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KINETIC ENERGY DISSIPATION IN TI-SS EXPLOSIVE CLADDING WITH MULTI LOADING RATIOS*

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Abstract– Explosive cladding is a metal cladding technique, wherein restricted detonation impinges two or more metals to fuse together. On detonation, the chemical energy stored in the chemical explosive is converted instantaneously into kinetic energy, forcing the flyer plate to impinge obliquely with the base plate to craft a metallurgically strong bond. The kinetic energy available at the interface characterizes the interface microstructure and mechanical properties of explosive clad which depends on process parameters viz. explosive loading ratio, standoff distance and preset angle. Titanium-stainless steel 304L plates are explosively cladded with multi loading ratios, stand off distance and preset angle. Formation of smooth wavy interface is observed at lower explosive mass while formation of intermetallic compounds is observed at higher energetic conditions. Amplitude and wavelength of the interfacial waves are directly proportional to kinetic energy lost at the interface. The increase in mechanical strength of the explosive clads is also reported.

Keywords– Explosive cladding, titanium, steel, kinetic energy loss, strength

1. INTRODUCTION

Explosive cladding is a dissimilar metal cladding technique which employs the energy available in a chemical explosive to craft a strong metallurgical bond [1-3]. The microstructure and mechanical properties of explosive clads remain unaltered with respect to those of mating materials as the process is accomplished in a few microseconds. On detonation, the chemical energy stored in the explosive is transformed into kinetic energy of the flyer plate and dictates the formation of clad or otherwise. Since the process is very rapid, the judicial selection of process parameters viz. mass of explosive, stand off distance, velocity of detonation of explosive, thickness of flyer plate and the angle of impact influences the kinetic energy loss [4, 5]. Titanium offers greater corrosion shield in autoclaves for pressure acid leaching and pressure oxidation leaching of metal ores while stainless steel provides good strength at lesser cost [6]. Explosive cladding is a viable method to clad titanium-stainless steel 304L combination which is very effective in corrosive environments.

Various researchers [6-9] reported that the explosive clad interface transforms from straight to wavy with increase in explosive mass. They further reported the influence of process parameters on the mechanical strength of the clad. However, the studies on the influence of kinetic energy dissipation on the nature of interface and mechanical strength of clads are still limited and hence attempted in this study. Titanium-steel explosive clad specimens for metallographic observations were sectioned parallel to the detonation direction following standard metallurgical procedures. To determine the mechanical properties

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of the Ti-SS304L explosive clads, microhardness and Ram tensile tests were conducted and the results are reported. 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 cross head speed.

2. MATERIALS AND METHODS

Titanium Gr-1 and Stainless steel 304L plates were employed as flyer and base plates respectively. To study the influence of kinetic energy loss the process parameters were varied as follows. The preset inclination between flyer and base plate ranges from 3 to 15 degrees, while the distance of separation varies from 5 mm to 10 mm. Nitroglycerine explosive (detonation velocity 2800 m/s) was the energy generator with loading ratio varying from 0.75 to 1.75 (ratio of mass of explosive and mass of flyer plate). The plates were polished to obtain a clean surface before cladding. Explosive was packed on the flyer plate and a detonator was positioned on one corner of the flyer plate. The experimental condition and process parameters are shown in Table. 1. The collision conditions viz. flyer plate velocity, collision velocity and dynamic bend angle were calculated using empirical relations reported elsewhere [10].

Table. 1. Experimental conditions

S. No	Flyer thickness (mm)	Initial angle, α (degree)	Standoff distance, S (mm)	Loading ratio, r	Bend angle, β (degree)	Plate velocity, V_P, (ms^{-1})	Collision velocity, V_w, (ms^{-1})	Kinetic energy loss, ΔKE, (MJm^{-2})
1	3.5	3	5	1	14.7	571.2	2239.2	2.8
2	3.5	8	10	1.75	24.4	799.6	1915.8	5.3
3	6	10	5	0.75	19.57	467.3	1390.2	1.8
4	6	10	5	1.0	21.7	571.2	1536.8	2.8
5	6	15	10	0.75	24.57	467.3	1119.9	1.8
6	6	15	10	1.0	26.7	571.2	1264.6	2.8

3. EXPERIMENTAL RESULTS AND DISCUSSION

a) Microstructural characterization

The experimental results of explosive cladding of Titanium (Gr-1)-SS304L show the characteristic undulating morphology. The interface is absent of any "molten layered zones" for 6 mm thickness flyer plates while formation of interfacial melting and trapping of jet are witnessed for 3.5 mm thick flyer plate (Titanium) at higher energetic conditions (loading ratio-1.75). The microstructure of a Ti-SS304L explosive clad with a stand off distance 5 mm and a preset angle of 3 degrees (Fig. 1) reveals undulating interfaces having amplitude of 35 μm and a wavelength of 201μm. When the loading ratio was increased to 1.75, the emergence of continuous molten layer is witnessed (Fig. 2) as a consequence of higher kinetic energy dissipation (ΔKE=5.3 MJ/m^2). Hokamoto et al. [11] emphasized the significance of kinetic energy loss and deduced an empirical relation given by

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

where, 'm_f' and 'm_b' represents mass of flyer and base plate respectively, 'V_p' is the flyer plate velocity. The kinetic energy loss at the interface depends on the mass of participant metals and velocity of flyer plate (Eq. (1)). The kinetic energy loss at the interface depends largely on the flyer plate velocity (V_p) which, consecutively, depends on the detonation velocity of the explosive and is estimated by [11]

$$V_p = V_d \frac{0.612R}{(2+R)} \tag{2}$$

Where R is the loading ratio, V_d is the detonation velocity of the explosive in m/s. The nature of intermetallic formation is inherently related to amount of kinetic energy dissipated at the interface as it is converted into thermal energy. At high kinetic energy conditions, the dissipated heat causes metals to melt and results in the formation of molten zones. Material reactivity is greatly enhanced by the high kinetic energy dissipation which leaves more reacted products at the interface. Due to rapidity of the process (in the order of 50 µs), the unescaped jet manifests into a trapped jet (marked as 'A' in Fig. 2), either partially or completely, in the single vortex formed before and after each undulation obtained by an oscillation in the fluid like jet flow. The density ratio of the participant metals (density ratio-0.56) is directly proportional to the amount of kinetic energy spent at the boundary, and consequently, the nature of interface. When similar density metals are cladded, formation of intermetallic compounds is grim, while cladding metals have a wide difference in density, lower density metals deform more and tend to create a molten layer as reported by Saravanan and Raghukandan [13].

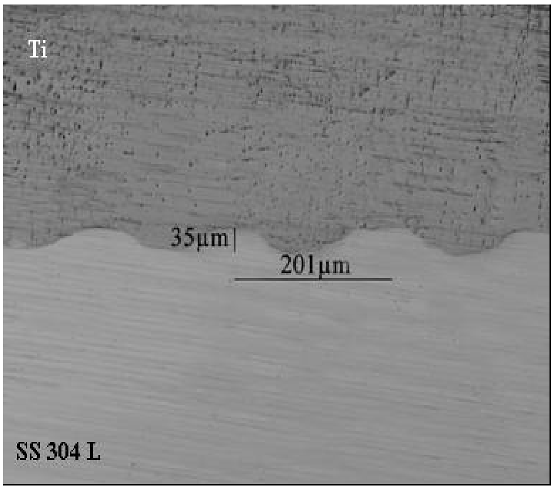

Fig. 1. Microstructure of 3.5 mm flyer thick Ti-Steel explosive clad (α=3°, S=5 mm, R=1) (expt.no-1)

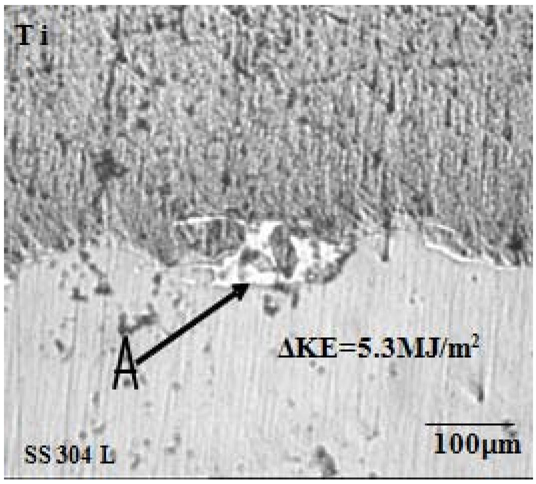

Fig. 2. Microstructure of 3.5 mm flyer thick Ti-Steel explosive clad (α=8°, S=10 mm, R=1.75) (expt.no-2)

When higher thickness titanium flyer plate is cladded, the mass of flyer plate increases and restricts the kinetic energy loss at the collision boundary. The microstructures of Ti-SS304L explosive clad (6 mm thick flyer plate) for a loading ratio of 0.75 and 1.0 are shown in Figs. 3 and 4. The interface shows a smooth wavy interface devoid of intermetallic compounds. The waves are smaller (amplitude-18µm, wavelength-101 µm) for a loading ratio of 0.75, while the waves are larger for a loading ratio of 1.0 (amplitude-45µm, wavelength-248µm) with other parameters remaining unchanged. When the explosive mass is enhanced, the kinetic energy available leads to more deformation and, therefore, results in larger waves with higher amplitude and wavelengths. When the preset angle, α, is altered to 15 degrees for stand off distance, S=10 mm and loading ratio, R = 0.75, the interfacial wave displays an amplitude of 35 µm and a wavelength of 186 µm (Fig. 5), whereas a larger wave (amplitude of 53 µm and wavelength of 293 µm) is observed when the loading ratio is increased to 1.0 (Fig. 6).

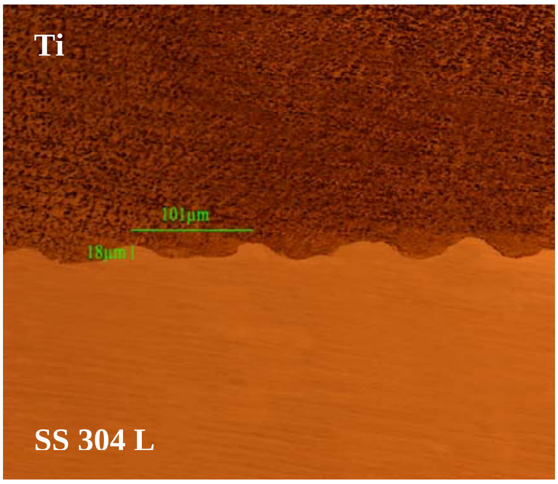

Fig. 3. Microstructure of 6 mm thick Ti-SS explosive clad (α=10°, S=5 mm, R=0.75) (expt.no-3)

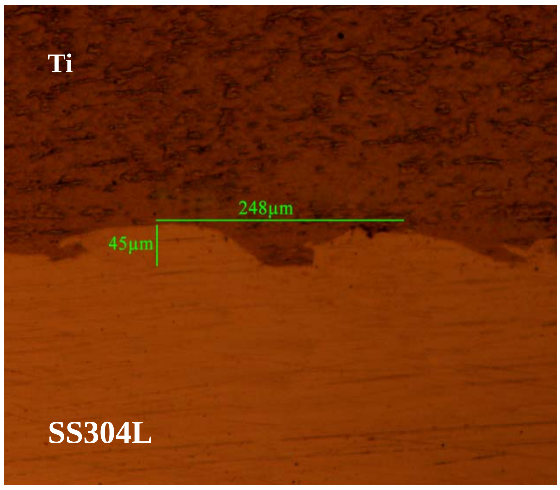

Fig. 4. Microstructure of 6 mm flyer Ti-SS explosive clad (α=10°, S=5 mm, R=1.0) (expt.no-4)

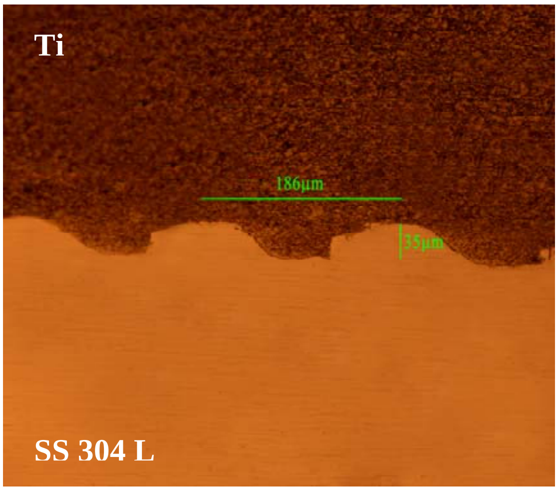

Fig. 5. Microstructure of 6 mm thick Ti-SS explosive clad (α=15^0, S=10 mm, R=0.75) (expt.no-5)

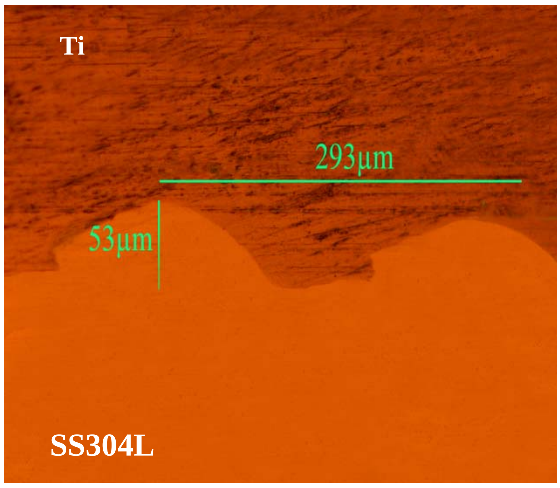

Fig. 6. Microstructure of 6 mm flyer Ti-SS explosive clad (α=15°, S=10 mm, R=1.0) (expt.no-6)

The interface micrographs highlight the effect of process parameters viz. loading ratio, preset angle and standoff distance on amplitude and wavelength of the interfacial waves. The increase in explosive mass enhances the amplitude and wavelength of the interfacial waves as reported by various researchers [14-17]. Though the interface amplitude and wavelength increases with increase in explosive mass, formation of strong clad is feasible even at lower energetic condition (minimum explosive mass) by judicious selection of process parameters. When the explosive mass is increased above a critical limit, excess kinetic energy dissipation induces the formation of intermetallics at the interfacial boundary. Manikandan et al. [6], while cladding titanium and stainless steel, observed Fe_2Ti and FeTi intermetallic compounds at higher kinetic energy conditions and recommended the use of thin interlayer for suppressing the excess kinetic energy dissipation when a high detonation velocity explosive is employed.

b) Mechanical strength

1. Microhardness: The Vickers hardness of the explosively cladded titanium-steel plates were measured at uniform interval (0.5 mm) and with a load of 500g. For each sample, three measurements were taken and the average values are reported. In explosive cladding, both flyer and base plates experience an extreme stress wave consequential from high velocity impact and give rise to considerable increase in hardness which influences the ductility and impact strength of the clad. From Fig. 7, it is observed that hardness values increase with increase in loading ratio. The kinetic energy dissipation at the interface resulting in adiabatic temperature rise and the hardening effect and/or excess plastic deformation in the explosion area causes higher hardness at the interface. The post clads exhibit higher hardness than the preclad metals. However, there is no considerable increase away from the interface (1000 μm) as reported by Honarpisheh et al. [17], while joining aluminium with copper.

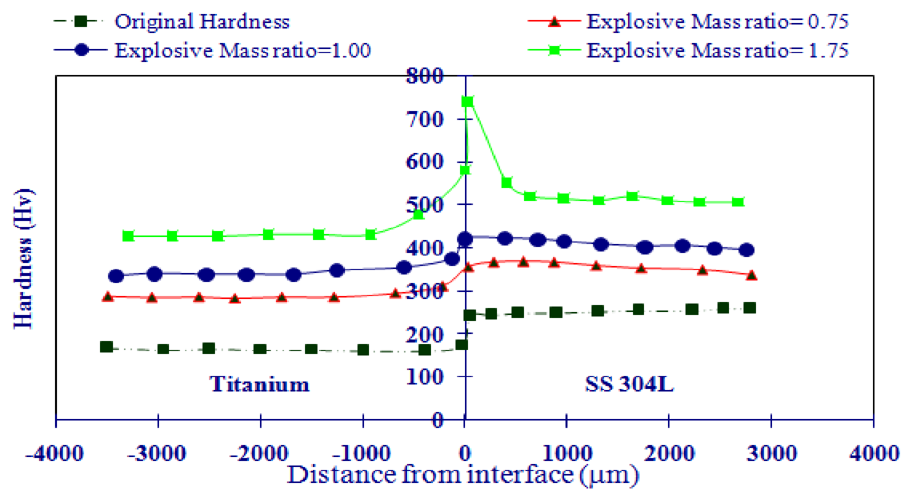

Fig. 7. Microhardness across Ti-SS304L explosive clad

2. Ram tensile test: The specimen preparation and the conduct of Ram tensile tests were executed as per ASTM A-264[17]. The tensile strength of the clads are invariably higher than the weaker of the participating metals as reported by earlier researchers [19, 20]. In this case, the strength of the clads are higher than that of Ti (170MPa) flyer plate. In fact the lowest strength of the clad is seen for expt. no. 2, $\alpha=8^o$, S=10 mm, R=1.75, (186MPa) which is 10% higher than that of Ti. It is interesting to note that the range of Ram tensile strength of clads is from 186 MPa to 293 MPa. The highest value is obtained for expt.no.3, $\alpha=10^o$, S = 5 mm, R=0.75, (293MPa) which is very close to the tensile strength of SS304L. Further, it is noted that the wave morphology influences the Ram tensile strength of the welds. The highest Ram tensile strength is for expt.3 (wavelength-101μm and amplitude-18μm) and lowest is for expt.2 (amplitude-59 μm and wavelength-316μm). Wavy interfaces serve as a better interlocking mechanism and therefore, as the size of the waves are small, the 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.

Table. 2. Strength of explosive clads

Expt. No	Thickness of flyer plate, (mm)	Preset angle, (degrees)	Distance of separation (mm)	Explosive mass ratio	Bonding strength, (MPa)
1	3.5	3	5	1.00	275
2	3.5	8	10	1.75	186
3	6	10	5	0.75	292
4	6	10	5	1.00	264
5	6	15	10	0.75	278
6	6	15	10	1.00	243

4. CONCLUSION

The objective of this present study is to study the effect of process parameters on the kinetic energy dissipation, interface microstructure and mechanical properties of Ti-SS304L explosive clad. The following conclusions were drawn from this study

1. Formation of strong clad is predominant at lower energetic conditions.
2. At higher energetic conditions, formation of molten intermetallic compounds is observed due to excessive kinetic energy dissipation.
3. The technical parameters loading ratio, distance of separation and preset angle significantly influences the kinetic energy and, consequently, the nature of interface and strength.
4. Explosive mass is directly proportional to amplitude and wavelength of the interface.
5. Undulating interfaces devoid of intermetallics was obtained at lower energetic conditions.

Post clad exhibited higher hardness than preclad metals.

REFERENCES

1. Grignon, F., Benson, D., Vecchio, K. S. & Meyers, M. A. (2004). *International Journal of Impact Engineering*, Vol. 30, pp. 1333–1351.
2. Saravanan, S. & Raghukandan, K. (2013). Materials and manufacturing processes. Vol. 28, No. 5, pp. 589-594.
3. Mallesham, P., Gokhale, A. A. & Murti, V. S. R. (2003). *Journal of Materials Science*, Vol. 38, pp. 1869–1873.
4. Saravanan, S. & Raghukandan, K. (2011). Materials science forum. Vol. 673, pp. 125-129
5. Narimanzadeh, N., Darvizeh, A. & Gharababaei, H. (2003). *Iranian Journal of Science and Technology, Transaction B: Engineering*, Vol. 27, No. 3, pp. 551-562.
6. Manikandan, P., Hokamoto, K., Fujita, M., Raghukandan, K. & Tomoshige, R. (2008). *Journal of Materials Processing Technology*, Vol. 195, pp. 232–240.
7. Gulenc, B. (2008). Materials and design, 29, pp. 275–278.
8. Acarer, M. & Demir, B. (2008). *Materials letters*, Vol. 62, pp. 4158–4160.
9. Kahraman, N., Gulenc, B. & Findik, F. (2005). *Journal of Materials Processing Technology*, Vol. 169, pp. 127–133.
10. Crossland, B. (1982). *Explosive welding of metals and its applications*. Oxford University Press, London.
11. Hokamoto, K., Izuma, T. & Fujita, M. (1993). *Metallurgical Transactions A*, Vol. 24A, pp. 2289-96.
12. Chadwick, M. D. (1968). *Proc. of the Select Conf. on Explosive Welding*, Welding Inst.
13. Saravanan, S. & Raghukandan, K. (2012). *Science and Technology of Welding and Joining*, Vol. 17, No. 2, pp. 99-103.
14. Acarer, M., Gulenc, B. & Findik, F. (2004). *Journal of Materials Science*, Vol. 39, pp. 6457–6466.
15. Wronka, B. (2011). *International Journal of Impact Engineering*, Vol. 38, No. 5, pp. 309-313.
16. Zamani, E. & Liaghat, G. H. (2012). *Journal of Materials Science*, Vol. 47, No. 2, pp. 685-695.
17. Honarpisheh, M., Asemabadi, M. & Sedighi, M. (2012). *Materials and Design*, Vol. 37, pp. 122–127.
18. ASTM A 264, American National Standard, (1995). ANSI/ASTM A 264-77.
19. Raghukandan, K. (2003). *Journal of Materials Processing Technology*, Vol. 139, pp. 573–577.
20. Akbari Mousavi, S. A. A., Al-Hassani, S. T. S. & Atkins, A. G. (2008). *Materials and design*, Vol. 29, pp. 1334–1352.