Article

The effect of experimental parameters on the explosive welding of Ti and stainless steel

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Abstract

This study addresses the effects of experimental parameters on the welded interface of titanium and stainless steel clad produced by explosive welding. A weldability window was formulated for titanium / stainless steel clad and experimentally verified. The effects of experimental parameters with wavelength, amplitude, and interfacial layer are correlated. Microstructural characterization of the bonded interface shows a wavy morphology with the formation of brittle intermetallic layer in some cases. The results provide evidence that higher plate velocities enhance the formation of intermetallics at the vortices, thereby causing local melted zones.

Keywords: Explosive welding, Weldability window, Experimental parameters, Microstructural characterization, Intermetallic layer

1. Introduction

The development of high corrosion resistant plates for tanks, pressure vessels, autoclaves and heat exchangers are a part of a rapidly expanding segment of the explosive cladding technology market[1]. For these applications, titanium is particularly sought due to its high corrosion resistance and high strength to weight ratio. When the size demands very thick plate, titanium is considerably more expensive. Titanium clad stainless steel offers a reliable and cost effective alternative than other less reliable alternatives[2]. The formation of intermetallic compounds and the difficulty in joining titanium-stainless steel combination renders it difficult to be cladded by conventional solid-state processes[3), 4)]. This is an obvious roadblock to their practical utility. Explosive welding, on the other hand, holds the promise of joining dissimilar materials with superior properties[5)~12)]. However, very limited information is available regarding the characterization of Ti / steel clad[13)~14)]. From literature review it is concluded that formulation of an experimentally determined weldability window is a prerequisite to develop an accurate set of welding conditions. The current contribution describes a detailed investigation to determine the effect of the parameters on the welding of Ti / stainless steel combination and its effect on the weldability window to establish the welding conditions for a satisfactory weld.

2. Experimental

Commercially pure grade titanium (JIS TP 340) was used as flyer plate owing to its excellent corrosion resistance. Based on high strength and economical considerations, 304 stainless steel (JIS SUS 304) was used as base plate. The areas of the flyer and parent plates were taken as 200 mm × 90 mm. The thickness of the parent plate was fixed as 9 mm while the flyer plate was varied as 5, 3 and 1 mm. The powder explosive, PAVEX, of density 530 kg m^{-3} and detonation velocity 2000 - 3000 m s^{-1} was used in the present study (supplied by Asahi Kasei Chemicals Corp., Japan). The parallel plate configuration was used for explosive welding as schematically shown in Fig. 1. Prior to use, the mating surfaces of the plates were mechanically polished and thoroughly cleaned by acetone.

The experiments were conducted by changing the parameters such as stand off distance and the thickness of explosive. The stand off distance was varied from 5 mm to 15 mm and the thickness of explosive was increased up to 60 mm. The welding conditions were estimated based on empirical equations so far proposed and explained in the following section.

Samples were cut parallel to the detonation direction and prepared by conventional techniques for metallographic observation.

3. Estimation of welding conditions

The flyer velocity, V_P, can be calculated from Gurney equation[5] which predicts the terminal velocity. However, the Gurney equation does not take into account the effect of stand off distance. The problem of stand off distance is considered in this study.

It is well known that the relationship between the plate velocity and the dynamic bend angle is expressed by the following equation[5]

$$V_P = 2V_D \sin\frac{\beta}{2} \tag{1}$$

where V_D is the detonation velocity of the explosive and β is the dynamic bend angle. The dynamic bend angle β was calculated using the following equation[15].

$$\beta = \left(\sqrt{\frac{k+1}{k-1}} - 1\right)\cdot\frac{\pi}{2}\cdot\frac{r}{r + 2.71 + 0.184\,\delta / h} \tag{2}$$

where r is the loading ratio (mass of explosive for unit mass of flyer plate), δ is the thickness of the explosive layer and h is the stand off distance. The parameter 'k' in eq. (2) ranges from 1.96 to 2.6 depending on the thickness of the explosive layer[15, 16].

Eq. (3) gives the lower limit of bending angle for successful welding[5].

$$\beta = k_1\sqrt{\frac{Hv}{\rho\cdot(V_C)^2}} \tag{3}$$

In eq. (3), β is in radians, H_v is the Vickers hardness in N m^{-2} and ρ is the density in kg m^{-3}. The value of k_1 is 0.6 for high quality precleaning of the surfaces and 1.2 for imperfectly cleaned surfaces. The value of k_1 = 1.2 was adopted in our study, taking into account the quality of the surface preparation of plates.

The upper limit was calculated using the following equation[5, 17]:

$$\sin\frac{\beta}{2} = \frac{k_3}{t^{0.25}V_C^{1.25}} \tag{4}$$

In eq. (4) $k_3 = C_f/2$, $C_f = \sqrt{K/\rho}$, $K = E/3\,(1-2\upsilon)$, where C_f is the compressive wave velocity, t is the thickness of the flyer plate, V_C is the horizontal collision point velocity, K is the bulk modulus and E is the Young's Modulus.

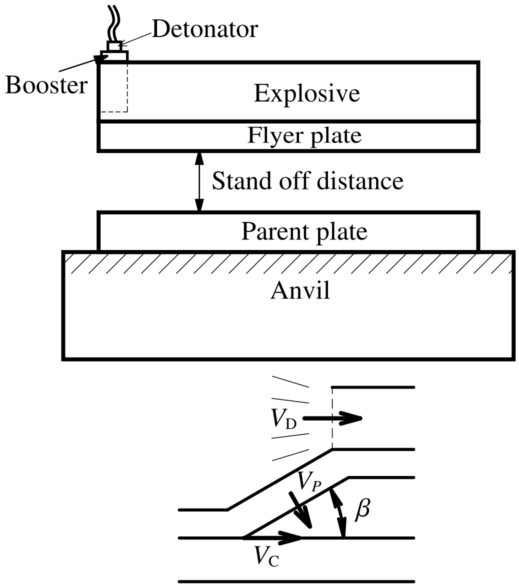

Fig. 1 Schematic of parallel plate configuration of explosive welding and the parameters.

4. Results and Discussion

4.1 Microstructural characterization

The optical micrograph of the bonding interface of Ti / SUS 304 clad is presented in Fig. 2. The microstructure is

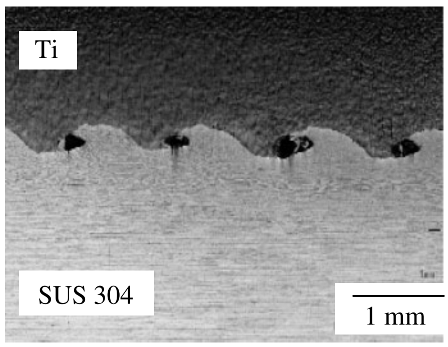

Fig. 2 Optical micrograph of welded interface showing maximum reacted vortex layer.

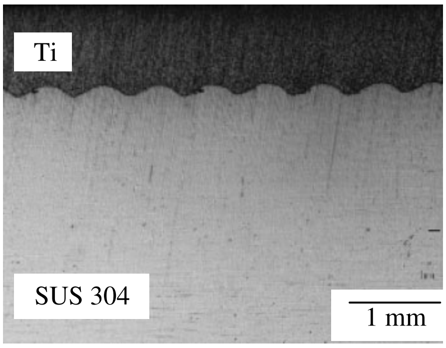

Fig. 3 Optical micrograph of welded interface with less reacted vortex layer.

seen to consist of a uniform wave formation between the two metals. This is typical of an explosive welded joint formed at satisfactory welding conditions. However, at the vortices the two metals react together to form intermetallic compounds with unfavorable mechanical properties. At the vortices, the release of kinetic energy of the trapped jet and a concomitant increase in temperature, due to intense deformation and the reaction between titanium and stainless steel, lead to the molten zones. XRD characterization confirmed the presence of the mixture of FeTi and Fe_2Ti intermetallics at the interfacial zone[18].

Figure 2 shows the response of the metals at the interface for 60 mm thickness of explosive. The wavelength and amplitude are high leaving a thick reacted vortex with solidification zones. The welded interface between the metals plays a critical role in determining the properties of the clad. The interfacial reaction at the vortex must be controlled to achieve an optimal combination of mechanical properties. Hence the intermetallic layer was controlled to minimum by reducing the thickness of the explosive (20 mm) as shown in Fig. 3.

4.2 Effect of parameters

Figure 4 displays the variation of the wavelength with the kinetic energy loss by collision (ΔKE). The results exhibit a linear trend for the wavelength-ΔKE relationship as reported earlier[11]. This dependence could be attributed to the energy spent at the collision to produce waves.

The effect of the variation of flyer plate velocity was investigated, and at a velocity of 300 m s^{-1}, the flyer plate sheared off. This could be attributed to the insufficient impact velocity at the collision point for the metals to behave like fluids. The wavelength and amplitude depends not only on the flyer plate velocities, but also on other variables, such as the dynamic bend angle and horizontal collision velocity and will be discussed later. It should be noted here that flyer plate velocity is influenced by the dynamic bend angle as empirically shown by eq. (1), when the detonation velocity is considered to be constant.

The formation of high velocity jet, which removes the surface layer of oxides leading to a clean metallurgical bond, is mandatory for explosive welding. The jet thickness depends on the dynamic bend angle. The minimum critical dynamic bend angle, above which the welding occurs, is shown in Figs. 5 - 7.

The horizontal collision point velocity is equal to the detonation velocity of the explosive in the case of parallel configuration. This velocity varies depending on the thickness of the explosive[16]. As the welding region is wider at lower collision velocities, some experiments were conducted along this range. The results at lower collision velocities yielded less interfacial layer with uniform wave formation.

Closer to the lower limit of welding, the two plates remain bonded after the amplitude has dropped to zero and the interface has become straight as shown in Fig. 6.

There is a minimum impact velocity or dynamic bending angle for the welding to occur. Above this minimum impact conditions, the state of an acceptable weld appears to be associated with the kinetic energy dissipated to the welded interface by the collision of the flyer plate[5, 16]. The growth of vortices and the associated melting zones within the vortices is interpreted as releases from the kinetic energy of the jet.

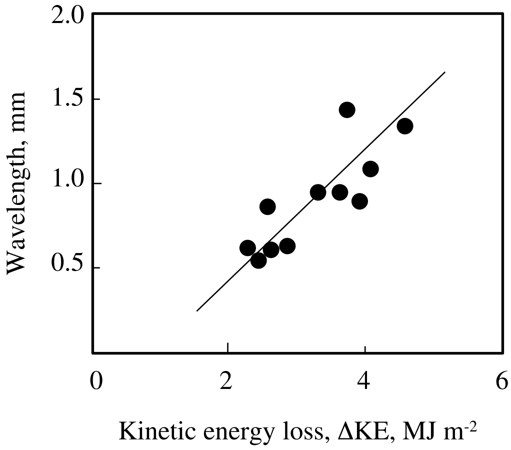

Fig. 4 Variation of wavelength with kinetic energy loss, ΔKE.

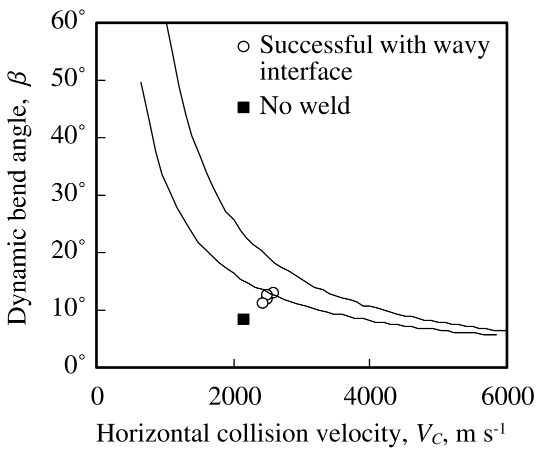

Fig. 5 Weldability window for Ti / SUS 304 clads (5 mm flyer thickness).

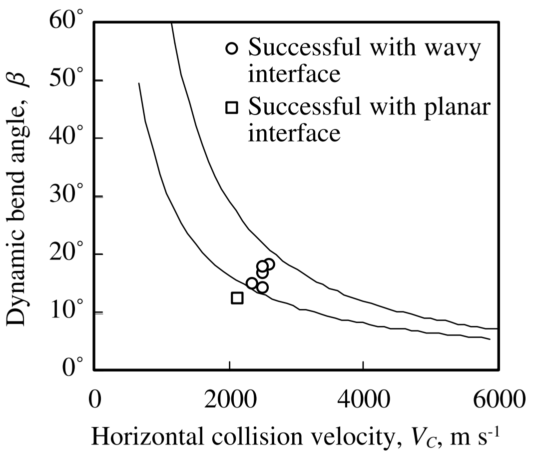

Fig. 6 Weldability window for Ti / SUS 304 clads (3 mm flyer thickness).

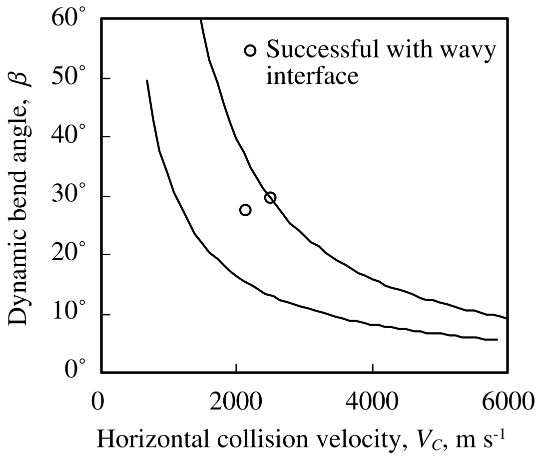

Fig. 7 Weldability window for Ti / SUS 304 clads (1 mm flyer thickness).

4.3 Weldability window

Wittman[19] and Deribas[20] constructed a plot named weldability window, in which the dynamic bend angle is plotted in the ordinates and the horizontal collision velocity is plotted in the abscissa. The lower boundary refers the conditions to achieve fluid like conditions at the collision point so that jetting occurs. The upper limit defines the limit above which excessive defects occur at the interface. The right limit is known as the sound velocity of materials[5], but the limit is too high in comparison with the detonation velocity which is equal to the horizontal collision point velocity V_C, for the explosive employed in the experiments.

The weldability window was formulated theoretically using equations (3) and (4). The lower limit was same for the combination, while the upper limit depends on the flyer plate thickness. To get a clear picture of the experimental conditions, different windows are shown for flyer thickness 5 mm, 3 mm and 1 mm. As seen from Figs. 5 - 7, the weldability region becomes narrow for the increase in flyer plate thickness.

In one of the classical references it was indicated that an equally strong weld could be obtained from a planar interface[5]. The weld with an intermetallic free planar interface, produced by minimum thickness of explosive has the exciting prospect of achieving all-around superb mechanical properties for dissimilar joints. This was achieved for a flyer plate thickness 3 mm as presented in Fig. 6.

The maximum wavelength and interfacial layer was attained for which the kinetic energy loss is also maximum value as shown in Fig. 4. In order to elucidate the upper limit of weldability window, an experiment was conducted along the upper limit for flyer plate thickness 1 mm as shown in Fig.7. The combination was welded with more reacted intermetallic layer. The bonding strength of such clad is expected to be less.

The value of kinetic energy loss by collision reduced for a thin flyer plate in comparison with a thick plate (welded at the same flyer plate velocity). The decreased kinetic energy loss reduced the formation of intermetallic layer, thus leading to a good bonding strength. Efforts are underway to evaluate the bonding strength for all clads bonded at different conditions.

5. Conclusion

Explosive welding can be successfully used to join dissimilar materials, titanium and stainless steel. The microstructural characterization of the Ti-SUS 304 clad showed a uniform wave formation with the formation of intermetallics at the vortices when collided at high energetic conditions. The effects of the parameters were discussed based on the weldability window. The weldability window for Ti-SUS 304, which was not formulated earlier, was verified using experiments. Research is underway to determine the strength and delineate the predominant mechanism that leads to the fracture at the interface based on further microstructural characterization.

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