the HSLA steel and restoring its microstructure.

3.5.4 Microhardness Analysis of the Bimetallic Composite Plates. The measured microhardness values of HSLA steel 10CrNi3MoV/SS304L bimetallic plates interface are shown in Fig. 15, from which a remarkable difference in the microhardness between the two metals can be observed. The microhardness measurements were taken using 0.98 N (100 g) across the bimetallic interface with an interval of 0.1 mm.

It can be seen from Fig. 15 that the maximum hardness 407 HV was obtained on the SS304L flyer layer side near the explosive welding interface. The lowest hardness value appeared in the middle of the explosive welding interface 192 HV. Compared with the materials before explosive welding, the hardness of both HSLA steel 10CrNi3MoV and SS304L increased significantly after explosion. For example, the hardness values of the materials before explosive welding were 237 HV and 213 HV corresponding to HSLA steel 10CrNi3-MoV and SS304L, respectively. However, the hardness values near the interface increased to 270 HV and 407 HV, respectively. The values increased with increasing distance from the interface to the maximum value, and then gradually decreased. The trend distribution of hardness in this study was inconsistent with the frequently reported results. Hardness values of the cladded interface were increased after the explosive cladding (Ref 20, 28). This phenomenon might be explained by the fact that the microstructure in the explosive-welded interface region was quite different from that in the region far away from the interface, as shown in Fig. 3(e) and 4(e). The high heat and high pressure generation in the interface region by instantaneous explosion then accompanied a heat treat process that caused annealing of the shock-hardened material. The authors would like to further explain this phenomenon as that the element composition changes within a very thin interface as shown in Fig. 6 and 7.

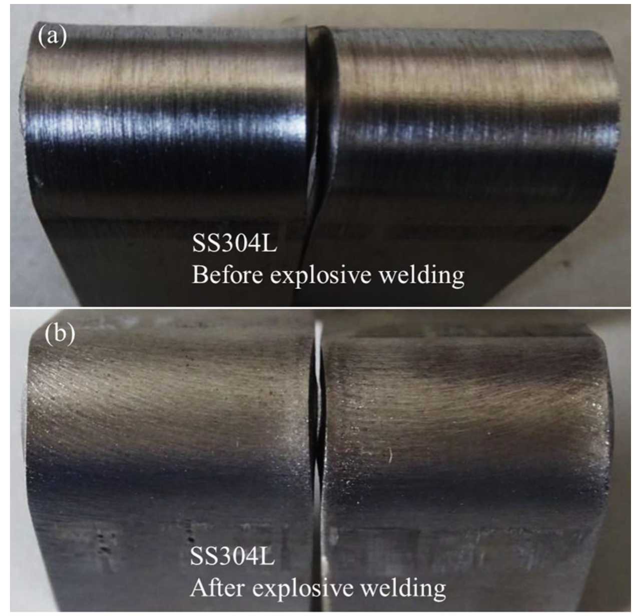


Fig. 16 Intergranular corrosion specimens: (a) the SS304L before explosive welding and (b) the SS304L after explosive welding

3.6 Intergranular Corrosion Resistance of the SS304L

Intergranular corrosion test was carried out according to ASTM A262 standard and the photographs of the SS304L specimens are shown in Fig. 16. The specimens were bent till to 180° and no cracks observed induced by intergranular corrosion on the external surface. SS304L had good resistance to intergranular corrosion before and after explosive welding. Therefore, the manufacturing process of explosive welding 10CrNi3MoV/SS304L bimetallic plates did not affect the functional design goal of SS304L for corrosion resistance.

4. Conclusions

HSLA steel 10CrNi3MoV (parent base plate) and SS304L (flyer layer) plates were cladded through explosive welding process and their microstructure and mechanical properties were investigated. The following conclusions can be drawn from this investigation:

- SS304L plate can be cladded onto base HSLA steel 10CrNi3MoV with 9 mm initial gap and formed a metallurgical bonding waveform interface by the explosive welding technique. The phases of investigated interface were mainly ferrite (α-Fe) and austenite (γ-Fe) mixed both HSLA steel and SS304. The average wavelength and wave width were 0.83 mm and 0.28 mm, respectively.
- Recrystallizations of the deformed grains on both sides of the interface are depending on explosion distortion and on the subsequent heat treatment conditions at temperature 645 °C and keep for 240 min. The interface diffusion layer was thin, which results in a microhardness distribution. The maximum hardness value 407 HV was obtained near the joint interface on the side of SS304L, and the minimum one 192 HV appeared in the middle of the explosive-welded interface.
- The mechanical properties of the bimetallic plates experienced explosive welding maintained good performance. The average values of UTS and YS of the HSLA steel 10CrNi3MoV after explosive welding were 727 MPa and 666 MPa, respectively. The impact energy of the steel 10CrNi3MoV experienced explosive welding was 258 J higher than the one before explosive welding 221 J. The shear strength of the bimetallic plates was 432 MPa higher than the requirement of GB/T 8165-2008 210 MPa.

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Conflicts of interest

All authors declare that they have no conflicts of interest.

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