Research paper

Characterization of titanium / stainless steel welded using underwater shock wave technique

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Abstract

Commercially pure titanium and stainless steel was explosively welded using underwater shock wave. The experimental results were obtained by changing the parameters, the distance between the sample and explosive and the thickness of explosive. The results demonstrate a good welding interface with small waves devoid of intermetallics, as the kinetic energy spent at the interface is less. An increase in kinetic energy loss resulted in waves with vortices, where intermetallic layer is formed.

Keywords : Titanium, Stainless steel, Underwater Shock Wave, Intermetallics, Kinetic energy loss

1. Introduction

The increasing demand for superior corrosion resistant plates and low manufacturing cost in chemical and nuclear industries has led to the development of joining technology for titanium/stainless steel bimetal system[1]. Joining by conventional fusion welding results in the segregation of chemical species and formation of brittle intermetallics at the interface due to low solubility of Ti and Fe. In such cases, solid state welding processes are considered for dissimilar materials with extremely different physical and mechanical properties. Diffusion bonding has realized the joining of titanium/stainless steel with low bonding strength of the joints[2][3]. Further, the technique cannot be used for large plate cladding. Explosive welding offers a reliable solution for the joining of titanium/stainless steel. The process uses high pressure generated by an explosive and occurs in a micro second duration of bonding time, which in many cases, useful for the joining of metallurgical incompatible combinations[4)–11]. Conventional explosive welding used for the welding of titanium/stainless steel resulted in a good welding. However, at high kinetic energy conditions the interface develops brittle intermetallics[12][13]. Therefore, underwater shock wave technique, in which the kinetic energy loss is less, was used to join titanium/stainless steel. This technique offers the capability of joining very thin flyer plates on substrates. In this study, titanium and 304 stainless steel welded using underwater shock wave was investigated. Various parameters in obtaining an intermetallic free interface, such as initial angle, distance between explosive and center of the sample, and thickness of explosive and its influence on the microstructure are reported.

2. Experimental

Commercially pure grade titanium (JIS TP 340) was used as a flyer plate and 304 stainless steel (JIS SUS 304) was used as a base plate. Titanium flyer plates of dimensions 90 mm x 40 mm x 0.1 mm was welded on 304 stainless steel base plate of dimensions 90 mm x 40 mm x 1 mm using underwater shock wave, detailed elsewhere[14)–16]. No cover plate was used for the experiments. The explosive, SEP, of density 1310 kg m^{-3} and detonation velocity 6970 m s^{-1} was used in the present study (supplied by Asahi Kasei Chemicals Corp., Japan). The initial setup angle of the explosive is 20 °. The horizontal collision velocity Vc achieved for such initial angle using SEP explosive is less than the sonic velocity of the welding metals[14]. The distance between the sample and explosive, D, was varied as 20, 30, 40 and 50 mm and the thickness of explosive was varied as 5 mm and 10 mm. Fixed thickness explosive was used for the experiments. The stand off distance was fixed as 0.5 mm for all the experiments. The experimental condi-

Table. 1 Experimental conditions

Experiment No.	Thickness of explosive[mm]	Distance, *D* [mm]	Flyer velocity [m s^{-1}]	Collision angle, β [°]	Kinetic energy loss[MJ m^{-2}]	Horizontal Collision velocity, *Vc* [m s^{-1}]
1	5	20	2460−1360	32−21	1.36−0.41	4410−3685
2	5	30	1910−1240	27−20	0.82−0.35	4040−3610
3	5	40	1580−1145	24−18	0.56−0.30	3820−3550
4	5	50	1360−1060	21−17	0.42−0.25	3680−3500
5	10	40	2015−1520	28−23	0.92−0.52	4130−3800

tions are given in Table 1.The welding area was sealed against water. Samples for metallographic observation were cut parallel to the detonation direction. The important parameters in deciding the welding conditions, such as, the collision angle and the horizontal collision point velocity are difficult to be measured experimentally. Hence, the welding conditions were estimated from the pressure and density profiles obtained from simulation using AUTODYN 2 D[17][18].

3. Results and Discussion

During explosive welding, as the flyer plate collides on the base plate an extremely high pressure is generated at the collision point. As the pressure in this region is higher than the dynamic yield strength of metals, the material transforms into quasi−liquid state and participates in jet formation. A jet is formed if the parameters, the collision angle and collision velocity, are in the required range for welding. When the velocity is low, bonding with smooth waves are formed and above a certain velocity waves with vortices are formed. At high velocities, the jet, comprising layers of flyer and base plate, is trapped and forms cooling cavities. This raises the concern when welding titanium and stainless steel, in which brittle intermetallic compounds are formed in the vortices. Figure 1 shows the microstructure of the titanium/stainless steel bonded by two layer conventional welding technique[13]. A sharp transition with waves associated with the vortices can be seen. The intermetallic compounds in the vortices were identified as a mixture of FeTi and Fe_2 Ti using X−ray diffraction[19]. The presence of intermetallics led to the formation of microcracks across the vortex, and thus can reduce the strength of the clad. It can also lead to problems for any fabrication process on the post clad. The driving force for intermetallic formation is related to plastically deformed layer induced by the kinetic energy loss at the interface. For the welding of thick plates, the kinetic energy loss is simply too large for thick intermetallic layer to form. The welding regime for the formation of planar interface or smooth waves is limited. Using a thin stainless steel interlayer in between titanium and stainless steel, as reported earlier[20], can control the formation of vortices and consequently brittle intermetallics.

Another way of reducing kinetic energy loss is the use of underwater shock wave technique. Explosive welding through the pressure created by underwater shock waves has the fascinating ability to weld thin foils on a substrate. The high explosive used to create the strong shock waves is set up at an inclined angle so as to decrease the horizontal collision point velocity, which should be lower than the sonic velocity of the metals to be welded. The inclined angle should be higher than 10 ° for most of the combinations. With an increase in angle (20 °−30 °), the wavy interface can be observed[14]. It is well established in explosive welding that the interfacial waves is proportional to $t\ (1-\cos b)$, where t is the thickness of flyer plate, and b is the collision angle. Using a low angle initial set up decreases the collision angle, leading to small waves at the interface. The interfacial waves should be smooth, without any formation of vortices in the welding of titanium and steel. Therefore, in this study, the experiments were conducted for an angle 20 °.

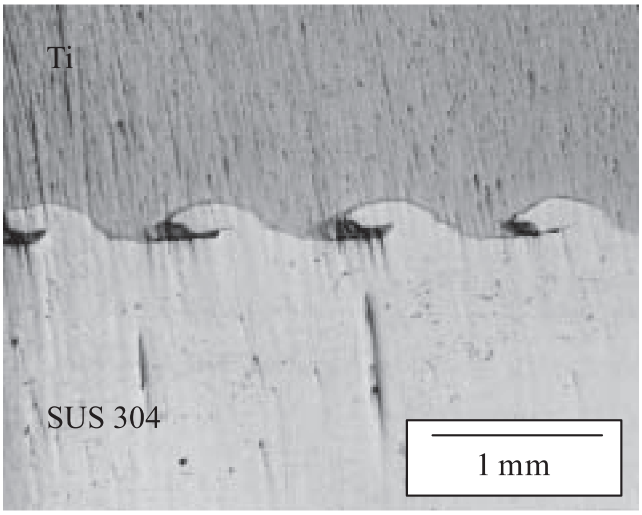

Fig. 1 Optical micrograph of titanium/stainless steel welded using conventional explosive welding ($\triangle$KE=3.72 MJ m^{-2}).

Figure 2 shows the microstructure of the interface for D =50 mm. A sharp transition with very small waves between the welded metals can be observed. No traces of intermetallic layer were observed. Upon detonation of explosive, the high pressure shock waves are generated, which strikes on the flyer plate at a massive force. The pressure of underwater shock waves depends on the distance between the explosive and the sample and the thickness of explosive. The relationship between peak pressure and the distance is related by the following expression :

$$Pm=K(T/D)^{n} \quad (1)$$

Where K, n is constant and T is the thickness of explosive. As the distance between the sample and the explosive is significantly large, the shock wave pressure is less. This reduces the vertical collision velocity and the horizon-

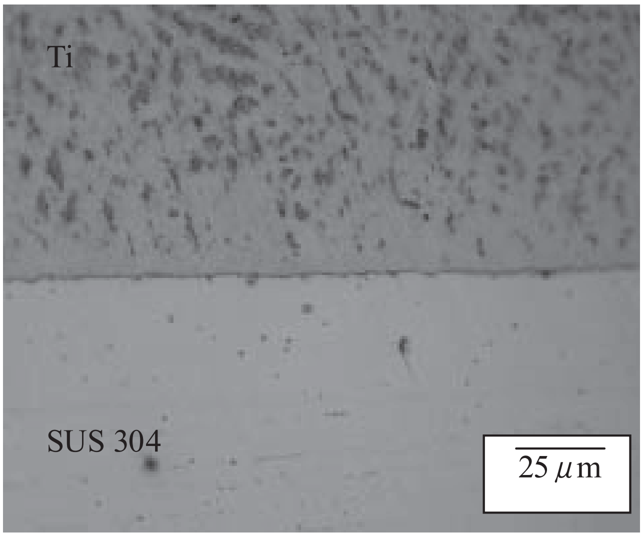

Fig. 2 Optical micrograph of the welded interface, D =50 mm.

tal collision point velocity. Consequently, the kinetic energy delivered on the interface in plastically deforming the interface is less. The energy is sufficient for the bonding of the two metals but is insufficient to modify the microstructure to form vortices. The underwater shock pressure decreases with the increase in the distance. As an inclined set up is essential, the parameters, namely, the collision angle, the horizontal collision point velocity and the kinetic energy loss, changes along the welding direction due to the change in the underwater shock pressure[18]. Hence, the range of the values of the parameters is given in Table 1. Though the kinetic energy loss values vary along the welding direction, it is very less in comparison with the conventional explosive welding process. The weld is acceptable considering that no defect along the interface and no intermetallics are formed.

Previous reports have indicated the importance of using thin cover plates attached or placed above the flyer plate to avoid the cracks generated in the welded plates, in particular, when welding amorphous films on a metal substrate[14]. The cover plate also acts as a momentum trap to decrease the reflected shock pressure. However, in this study, no cracks were generated in either of the welded plate, though no cover plate was used. This could be attributed to the difference in the welding of brittle amorphous film and metal plate.

Figure 3 displays the microstructure of titanium/stainless steel interface for D =40 mm. An increased interfacial oscillation was pronounced on the interface with apparently no traces of intermetallic formation. This trend of increase in the wave size is obvious, when comparing the kinetic energy loss at the interface for the distance 40 mm and 50 mm. It seems likely that the micro structural changes at the interface are driven by the plastic deformation generated by the kinetic energy loss. The thickness of the flyer plates used in this study is same. Hence the difference in the kinetic energy loss is caused by the difference in the vertical velocity.

A similar response can be observed when the interface for D =30 mm is examined, the results of which is shown in Fig.4. The result shows relatively large waves in comparison with the microstructures for large distances.

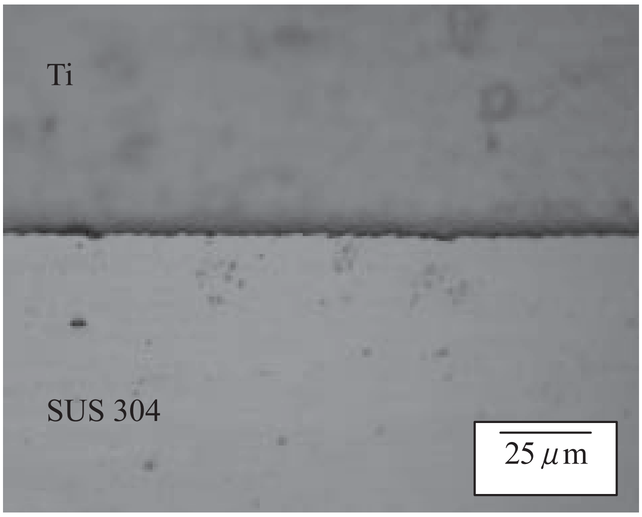

Fig. 3 Optical micrograph of the welded interface, D =40 mm.

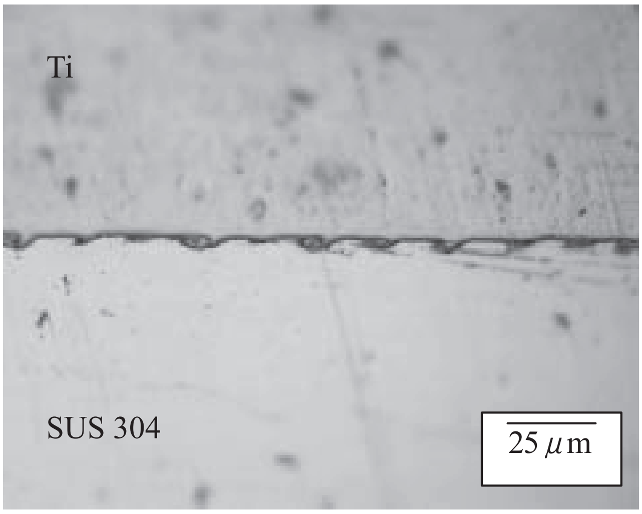

Fig. 4 Optical micrograph of the welded interface, D =30 mm.

Figure 5 shows the microstructure observed for high kinetic energy loss using D =20 mm. The topography of the interface indicates the characteristic uniform waves with vortices, typical of conventional two layer welding. At these vortices both the components mixed together to form the intermetallic layer. The difference with the other microstructure is the increase in the wave parameters pronounced by the increase in kinetic energy loss. The short distance led to the increase in the wave parameters and also promoted the formation of vortices. However, the size of the vortices is small in comparison with the results obtained by conventional welding technique. In under water shock wave processing, the shock pressure generated by the high explosive is intensive and is strong enough to drive the thin plate to a required collision velocity within very small stand off distances. The lower limit of welding, where the fluidized area at the collision point is generated, is achieved within 0.1 mm stand off distance. The stand off distance, 0.5 mm, used in this study is significantly above the lower limit for the welding of titanium and stainless steel.

The effect of the thickness of explosive on the welding interface was studied by increasing the thickness of explo-

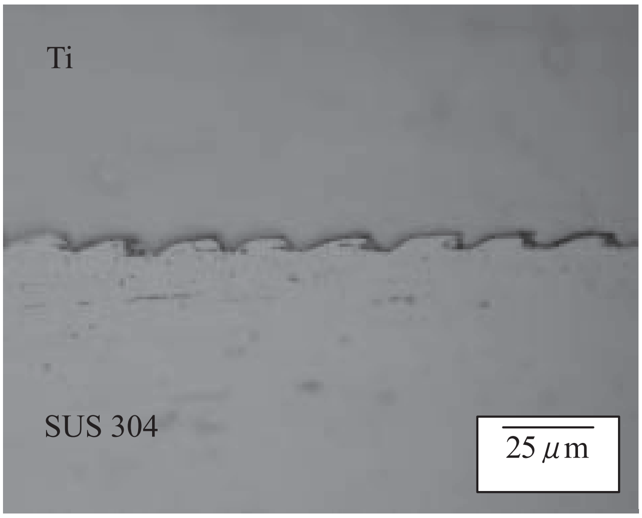

Fig. 5 Optical micrograph of the welded interface, D=20 mm.

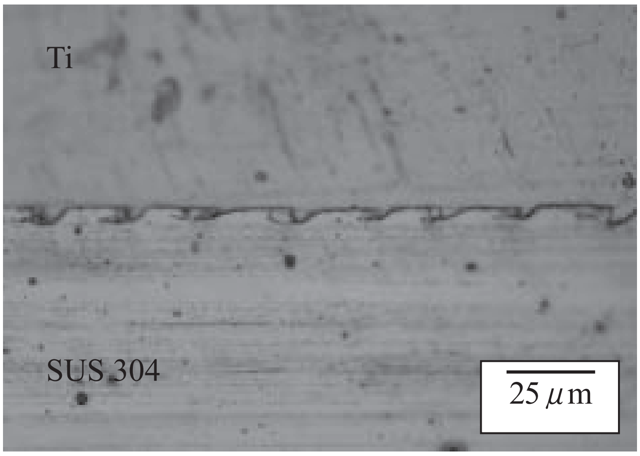

Fig. 6 Optical micrograph of the welded interface, D=40 mm, thickness of explosive=10 mm.

sive as 10 mm. Figure 6 shows the microstructure for the welded interface for D=40. In comparison to the experiment done at the similar conditions, except the thickness of explosive (Fig.3), the results revealed an increase in the wave parameters. This is attributed to the difference in the shock pressure in these two cases.

At this juncture, it is important to distinguish between the energy dissipated in a conventional welding and underwater shock wave welding. Typically, wave formation depends on the parameters, collision velocity, collision angle, flyer velocity and the properties of the welded plates. It is possible that, within a certain range, an increase in the parameters leads to the increase in plastic flow. It is difficult to establish a direct comparison between the two welding techniques based on the values of the parameters. For instance, flyer velocity of about 450 m $s^{-1}$is sufficient for the welding of titanium/stainless steel through conventional technique. The same velocity may not be sufficient for welding through underwater shock wave. Similarly, the plastic deformation developed by the kinetic energy loss in forming the wavy interface differs in either of the techniques. While a kinetic energy loss required in forming a wavy interface in two layer welding is 2.33 MJ m^{-2} 13), the conditions are substantially high for welding using interlayer and welding using underwater shock wave. Despite considerable complexity of the problem it seems possible to control the energy conditions using underwater shock wave. The welding regime for attaining intermetallic free interface is wide enough and the conditions can be altered in a wide range. Work is underway to optimize the welding conditions by varying initial angle and the distance, D. As the reliability of explosive welded joint is high, welding using underwater shock wave offers a viable alternate solution to conventional surface coating methods. In addition, the welded titanium/stainless steel can serve as an interlayer for fabricating thick multi layered plate.

4. Conclusion

Explosive welding using underwater shock wave was used to clad thin plate of commercially pure titanium and stainless steel. The results of conventional two layer welding resulted in a wave morphology associated with the vortices due to high kinetic energy loss. Hence, under water shock wave technique was used to control the morphology of the weld. Experiments conducted by varying the distance between the center of the sample and explosive, and thickness of explosive demonstrated the use of this technique for welding titanium and stainless steel. The results, in general, revealed an interface with small waves devoid of intermetallics. Waves with vortices comprising intermetallic layer was formed for high kinetic energy loss.

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