Journal of Manufacturing Engineering, September 2015, Vol. 10, Issue. 3, pp 161-165

PARAMETRIC STUDIES ON EXPLOSIVE CLADDED TITANIUM-STAINLESS STEEL COMPOSITES

***Saravanan S[1], Raghukandan K[2] and Tamilchelvan P[2]**

[1]Department of Mechanical Engineering, Annamalai University, Tamilnadu, India
[2]Department of Manufacturing Engineering, Annamalai University, Tamilnadu, India

ABSTRACT

Explosive cladding is achieved by the application of pressure released from explosives to cause plastic deformation at the interface of dissimilar metals. This study focuses on explosive cladding of titanium Gr-1 and stainless steel 304L plates with varied flyer thickness, preset angle and standoff distance with uni-loading ratio (ratio of flyer plate mass and explosive mass). The Ti-SS304L explosive clad composite with minimum amplitude and wavelength shows higher mechanical strength than the interfaces having larger undulations. The relationship between the interfacial undulations and the positioning in weldability window is also reported

Keywords: *Explosive cladding, Titanium, Stainless Steel, Strength and Weldability Window.*

1. Introduction

Explosive cladding is a solid state process, wherein controlled explosion impinges two or more metals to fuse together to form a clad. The energy emanating from a chemical explosive accelerates the flyer plate, across a predetermined distance onto the base plate, to be pressed together to form a metallurgical strong weld [1&2]. Titanium finds extensive application in aerospace industry because of its lower density, excellent corrosion resistance, high strength, attractive fracture behaviour and high melting point. Stainless steel provides good strength at low cost. Titanium-steel clad composite replaces solid titanium, and thereby, reduces the cost and is employed in construction of reactors, pressure vessels and corrosion resistant applications. Various researchers [3-6] reported the influence of process parameters viz., explosive mass, standoff distance and preset angle on the nature and strength of explosive clad interface. The studies on the relationship between the interfacial undulations (amplitude and wavelength), and the properties of the clad is limited and is attempted herein. Ti-SS304L plates are explosively cladded and the specimens for metallographic observations were sectioned parallel to the detonation direction following standard metallurgical procedures. To study the mechanical strength, Ram Tensile test specimens (25 mm X 25 mm) were prepared in the direction of detonation and the tests were carried out in a 10T servo hydraulic testing machine, in the compression mode with 0.5 mm/min strain rate.

2. Experimental Procedure

Titanium Gr-1 (60 mm X 90 mm and thickness 3.5 mm and 6 mm) were employed as overlay plate, while stainless steel 304L (60 mm X 90 mm X 9 mm) was the base plate. The chemical compositions of the flyer and base plates are given in Table 1.Titanium Gr-1 plates (Flyer plate) were cladded by employing Nitroglycerine explosive (detonation velocity 2800 m/s) as the energy generator. A loading ratio of 1.0 is maintained for all the experiments. The preset angle (α) was varied from 3 to 15 degrees, while standoff distance between flyer and base plate was varied between 5 mm and 10 mm. The collision conditions were estimated employing empirical relations reported by various researchers reported elsewhere [7&8] and is given in Table.2.

Table.1 Composition (wt %) and strength of participant metals

Materials	C	O_2	N	Fe	Ti	Si	Yield Strength (MPa)
Ti.Gr.1	-	0.10	0.05	0.20	99.8	-	170
SS 304L	0.030	-	0.058	71.98	-	0.55	215
Materials	Mn	P	S	Ni	Cr	Cu	
Ti.Gr.1	-	-	-	-	-	-	
SS 304L	1.49	0.035	0.005	8.13	18.27	0.45	

**Corresponding Author - E- mail:* ssvcdm@gmail.com

Table.2 Experimental conditions

Combination	Flyer Thickness (mm)	Preset angle, α, (degree)	Standoff Distance S (mm)	Collision velocity V_c (m/s)	Dynamic bend angle β (degree)	Collision Angle α(degree)
Ti-SS304L	3.5	3	5	2239.6	14.7	17.7
Ti-SS304L	3.5	3	10	2239.6	14.7	17.7
Ti-SS304L	3.5	8	5	1685.6	19.7	27.7
Ti-SS304L	3.5	8	10	1685.6	19.7	27.7
Ti-SS304L	6	10	5	1536.8	21.7	26.7
Ti-SS304L	6	10	10	1536.6	21.7	31.7
Ti-SS304L	6	15	5	1264.6	26.7	41.7
Ti-SS304L	6	15	10	1264.6	26.7	41.7

3. Results and Discussion

3.1. Microstructural characterization

The microstructural observation of the titanium Gr-1 with stainless steel (SS304L) explosive clad composites show wavy morphologies (Fig.1 and Fig.2) as reported by previous researchers [2,4]. The undulating interfaces are characteristics of explosive cladding process, is designed by the system parameters viz., nature of explosive, standoff distance and preset angle. Grains closer to the interface get elongated in the direction of detonation as a consequence of rapid impact for all experimental conditions.

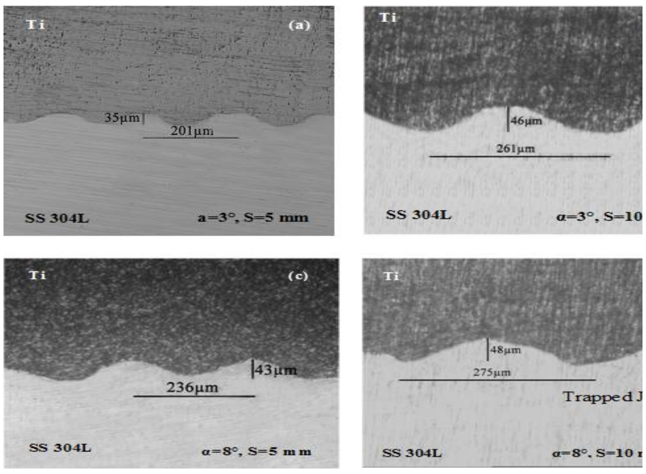

Fig.1 Microstructure of Ti-SS304L explosive clad composites (3.5 thick flyer plates)

The clad is sound without "molten layered zones" (solidified melts) which are formed due to excessive kinetic energy dissipation at interface and subsequent rapid cooling. As the kinetic energy loss at the interface is converted into thermal energy, higher the kinetic energy loss, chances of strong clad diminishes. The kinetic energy loss at the interface depends on flyer plate velocity and the mass of participant metals given by [7].

$$\Delta KE = \frac{m_f m_b V_P^2}{2(m_f + m_b)} \tag{1}$$

Where, 'm_f' and 'm_b' represents mass of flyer and base plate per unit area respectively, 'V_p' is the flyer plate velocity. The increase in flyer plate velocity, which depends on the properties of explosive, enhances the kinetic energy loss at the interface (Eqn.1). The undulations are seen in Fig.1a, where the preset angle is 3^o and the distances of separation is 5 mm. With increase in standoff distance and preset angle, the amplitude and wavelength of undulations is altered. From Fig.1a, and Fig.1b, it is observed that an increase of 20% in amplitude and wavelength is found for a constant preset angle and double standoff distance. Fig. 1c and Fig. 1d exhibits the microstructure of Ti-SS304L explosive clad with 8^o preset angle having 5 mm and 10 mm standoff distances respectively. When the initial angle is increased from 3^o to 8^o, 10% increase in amplitude and wavelength resulted. The increase in standoff distance allows the flyer plate to reach the terminal velocity providing higher deformation which resulted in the increase of amplitude and wavelength.

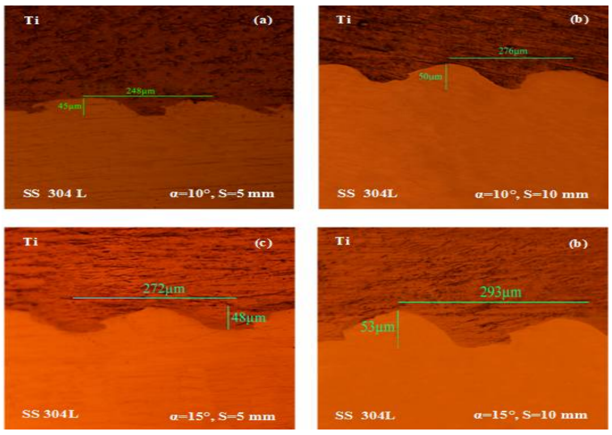

Fig. 2 Microstructure of Ti-SS304L explosive clad composites (6 mm thick flyer plate)

Durgutlu et al. [10] investigated the effect of standoff distance on explosive cladding of Cu-Steel and reported an increase in amplitude and wavelength with increase in standoff distance as observed from this study. The wave form closely depends on the density ratio of participant metals. When the densities of constituent phases are similar, high pressure is generated at the vicinity of collision point resulting in wavy interface due to fluid like behavior of metals. When the metals having wide difference in density viz., Al-Steel (density ratio-0.34) are cladded, a planar interface and occasional melt emerges as reported by Saravanan and Raghukandan [11].

Manikandan et al. [7] recommended employing a thin interlayer between dissimilar metals having wide difference in density to reduce the kinetic energy dissipation at the interface. The Ti-SS304L explosive clad with smaller waves exhibited the highest tensile strength while the waves with higher amplitude exhibited the least value, though higher than the weaker metal titanium (shown in next section). Formation of Trapped jet is observed at Ti-SS304L (density ratio-0.54) interface (Fig.1d) for higher preset angle (8^o) and standoff distance (10 mm). At higher preset angle and standoff distance, more shear deformation prevails and the additional kinetic energy loss tends to trap the jet. Yan et al. [12] reported adiabatic shear bands on Mg-Al explosive clad due to shear deformation and further reported the significance of local diffusion in clad formation. The Ti-SS304L explosive clad (6 mm thick flyer plate) microstructure shown in Fig.2 reveals an undulating interface, devoid of defects and intermetallic compounds. Under optimum conditions, metal flow around the collision point is unstable and oscillates, generating a wavy interface. Typically wave formation is a function of variables viz., collision angle, collision velocity, flyer plate velocity and properties of participant metals. Collision velocity dictates the time available for cladding while a minimum collision angle and plate velocity is required for bond formation. When the collision velocity increases, amplitude and wavelength increase, as observed by Kahraman et al. [13]. The grains are elongated and trailing of the tip behind the interfacial waves is observed (Fig.2) which is consistent with earlier researchers [11, 14-16]. The Ti-SS304L explosive clad interface shows a single vortex due to predominance of one vortex over the other due to significant difference in densities between participant metals. Due to deflection of jet away from lower density metal, impingement occurs largely on the lower density metal. The formation of hump, indication for perfect interlocking is observed on Fig.2 as a consequence of the complete block of reentrant jet which is consistent with Manikandan et al. [14]. For a constant loading ratio, the amplitude and wavelength of the interfacial waves changes (Fig.1 and Fig.2) indicating the collision front is being influenced by other factors viz., standoff distance, quality of surface finish, density ratio and preset angle.

3.2. Mechanical Strength

3.2.1. Ram tensile test

The microstructure at the cladded interface characterizes the mechanical properties and is essential to evaluate the bonding strength. It is observed from Fig.2 and Fig.3 that, the amplitude and wavelength of the interfacial waves are getting bigger with increment in preset angle and standoff distance. The range of Ram tensile strength varies from 243 MPa to 275 MPa. It is observed that, the highest value of tensile strength is 275 MPa for a 3.5 mm thick flyer plate while it is 264 MPa for 6 mm thick flyer plates which are closer to tensile strength of stainless steel (293 MPa). The interface exhibiting smaller waves possess higher strength for all experimental conditions. Wavy interfaces serve as a better interlocking mechanism and therefore, as the size of waves are small; contact surface area is enhanced-leading to an increase in Ram tensile strength. This is in agreement with the experimental results, as evidenced in the microstructures. Ram tensile strength of the clad decreases with increase in amplitude and wavelength which is consistent with Mousavi et al.[17]. During testing, the weaker metal (Titanium-tensile strength-170MPa) detached from SS304L for all experimental conditions, not the Ti-SS304L explosive clad interface, indicating bond strength is higher. Mousavi et al.[17] reported that under perfect cladding conditions, the tensile strength of the clad is superior to weaker of the participant metals.

3.2.2. Microhardness

The Vickers microhardness profile of Ti-SS304L explosive clads is shown in Fig.3. For each sample, three measurements were taken and the average values are reported.

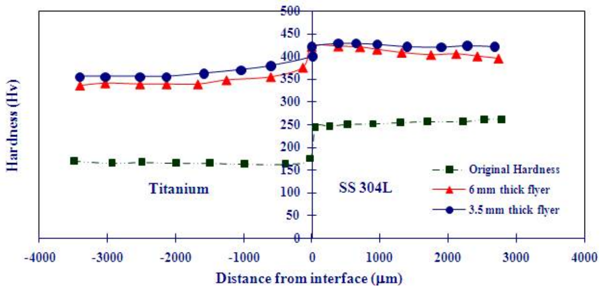

Fig. 3 Hardness profile of titanium-stainless steel SS304L

The post clad Ti-Steel composite exhibited higher hardness than the preclad base plates because of cold deformation during explosion. Maximum hardness was obtained near the interface due to high level of plastic deformation adjacent to collision interface. The explosive clad composites having smaller waves (minimum amplitude and wavelength) exhibits higher hardness than interface possess larger waves.

After being subjected to shock loading, hardness of the clad is higher than the preclad metals whereas away from the interface (1000µm) there is no significant increase. Kahraman et al. [13] joined aluminum with steel at varied explosive mass and found that zones near the collision interface exhibits higher hardness at all explosive loads. Hardening of interface is greater adjacent to the interface where the collision and jetting has resulted in higher pressure while the magnitude of hardening depends on nature of metals.

3.3. Weldability Window

Weldability window provides an initial approximation about collision conditions for an interface devoid of interfacial melting, defects and flyer damage. The development of a theoretical model capable of predicting the mechanism by which waves are produced was attempted. The wavy or transition bond without any apparent intermetallic layer yields most desirable properties. Various researchers reported jet formation, critical impact pressure, maximum impact velocity and wavy smooth transition velocity. In this study, an attempt is made to develop a weldability window based on empirical relations reported by earlier researchers[8,18] for varied flyer thickness TiGr-1- SS 304L with welding velocity ‘V_w’ and collision angle ‘γ’ as its ordinates and is shown in Fig.4 and Fig.5 respectively.

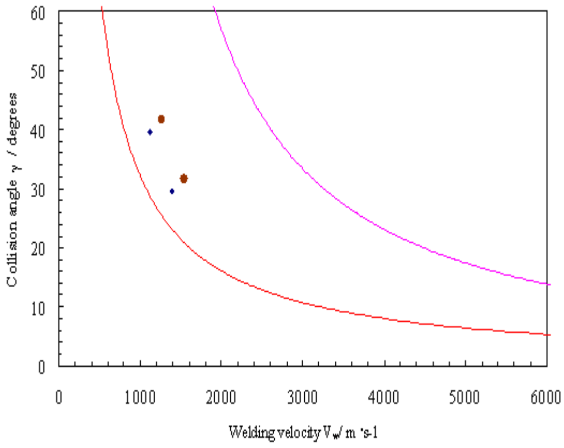

Fig.4 Weldability window for 3.5 mm thick flyer plate

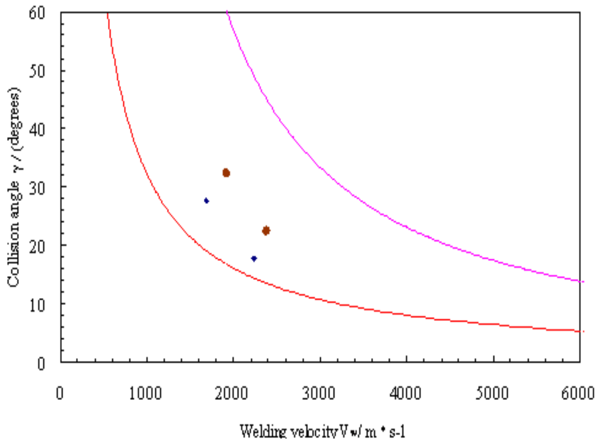

Fig. 5 Weldability window for 6 mm thick flyer plate

The accurate boundaries of the window are difficult to be defined as it involves various assumptions and constants during the formulation of window. Mousavi et al. [18] developed a weldability window for Ti-steel, by plotting collision angle ‘β’ in ordinates and welding velocity ‘V_c’ in abscissa. Weldability window becomes narrow as the thickness of flyer plate increases (Fig.4 and Fig.5).

Any point within the upper and lower boundary of the weldability window would mean successful cladding with a wavy interface. The experimental conditions, closer to lower boundary of weldability window exhibited smooth waves with minimum amplitude (Fig.1), resulting in better ram tensile strength, while the experimental conditions prevailing closer to upper boundary results in higher amplitude and wavelength reveals lower strength which is in accord with earlier researchers [14, 19]. The experimental conditions prevailing closer to the lower boundary shows higher strength than the conditions falling closer to upper boundary. Saravanan and Raghukandan [20] opined that, weldability area in weldability window increases with the introduction of interlayer between flyer and base plates. Experimental conditions falling within the upper and lower boundaries of weldability window indicate a wavy topography, though a straight interface can produce a sound joint as well. The experimental conditions of explosive cladding titanium-stainless steel 304L shown in Table.2 falls within the limits of weldability window produces a wavy interface (Fig.1 and Fig.2), indicating weldability window is effective in dictating the nature of interface.

4. Conclusion

The objective of this present study is to study the relationship between the nature of wavy interface and strength of titanium-stainless steel304 L explosive clad composite. Titanium plates of varied thickness are cladded with stainless steel with varied standoff distance and preset angle. The following conclusions were drawn from this study.

1. The explosive clad with smaller amplitude and wavelength exhibit higher strength due to increased contact area.
2. Ram tensile strength of the clad is higher than titanium indicating the bond is stronger than weaker metal.
3. The amplitude and wavelength of the interfacial waves changes even for uni-loading ratio indicating the influence of standoff distance, quality of surface finish, density ratio and preset angle.
4. When the standoff distance was doubled, amplitude and wavelength increases.
5. Microhardness of the post clad composite is higher than the preclad metals.
6. When the thickness of flyer plate increases, weldability window becomes narrower.

References

1. *Bataev I A Bataev A A Mali V I Pavliukova D V (2012), "Structural and mechanical properties of metallic-intermetallic laminate composites produced by explosive welding and annealing", Mater. Des, Vol.35, 225-234.*
2. *Saravanan S and K Raghukandan (2011), "Tri axial weldability windows on explosive cladding of dissimilar metals", Journal of Manufacturing Engineering, Vol. 6(2), 111-114.*
3. *Acarer M Gulenc B and Findik F (2012), "The influence of some factors on steel/steel bonding quality on their characteristics of explosive welding joints", J. Mater. Sci., Vol.39 (21), 6457-6466.*
4. *Kaçar R and Acarer M (2003), "Microstructure–Property relationship in explosively welded duplex stainless steel–steel", Mater. Sci. Eng., A Vol.363, 290-296.*
5. *Wronka B (2010), "Testing of explosive welding and welded joints. The microstructure of explosive welded joints and their mechanical properties", J.Mater.Sci. Vol.45 (13), 3465-3469.*
6. *Findik F (2011), "Recent developments in explosive welding", Mater. Des, Vol.32, 1081-1093.*
7. *Manikandan P Hokamoto K Fujita M Raghukandan K and Tomoshige R (2008), "Control of energetic conditions by employing interlayer of different thickness for explosive welding of titanium/304 stainless steel", J. Mater. Process. Technol, Vol. 195, 232-240.*
8. *Zamani E and Liaghat G H (2012), "Explosive welding of stainless steel-carbon steel coaxial pipes", J. Mater. Sci., Vol. 47(2), 685-695.*
9. *Gulenc B (2012), "Investigation of interface properties and weldability of aluminum and copper plates by explosive welding method", Mater. Des, Vol. 29, 275-278.*
10. *Durgutlu A Okuyucu H and Gulenc B (2008), "Investigation of effect of the stand-off distance on interface characteristics of explosively welded copper and stainless steel", Mater. Des, Vol. 29, 1480–1484.*
11. *Saravanan S and Raghukandan K (2012), "Thermal kinetics in explosive cladding of dissimilar metals", Sci. Technol. Weld. Joining, Vol. 17 (2), 99- 103.*
12. *Yan Y B Zhang Z W Shen W Wang J H Zhang L K and Chin B A (2010), "Microstructure and properties of magnesium AZ31B-aluminum 7075 explosively welded composite plate", Mater. Sci. Eng., A Vol.527, 2241-2245.*
13. *Kahraman N Gulenc B and Findik F (2007), "Corrosion and Mechanical-Microstructural aspects of dissimilar joints of Ti–6Al–4V and Al plates", Int J Impact Eng,Vol. 34, 1423-1432.*
14. *Manikandan P Hokamoto K Deribas A A Raghukandan K and Tomashige R (2006), "Explosive welding of titanium/stainless steel by controlling energetic conditions, Mater. Trans., JIM, Vol. 47(8), 2049-2055.*
15. *Bingfeng Wang Wei Chen Juan Li Zhaolin Liu and Xiebin Zhu (2013), "Microstructure and formation of melting zone in the interface of Ti/NiCr explosive cladding bar", Mater. Des, Vol. 47, 74-79.*
16. *Song J Kostka A Veehmayer M and Raabe D (2011), "Hierarchical microstructure of explosive joints: example of titanium to steel cladding", Mater. Sci. Eng., A, Vol.528, 2641-2647.*
17. *Akbari Mousavi S A A AL-Hassani S T S and Atkins A G (2008), "Bond strength of explosively welded specimens", Mater. Des, Vol. 29, 1334-1352.*
18. *Akbari Mousavi S A A and Farhadi P Sartangi (2009), "Experimental investigation of explosive welding of cp-titanium/AISI 304 stainless steel. Mater. Des, Vol.30 (3), 459-468.*
19. *Tamilchelvan P Raghukandan K and Saravanan S (2013), "Optimization of process parameters in explosive cladding of titanium/stainless steel 304L plates", Int. J. Mater. Res., Vol. 104 (12), 1205–1211.*
20. *Saravanan S and Raghukandan K (2013), "Influence of interlayer in explosive cladding of dissimilar metals", Mater. Manuf. Processes, Vol.28 (5), 589-594.*