Journal of Alloys and Compounds 485 (2009) 817–821

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Microstructural characterization of explosively welded rapidly solidified foil and stainless steel plate through the acceleration employing underwater shock wave

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ARTICLE INFO

Article history:
Received 17 April 2009
Received in revised form 12 June 2009
Accepted 12 June 2009
Available online 21 June 2009

Keywords:
Amorphous materials
Composite materials
Metallic glasses

ABSTRACT

Rapidly solidified amorphous and metallic glass thin foils clad on a stainless steel base plate was fabricated by employing underwater shock wave generated by the detonation of an explosive, and the microstructure of the welded interface was characterized. The rapidly solidified thin foils were successfully welded indicating waves without the formation of interfacial zone in most of the area. However, some interfacial zones caused due to the trapped metal jet were occasionally found. It is expected that the quality of welding would not be significantly affected by the presence of interfacial zones. The interfacial microstructure was characterized through optical, scanning electron and transmission electron microscopes as well as using micro-focus X-ray diffraction and EDX analyses.

1. Introduction

Explosive welding technique has been widely recognized as an industrial technique to join two dissimilar plates with tight bonding [1]. The welded interface normally undergoes minimal heating effect and does not affect the quality of the bonding. The thickness of metal plate is normally in the order of 1 mm or more as far as using a regular explosive welding technique. Underwater explosive welding technique has been developed and investigated by some of the authors [2–6] as a method to weld a thin foil or plate. Using this technique, the welding of rapidly solidified amorphous and metallic glass thin films on to stainless steel base plate was successfully demonstrated in a recently published paper [7]. The paper [7] discusses mainly with the welding conditions based on numerical analysis using a commercial code AUTODYN-2D. The result of literature studies indicates that very limited research has been made to analyze the microstructure in the interface of such joints, except few papers that report the characterization through TEM (transmission electron microscope) analysis for BMG (bulk metallic glass) and metal joints [8,9]. Accordingly, the present paper intends to deal with the microstructural characterization of the welded interface fabricated by the underwater explosive welding technique.

2. Experimental

A detailed description of the assembly and the conditions employed for the underwater explosive welding has been reported elsewhere [7]. A high explosive SEP, produced by Asahi-Kasei Chemicals Corp., was used for the experiment. The density and the detonation velocity of the explosive was 1300 kg/m^3 and about 7 km/s, respectively. The use of inclined set-up of the explosive and increased-thickness explosive assembly enables to weld thin foils without any change in the welding conditions along the welding direction. The welding conditions, namely, the dynamic bending angle β, about 20–22°, and the velocity to vertical direction Vp estimated as 1200–1350 m/s [7] are relatively higher than the welding conditions normally employed [1]. Such high energetic conditions are essential to induce fluidization of both the components to participate in explosive welding, especially in the welding of rapidly solidified films which has high hardness.

A Ni-based amorphous film (($Ni_{0.6}Nb_{0.4})_{65}Zr_{30}Co_5$: 38-μm-thick) or a Ni-based metallic glass film ($Ni_{53}Nb_{20}Ti_{10}Zr_8Co_6Cu_3$: 28-μm-thick) directly covered with a 0.1-mm-thick aluminum plate, was welded onto 304 stainless steel (S.S.) plate (1-mm-thick) with an air gap fixed at 0.5 mm for 40 mm in length. The aluminum plate used as a cover plate controls the velocity acting on the rapidly solidified film, and it also acts as a momentum trap block to release the reflected wave from bottom. The amorphous and metallic glass films, which have high strength and corrosion resistance, are being developed for fuel cell separator and hydrogen-permeable membrane, respectively. The technique of joining such film onto a base metal is currently under development.

The welded samples were cut at the center parallel to the welding direction, and the microstructure close to the welding interface was characterized. The microstruc-

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doi:10.1016/j.jallcom.2009.06.082

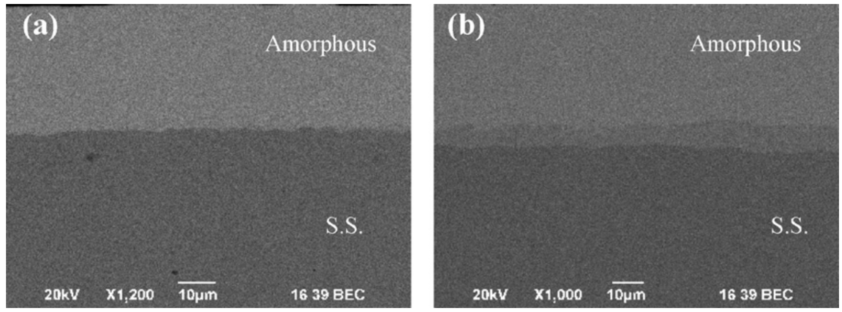

Fig. 1. Compositional image taken by SEM for interface in amorphous film welded on stainless steel base showing wave structure (a) and interfacial zone (b).

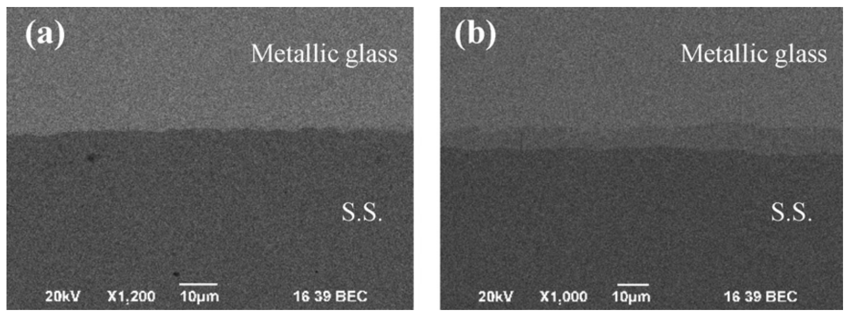

Fig. 2. Compositional image taken by SEM for interface in metallic glass film welded on stainless steel base showing wave structure (a) and interfacial zone (b).

tural characterization was done using various techniques including TEM, and the interface was analyzed using micro-focus X-ray diffraction analysis (collimator diameter at 50 μm) and EDX analysis.

3. Results and discussion

The thin films were successfully welded on the stainless steel substrate using underwater explosive welding technique, as reported in our previous paper [7]. The results observed, indicated the welded interface of wavy structure without interfacial zones. However, occasional presence of interfacial zones was observed which was considered to be induced by the trapped metal jet. Figs. 1 and 2 display the SEM images of the interface of amorphous/S.S. and metallic glass/S.S. combinations. As seen in Figs. 1(a) and 2(a), the wavelength is less than 5 μm and shows a non-uniform wavy structure because of the small size of the waves in comparison with the wave size found in conventional explosive welding. It has been reported that the height of fluidized zone is proportional to the thickness of flyer plate [1], whereas in the case of welding of thin films, the height or the thickness of fluidized zone is small. Normally, metal jet swept ahead of the collision point activates the welding surface [1], but in the case of welding of thin plate, the metal jet is relatively easy to get trapped due to the uneven thickness of the rapidly solidified films as seen in Figs. 1(b) and 2(b). It is interesting to note that the interfacial zone includes aluminum of less than 10 at.% as measured through EDX analysis. Since both materials welded do not contain aluminum, it is considered that the jetting of aluminum cover plate during its collision with the stainless steel base plate may have the chance to contact both components directly before the welding of rapidly solidified films on the stainless steel base. The existence of aluminum element of less than 5 mm from the starting point of the welding was confirmed, which means that the jet was swept for a certain length ahead of the welding point. This was observed in the welding of the rapidly solidified film even though a very narrow gap of 0.5 mm was used. Therefore, the following results were characterized at the middle part of the sample that is not affected by aluminum jet.

Figs. 1(b) and 2(b) suggest that the composition is uniformly distributed but the other region found in Fig. 3 for metallic glass/S.S. shows that the components are not mixed uniformly at the interfacial zone. The results of line analysis for the sample made using EDX is shown in Fig. 4. The measurements were carried out along the arrow as shown in Fig. 3. As expected, the interface showed mixed chemical composition of both the material and the composition gradually changed due to the short time in mixing of both components. It should be emphasized again that the welded interface shown in Figs. 1(a) and 2(a) without interfacial zone was more than 90% in length which may exhibit a substantially high bonding strength at the interface. The chemical composition measured by the point analysis using EDX at the center of the interfacial zone is shown in Table 1. Two measurements for amorphous/S.S. and one measurement for metallic glass/S.S. were performed. The results suggest that the elements of rapidly solidified films were higher and small amount of stainless steel component was entrapped in the interfacial zone. One of the authors has reported that the chem-

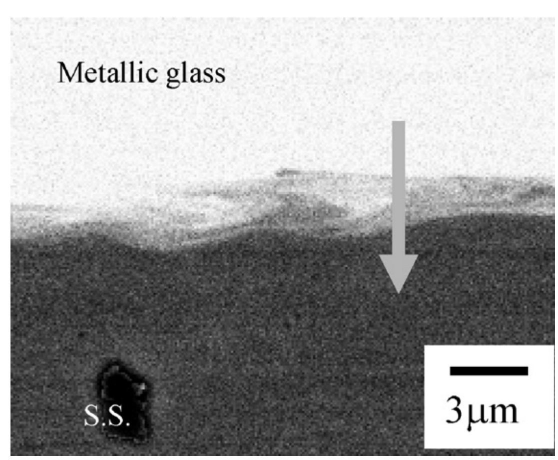

Fig. 3. Compositional image taken by SEM for interface in metallic glass on stainless steel base showing fluctuation and the mixing of each element.

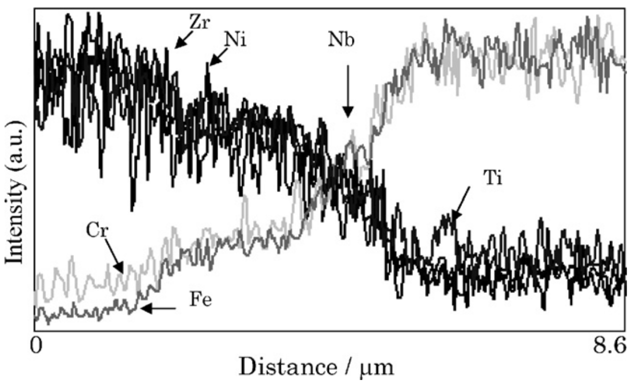

Fig. 4. Measured elemental distribution using EDX across the interfacial zone for metallic glass and stainless steel.

ical composition of the interfacial zone induced in conventional explosive welding entraps a high percentage of softer component [10]. In the present combination, the hardness of stainless steel of about 400 HV (Vickers hardness) is considerably smaller than the rapidly solidified films 650–850 HV. The phenomenon is not clearly known but the possibility of enhanced melting or fluidization of the rapidly solidified films may lead to such excessive melting.

Fig. 5 shows the optical micrographs of the penetration marks made by micro-Vickers hardness measurements under a load of 98 mN (10 gf). The average hardness of the amorphous and the metallic glass was 669 and 835 HV, respectively. The numbers indicate the Vickers hardness values at the interfacial zone although the boundary is not clear. The hardness of the interfacial zone is slightly higher for amorphous/S.S. and almost similar for metallic glass/S.S. While considering the insignificant difference in the hardness values and the formation of interfacial zone in limited area, it is expected that no significant degradation in the quality of welding would occur. From the thickness of the interfacial zone, it can be deduced that the cooling rate is quite high enough for solidification to occur into amorphous or glassy state as like the original rapidly solidified phase.

Figs. 6 and 7 show the results of micro-focus X-ray diffraction analysis for amorphous/S.S. and metallic glass/S.S., respectively. The measurements were made across the cross-sectional area, (a) at the center of rapidly solidified film, (b) and (c) at the welded interface (two measurements) and (d) at stainless steel 30 μm apart from the interface. Attempts made to measure the diffraction on the interface that contains interfacial zone showed no peaks of crystallization or formation of intermetallics other than the peaks of stainless steel.

Transmission electron microscope (TEM) analysis was made only for amorphous/S.S. sample due to the difficulty in the preparation of the samples. The amorphous/S.S. sample was cut into a

Table 1
Chemical composition at interfacial zone measured by EDX analysis.

	Chemical composition of elements (at.%)					
	Ni	Nb	Zr	Co	Fe	Cr
Amorphous/S.S.						
Zone 1	22.16	28.58	27.96	2.61	14.94	3.76
Zone 2	22.54	29.89	30.01	2.70	11.82	3.03

	Chemical composition of elements (at.%)							
	Ni	Nb	Zr	Co	Ti	Cu	Fe	Cr
Metallic glass/S.S.								
Zone 1	53.72	14.69	0.56	5.72	7.57	8.87	7.38	1.56

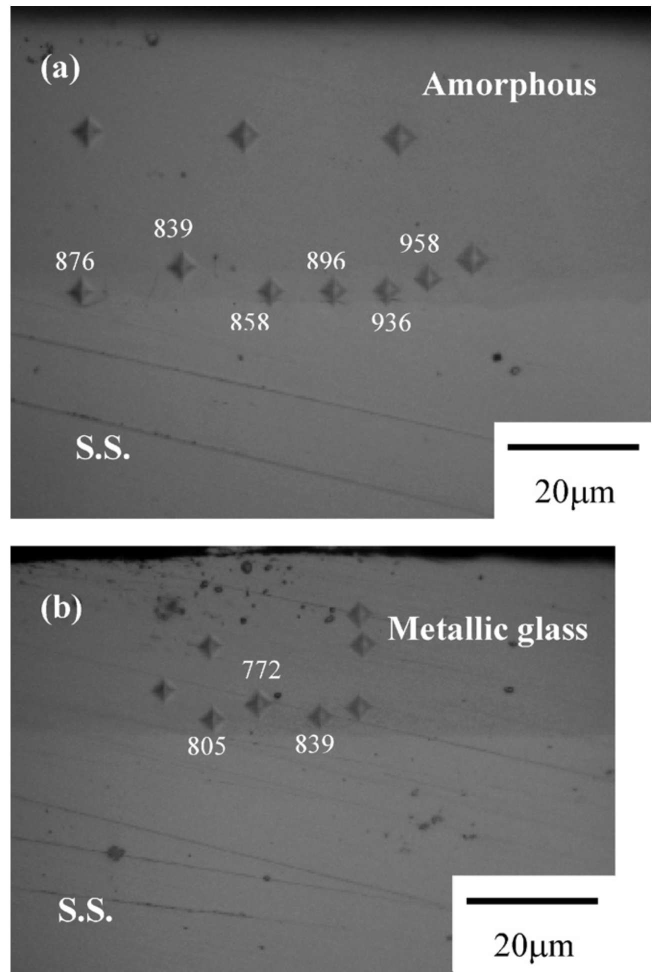

Fig. 5. Traces of micro-Vickers penetrator close to the interfacial zone for amorphous/S.S. (a) and metallic glass/S.S. (b).

slice and thinning of the sample was made through ion milling. Fig. 8 shows the results obtained through TEM analysis. The results shown in Fig. 8(a) indicate that the amorphous was in upper region and the stainless steel was in lower region, and no interfacial zone was found in this case. The interface shows slight fluctuation and a ripple seems to be formed at the interface along the line indicated by an arrow. The amorphous phase shows no significant change in its structure, and the stainless steel shows fine grains in the order of 100 nm or less. Fig. 8(b) and (c) shows the selected area diffraction (SAD) patterns, for the areas B and C in Fig. 8(a). The results confirmed that the amorphous phase is retained as indicated by the hallow pattern found in Fig. 8(b). Fig. 9 shows the analytical result for the SAD of stainless steel and it clearly indicates the gamma phase as the main phase. Fig. 10 shows the result of line analysis using EDX attached with the TEM along the arrow shown in Fig. 8(a). The result clearly shows the drastic change of the chemical composition at the interface in the order of 10 nm or less. The part suggested by an arrow in Fig. 10 is trapped amorphous region that shows almost the same ratio of the elements in the amorphous region indicating no elementally mixed region. In the research reports for the explosive welding of BGM, Chiba et al. [8] observed a thin elementally mixed zone of about 50 nm, and an amorphous-crystalline transition region about 3 nm with no elementally mixed zone was observed through high resolution TEM image by Liu et al. [9]. The present result does not indicate such transition zone but the

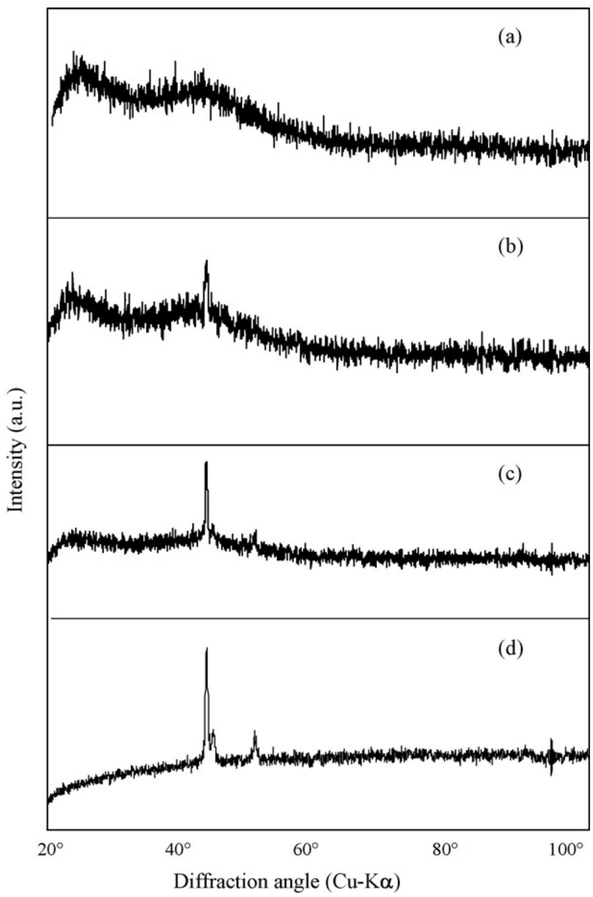

Fig. 6. Diffraction patterns for amorphous/S.S. measured by micro-focus X-ray diffraction analysis. Patterns were taken from amorphous film (a), interface (b and c) and stainless steel (d).

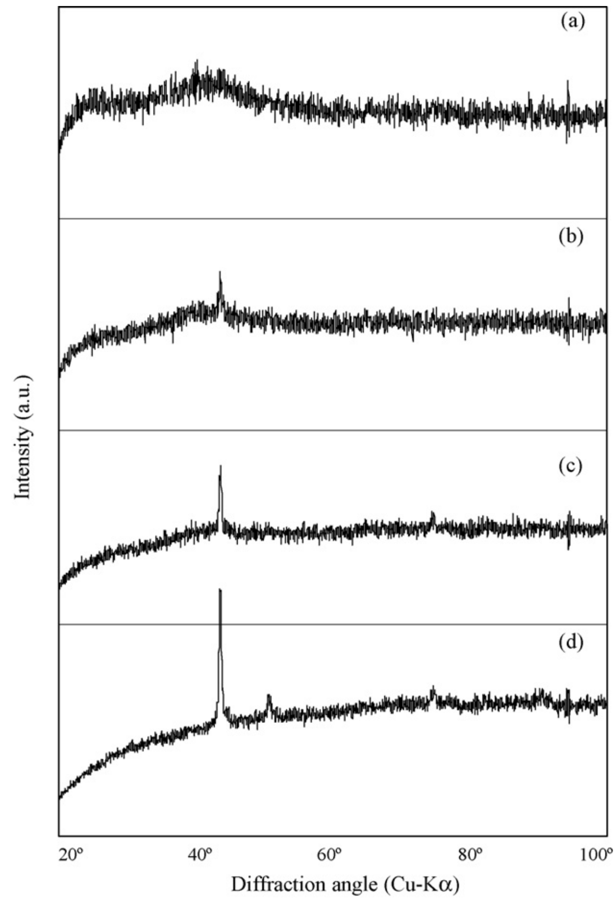

Fig. 7. Diffraction patterns for metallic glass/S.S. measured by micro-focus X-ray diffraction analysis. Patterns were taken from metallic glass film (a), interface (b and c) and stainless steel (d).

real phenomena should include both cases with and without the interfacial zone depending upon the area to be welded. When the heating effect due to jet is significant, the interfacial zone is expected, and this zone should be minimal when the welding is achieved through solid–solid deformation by the high-velocity shearing.

In the interface of both combinations, cracks were rarely found but still exist due to the unevenness of the rapidly solidified films.

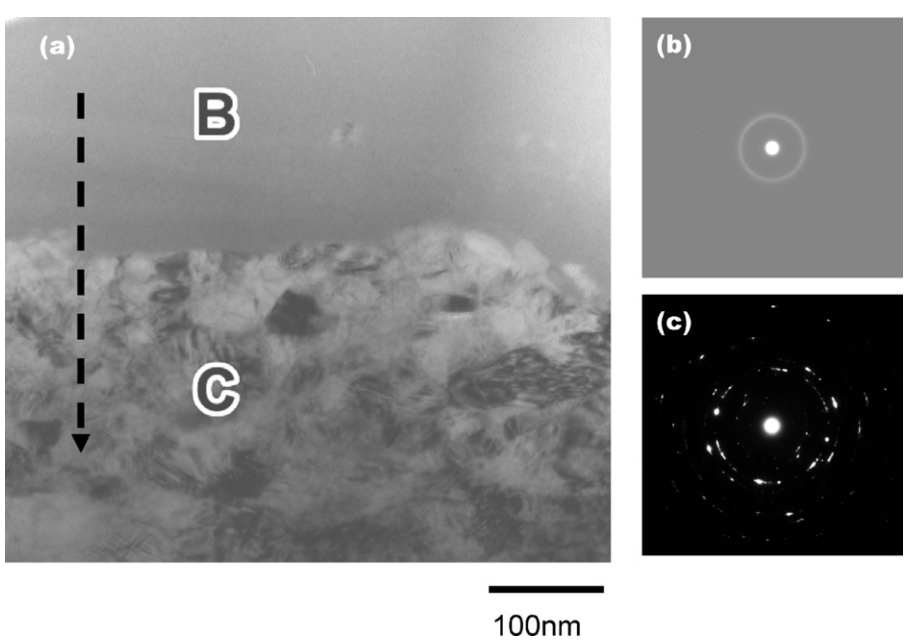

Fig. 8. TEM image close to interface of amorphous/S.S. (a) and selected area diffraction patterns for amorphous (b) and stainless steel (c) at positions B and C shown in (a).

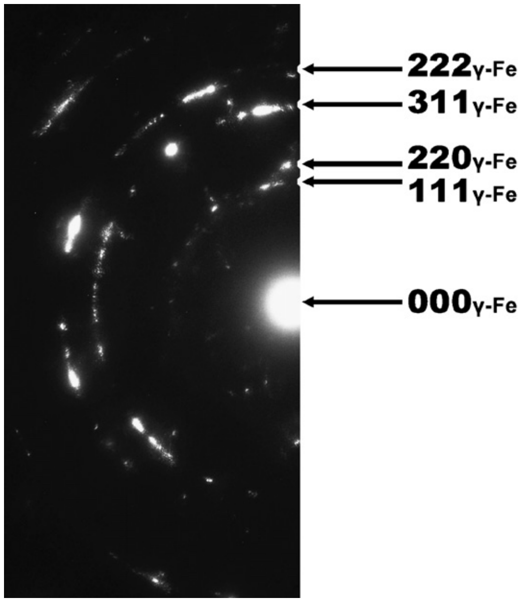

Fig. 9. Selected area diffraction pattern in stainless steel for amorphous/S.S. showing gamma phase.

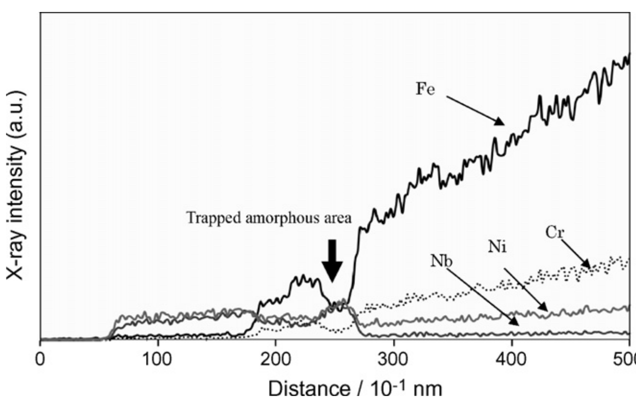

Fig. 10. Result of line analysis of elements using EDX across the interface of amorphous/S.S.

Fig. 11 shows the appearance of sheared crack at 45° which may be caused by changing the condition of collision. One of the authors has reported the possibility of double-layered welding by overlapping plates [11] which is expected to avoid the direct contact of the base plate with atmosphere. Such technique also enables to weld a wide plate. However, it has been suggested that the excessive jet trapped around the overlapped region may cause degradation of the bonding property [11]. Further investigation is currently underway to achieve the welding of a wide plate.

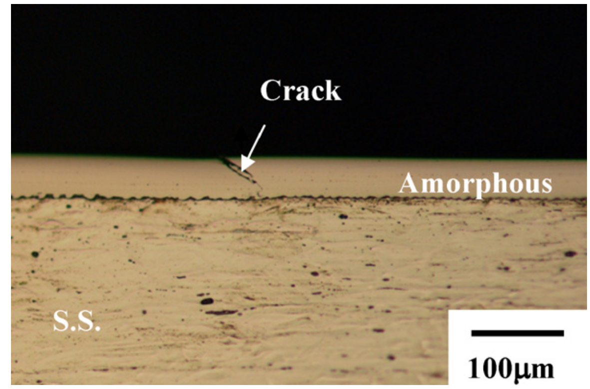

Fig. 11. Sheared crack found in interface for amorphous/S.S. interface.

4. Conclusions

The interfacial microstructure of the rapidly solidified films onto a stainless steel base made by underwater explosive welding was characterized using SEM, TEM and others. The interface shows an area with interfacial zone caused by the trapped jet and the other area without such interfacial zone. The interfacial zone was composed of both the components of welded materials. The composition of rapidly solidified film occupies the major part of the interfacial zone with small amount of the stainless steel. The hardness of the interfacial zone was not significantly changed in comparison with the rapidly solidified films.

Acknowledgement

The help of Mr. Susumu Akimaru, Shock Wave and Condensed Matter Research Center, Kumamoto University for the explosion experiments is gratefully acknowledged.

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