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# Characterization of Clad Joints of High Strength Low Alloy Steel with Stainless Steel and Titanium

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*DOI : 10.22486/iwj/2018/v51/i4/176799*

## ABSTRACT

In the present investigation, a study has been carried out to understand the structure-property correlations in explosive clad joints of high strength low alloy steel (Yield Strength >600 MPa) in as-clad, hot rolled and heat treated conditions. The cladding materials employed were austenitic stainless steel of AISI 347 grade and commercial pure (CP) titanium. An attempt has also been made to realise the structure-property correlations in the clad joint of the HSLA steel with AISI 347 grade austenitic stainless steel produced by weld overlay cladding technique. In explosive cladding, the interface was found to be wavy type and in weld overlay cladding, the interface was flat. Explosive clad joints of HSLA steel + austenitic stainless steel exhibited a bond strength of 491 MPa in as-clad condition and 408 MPa after hot rolling and heat treatment. Explosive clad joint of HSLA steel + CP titanium exhibited a bond strength of 356 MPa in as-clad condition as CP titanium possesses lower strength (337 MPa) compared to that of AISI 347 grade austenitic stainless steel (515 MPa). The weld overlay clad joint exhibited a bond strength of 488 MPa which is almost equal to that of explosive clad joint in as-clad condition. The clad joints of austenitic stainless steel and CP titanium, with the base plate in heat treated condition, exhibited good formability when three point bend tests were conducted upto 114º and 139º respectively.

**Key words**: Explosive cladding, weld overlay cladding, HSLA steel, Stainless steel, microstructure, shear bond strength.

## 1.0 INTRODUCTION

Defence Metallurgical Research Laboratory (DMRL) has developed two grades of high strength low alloy (HSLA) steels with Yield Strength >400 MPa and Yield Strength >600 MPa. The first grade of HSLA steel is mainly meant for fabrication/repair of ships and the second grade of HSLA steel is mainly meant for fabrication/repair of submarines [1, 2]. These steels are used for naval structures due to excellent toughness and resistance to dynamic fracture to meet the critical requirements in welded hulls. The increase of the service properties and service life of naval hull structures is at present one of the most important tasks faced by the Navy. Surface modification is essential for improving service properties of components. Cladding is one of the most widely employed methods for surface

modification. Hot roll-bonding, weld overlaying and explosive cladding are commonly used in naval applications. The most commonly used cladding materials are stainless steels and titanium for cladding on HSLA steels. Mechanical properties are considered important for satisfactory performance of clad joints used in several defence applications. Although stainless steels are easily cladded to HSLA steels by fusion and solid state joining processes, the service life of the clad joint in corrosive environments relies to a large extent on the behaviour of the clad-interface microstructure. In these materials, the clad-interface microstructure has until now received little attention. Keeping the above in view, and the shortage of published data on the performance of the clad joints, an attempt has been made to study, understand and characterize microstructure and mechanical properties of the clad joints.

The main aim of the present study is to understand the cladding of stainless steel and commercially pure titanium on high strength low alloy steel (Yield Strength >600 MPa) using explosive cladding and weld overlaying. The scope of the present work is to study:

- The effect of rolling reductions on structure and properties in explosive clad joints of high strength low alloy steel with 347 austenitic SS(1).
- The structure and properties of explosive clad high strength low alloy steel with CP titanium.
- Characterization of microstructure and mechanical properties of weld overlay clad joint of high strength low alloy steel with 347 austenitic SS(2).

## 2.0 EXPERIMENTAL DETAILS

A high strength low alloy (HSLA) steel having Yield Strength >600 MPa which is used for naval applications was used for base plate in the entire study. Austenitic stainless steel AISI 347 grade (designated as 347 SS) as well as commercially pure (CP) titanium were employed as cladding materials because of their good corrosion resistance coupled with optimum tensile strength. While CP titanium was used in plate-form, AISI 347 grade stainless steel was used in plate-form as well as electrode-form; steel plates were designated as 347 SS(1) and electrodes were designated as 347 SS(2). Chemical composition of base plate and cladding materials is presented in **Table 1**.

In the present investigation, three cladding experiments were carried out by two of the cladding techniques namely explosive cladding (parallel arrangement) and weld overlay cladding. In the first experiment, HSLA steel was explosive clad on both sides with AISI 347 SS(1). In the second experiment, explosive cladding of HSLA steel was performed with CP titanium. The clad plates were subjected for ultrasonic testing (UT) and unbonded regions of approximately 10 mm wide along the four edges were trimmed and the sound portions were subjected to further experimental work. Weld overlay cladding was employed in the third experiment. HSLA steel plate was cladded by shielded metal arc welding using AISI 347 stainless steel, i.e., 347 SS(2) electrodes. The clad plate was subjected to ultrasonic testing (UT) wherein no unsound regions were noticed.

Explosive clad plate of HSLA steel+ AISI 347 SS(1) was subjected to hot rolling at 1180°C and the thickness of the clad plates was brought down to desired thicknesses in 7 to 8 passes. Explosive clad plate of HSLA steel+ CP titanium and weld overlay clad plate of HSLA steel+347 SS(2) were not subjected to hot rolling and subsequent heat treatment as: (i) The thickness of base plates was 28 mm and 50 mm respectively and these thicknesses fall in the usage range of thickness of clad plates for fabrication of naval vessels. (ii) The base plates were already in heat treated condition. A portion from the rolled plate was subjected to heat treatment involving hardening and tempering to Improve the base plate properties. Hardening was carried out at 950°C followed by water quenching. The quenched clad plate was subjected to tempering at 650°C followed by water quenching.

Specimens from all the three cladding experiments were subjected for metallographic examination. Suitable size

**Table 1: Chemical composition of base plate and cladding materials**

| Material | Chemical composition, wt% | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | C | Cr | Ni | Mn | Si | S | P | Others |
| HSLA Steel | 0.095 | 0.56 | 1.89 | 0.37 | 0.29 | 0.007 | 0.01 | Mo:0.30 * |
| * Cu:0.45, V:0.05, Al:0.04 | | | | | | | | |
| 347 SS(1) | 0.038 | 17.20 | 9.36 | 1.54 | 0.54 | 0.003 | 0.04 | Nb:0.51 |
| 347 SS(2) | 0.042 | 17.10 | 10.70 | 1.46 | 0.28 | 0.010 | 0.01 | Nb:0.52 |
| Titanium (99.66% pure) | 0.053 | - | 0.005 | <0.002 | <0.005 | 0.042 | - | V:0.008 # |
| # Cu:0.0087, Nb:0.004, Fe:0.048, O:0.090, N:0.008, H:33ppm | | | | | | | | |

specimens were prepared by standard metallographic techniques. The samples were then examined under optical microscope for general microstructural features and under scanning electron microscope (SEM) for studying the structural changes near the bond interface. Electron probe micro analysis (EPMA) was carried out to study the chemical variations near the bond interface. X-ray diffraction studies were carried out to identify the phases present in the microstructure of the component plates as well as the intermetallics formed at the interface.

To evaluate the integrity of the clad joints, mechanical properties (plain tensile, notch-tensile, impact, shear, hardness, bend ductility) were evaluated using the test samples machined from as-clad, clad+rolled and clad+ rolled+heat treated plates as per ASTM standards such as ASTM E 8 [3] etc. Test samples were machined from base plate, flyer plate and the interface regions. Three samples were tested in each case and the average values are reported.

SEM fractography was carried out on tensile, notch-tensile and CVN tested samples pertaining to base plate region of as-clad plate and heat treated plate. Fractography of shear bond strength-tested samples from interface region of all the clad joints was also carried out.

## 3.0 RESULTS AND DISCUSSION

### 3.1 Explosive clad joints of HSLA steel with austenitic stainless steel - Effect of rolling reductions on structure and properties

Photographs of explosive clad plate as well as the rolled plates of 63, 45 and 27 mm plates are presented in **Fig. 1**. Micro-structure of the base plate (HSLA steel) was found to be ferrite+ pearlite+ bainite in as-clad as well as in hot rolled conditions (**Fig. 2a**). After heat treatment, the microstructure of the 27 mm thick plate changed to tempered bainite/ martensite (**Fig. 2b**). The flyer plate (stainless steel) exhibited austenite grains with twinned regions in as-clad condition. After hot rolling to 63 mm thickness, the microstructure changed to coarse polygonal grains. However, in case of 45 mm thick clad joint, the flyer plate exhibited fine polygonal austenite structure. The 27 mm thick clad joint revealed further fine austenite grains with little banding. The bond interface of the as-clad joint was found to be wavy in nature with melt zones at wave crests (**Fig. 3**). Amplitude, wave-length and width of the interface were estimated from the optical micrographs (**Fig. 3** and **4**) and presented in **Fig. 5**; all of them were found to decrease with rolled plate thickness. These results are matching with the reported literature [4-8].

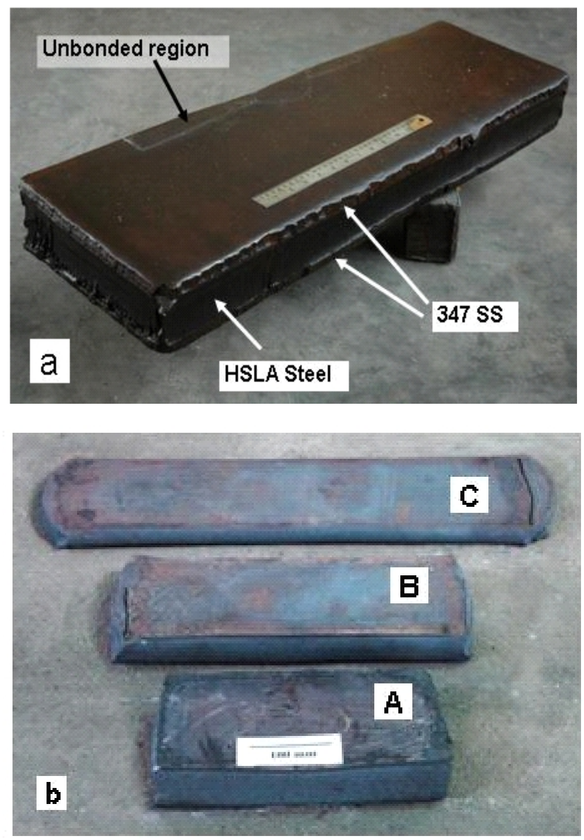


**Fig. 1 : a) The clad plate before hot rolling**
**b) Hot rolled plates:**
**A : 63 mm thick; B : 45 mm thick and C : 27 mm thick.**

**Table 2: Tensile and impact properties for base plate region.**

| Plate details | YS, MPa | UTS, MPa | %El | %RA | CVN at -40°C, J |
|---|---|---|---|---|---|
| 90 mm, As-clad | 574 | 670 | 19 | 65 | 17 |
| 27 mm, Heat treated | 610 | 683 | 23 | 74 | 221 |

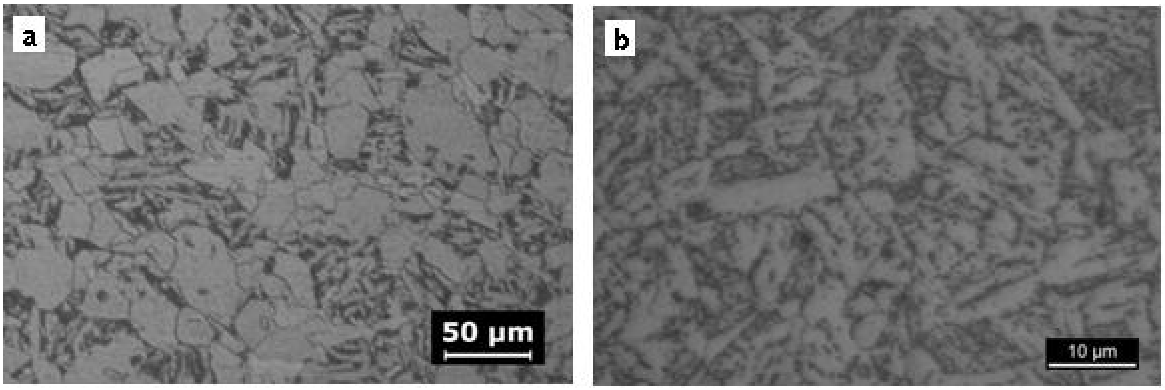


**Fig. 2 : Microstructure of base plate region: a) in as-clad condition and b) after heat treatment.**

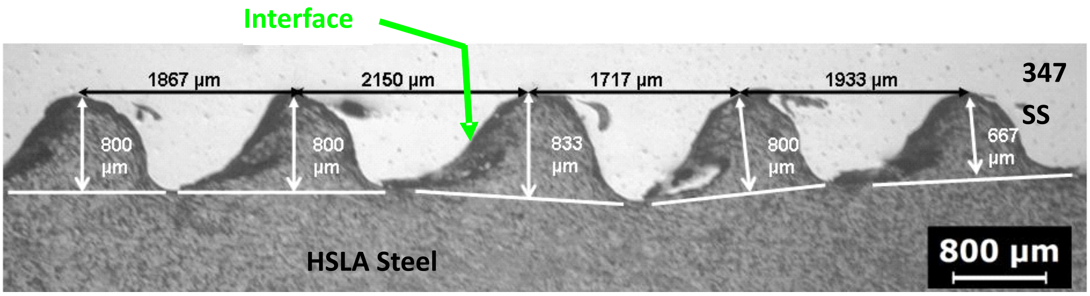


**Fig. 3 : Measurement of wave length and amplitude on enlarged photomicrographs for 90 mm thick as-clad plate.**

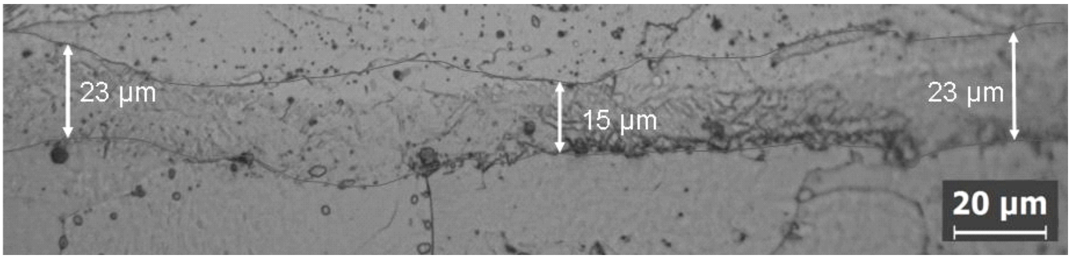


**Fig. 4 : Measurement of interface width on enlarged photomicrographs for 27 mm thick as-rolled plate**

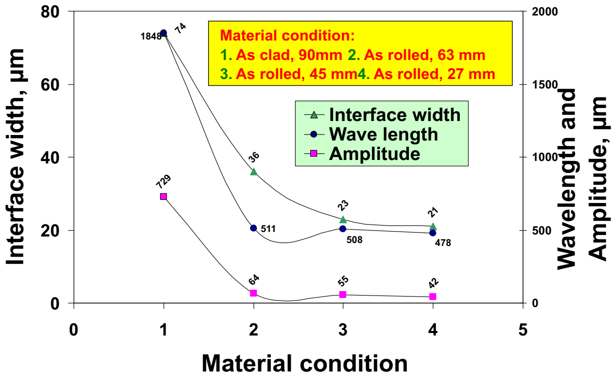


**Fig. 5 : Variation of interface properties with material condition**

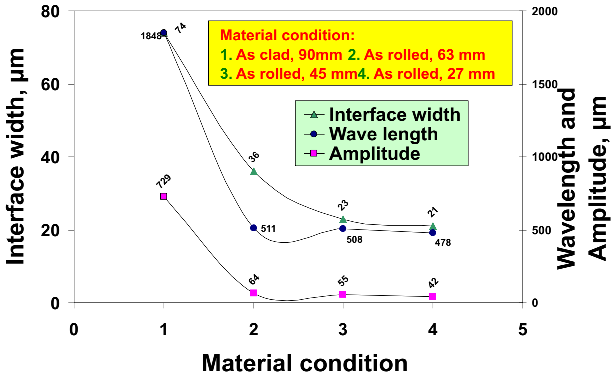


**Fig. 5 : Effect of material condition and rolled plate thickness on shear bond strength**

Tensile and impact properties for the base plate region of as-clad joint as well as heat treated clad joints are presented in **Table 2**. Tensile strength and ductility were found to improve marginally from 670 MPa to 683 MPa and 19 to 23 respectively upon heat treatment due to tempered bainite/ martensite microstructure (**Fig. 2b**). The Charpy V-Notch energy (CVN) was 17 J in as-clad condition and increased to 221 J after heat treatment. The Charpy V-Notch energy was very low in as-clad condition due to presence of pearlite in the microstructure and has improved significantly after heat treatment due to tempered bainitic/ martensitic microstructure.

Shear bond strength of the interface region for the as-clad, hot rolled and heat treated plates is presented in (**Fig. 6**). The shear bond strength was the highest in the as-clad condition (491 MPa) and decreased to 438 MPa due to hot rolling to 63 mm thickness. It gradually further decreased to 381 MPa with the rolled plate thickness from 63 mm to 27 mm (**Fig. 6**). Subsequent heat treatment slightly increased the shear bond strength of the 27 mm plate, which was found to be 408 MPa (**Fig. 6**). Tensile shear strength of the interface (491 MPa) in as-clad condition is found to match with the reported values of shear strength for austenitic stainless steel clad joints [9]. This shear strength was lowered to 381 MPa after hot rolling. Shear strength of the bond interface is mainly due to mechanical locking of the flyer and base plates provided by the wavy pattern [10]. The amplitude of the as-clad wavy pattern, which was 729 µm, decreased to 42 µm (**Fig. 5**) due to hot rolling reduction from 90 mm to 27 mm and the extent of mechanical locking provided is comparatively less and hence a lower shear strength was the result. Slight increase in shear bond strength was observed as the microstructure changed from ferrite +pearlite+bainite to tempered bainite+martensite (**Fig. 2**).

Average hardness values of all the six samples at different regions such as base plate, flyer plate and interface are presented in **Table 3**. The hardness on base plate, flyer plate and interface regions was 232, 375 and 328 HV respectively for the as-clad joint. The hardness of all the regions decreased to lower values in the hot rolled plates and slightly increased after heat treatment. These hardness variations are attributed to the microstructural changes taking place during (i) hot rolling of the 90 mm thick clad plate to 63 mm, 45 mm and 27 mm thickness and (ii) when the hot rolled plate of 27 mm thickness was further subjected to heat treatment through water quenching route.

**Table 3: Hardness values of clad plates (Average of two sets).**

| Sl. No. | Sample condition | Hardness, HV/300 gm | | |
|---|---|---|---|---|
| | | On base plate (HSLA Steel) | On flyer plate (347 SS) | On interface |
| 1 | 90mm, As clad | 232 | 375 | 328 |
| 2 | 63 mm, As rolled | 212 | 197 | 300 |
| 3 | 45 mm, As rolled | 215 | 208 | 263 |
| 4 | 27 mm, As rolled | 224 | 232 | 272 |
| 5 | 27mm, As WQ | 305 | 218 | 263 |
| 6 | 27 mm, WQ+T | 247 | 212 | 300 |

Three-point bend tests were conducted on the clad joint region of as- heat treated plate to evaluate bend-ductility of the clad joints. Bend tests were also reported by other investigators [11-13] on explosive clad joints. The heat treated clad joint withstood both the face bend and root bend tests successfully upto 110° bend angle without cracking. Photograph of the bend tested specimens is shown in **Fig. 7**.

Diffusion zone widths were calculated by plotting EPMA quantitative analysis data for different material conditions and presented in **Fig. 8**. From **Fig. 8**, it evident that Ni, Cr and Mn have diffused from stainless steel to HSLA steel over a distance of 43, 15 and 10 µm respectively at the interface of the as-clad joints. The diffusion zone width (DZW) was minimum in as-clad samples and maximum in rolled plate samples having 63 mm thickness. The diffusion distance decreased with rolled plate thickness from 63 mm to 27 mm. For the 27 mm thick plate, the DZW of the as-rolled plate remained nearly same even after the heat treatment involving hardening and tempering. After calculating the hypothetical DZWs prevailing at 1180°C in 90 mm thick clad plate prior to hot rolling, the DZWs obtained for the as-rolled plates were found to be in order in relation to the %deformation received by them.

SEM fractography was carried out on tensile and CVN tested samples pertaining to base plate region and shear bond strength-tested samples from interface region. All the samples pertaining to as-clad and rolled plates failed in brittle/mixed mode revealing quasi-cleavage fracture in some regions and dimpled fracture in other regions. However, all the specimens pertaining to heat treated plate failed in ductile mode and exhibited fibrous and dimpled fracture. Typical fractographs are presented in **Fig. 9**. Arrows in **Fig. 9a** indicate secondary cracks observed in brittle fracture regions.

### 3.2 Structure and properties of explosive clad HSLA steel with titanium

Explosive clad plate of HSLA steel with titanium is shown in **Fig. 10**. Microstructure of the as-clad sample shows that the interface between the HSLA steel and titanium is wavy in nature with melt pockets in wave crests (**Fig. 11**) which is similar to the clad joint of HSLA+347SS. The base plate reveals tempered bainite/martensite microstructure (**Fig. 11**). SEM studies revealed that carbides are present along lath boundaries. On the other hand, the flyer plate revealed α-phase with twinned regions (**Fig. 11**). XRD studies also confirmed the presence of bainite/martensite phase in the base plate and α-titanium in the flyer plate. In addition, intermetallic compounds such as $TiFe_2$, $Ti_2Ni$ and $Ti_2Cu_3$ were also found to form at the interface (**Fig. 12**).

The mechanical properties of the base plate, flyer plate and the clad joint are presented in **Table 4**. The yield strength (YS) of the base plate was 630 MPa and the tensile strength was 713 MPa. The flyer plate exhibited a YS of 237 MPa and a tensile strength of 337 MPa as titanium possesses lower strength compared to HSLA steel. The Charpy V-Notch (CVN) energy of the base plate at -40ºC was 164 J and this is found to be in order as the base plate was in quenched and tempered condition. Tensile shear strength of the base plate was 400 MPa and that of the flyer plate was found to be 335 MPa. The shear bond strength of the clad joint was found to be 356 MPa; this is in order as titanium possesses lower strength compared to 347 grade stainless steel.

Micro hardness measurements have shown that peak hardness of 306 HV was achieved on HSLA steel near the bond line. The hardness sharply decreased on either side of the bond line over a distance of 50-100 μm and reached base levels in both flyer as well as base plates. The base plate possessed an average hardness of 275 HV and at the boundary it has increased upto 306 HV over a distance of 100 μm. Similarly, average hardness of the flyer plate was found to be 210 HV and near the bond line, it has raised to 233 HV over a distance of 50 μm. Therefore, there is an increase of hardness of 20 to 30 HV on either side of the bond line over a distance of 50 to 100 μm. Similar phenomena were observed by other investigators [8, 11, 12, 14] for explosive clad joints.

Three-point bend tests were conducted to evaluate the integrity of the clad joint. The test specimens were machined in transverse direction in such a way that 2.5 mm thickness from titanium-side and 2.5 mm thickness from HSLA steel-side were maintained. Two specimens were face-bend tested up to 123º & 132º and two more specimens were root-bend tested up to 130º & 139º. All the samples were found to be intact without any sign of cracking (**Fig. 13**).

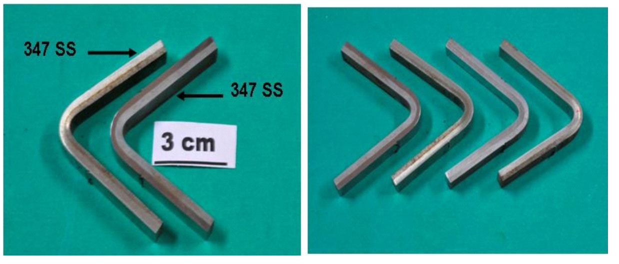


**Fig. 7 : Bend tested specimens of heat treated plate**

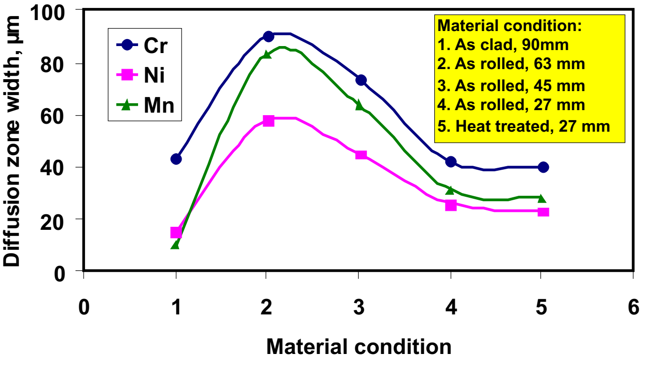


**Fig. 8 : Effect of material condition and rolled plate thickness on chemical variances**

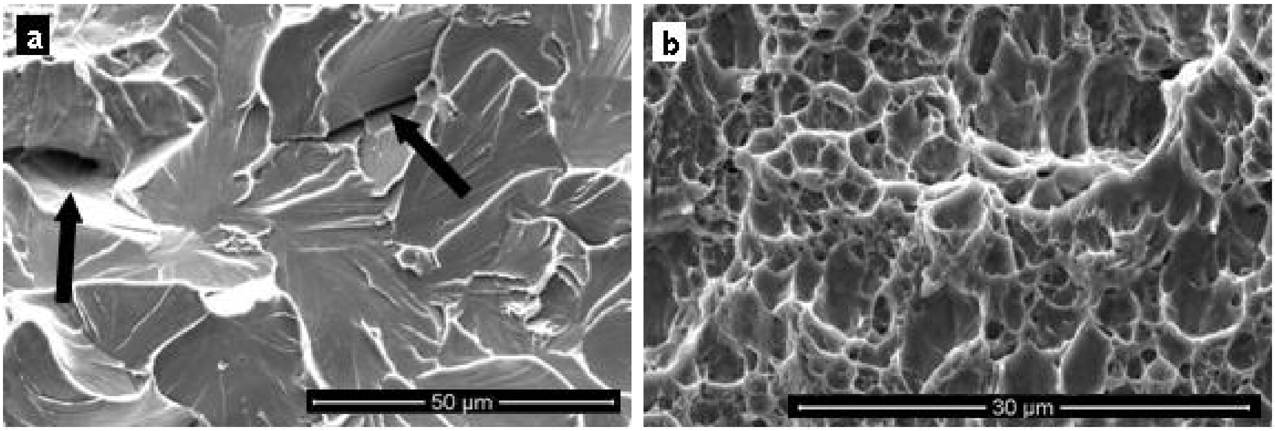


**Fig. 9 : Fractographs of shear bond test specimens pertaining to interface region: (a) Brittle fracture in 90 mm thick as-clad plate and (b) Ductile fracture in 27 mm thick heat treated plate.**

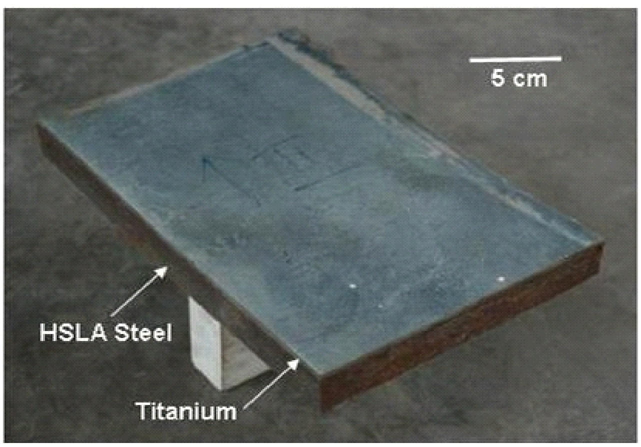


**Fig. 10 : Explosive bonded plate.**

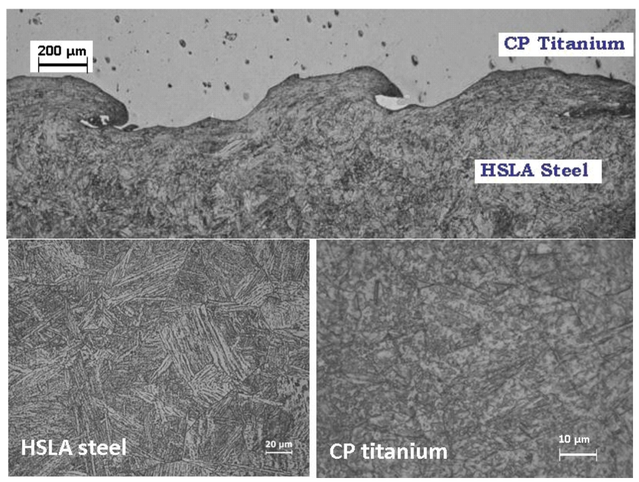


**Fig. 11 : Microstructure.**

**Table 4: Mechanical properties of HSLA steel, titanium and explosive clad plates (Tensile, CVN and shear strength for base and flyer plates & shear bond strength for interface).**

| Material | YS, MPa | UTS, MPa | %El | CVN, J at -40°C | Shear strength or * |
|---|---|---|---|---|---|
| HSLA steel (28mm) | 630 | 713 | 21 | 164 | 400 |
| Titanium (4mm) | 237 | 337 | 56 | - | 335 |
| Clad joint (28+4mm) | - | - | - | - | 356 |
| * shear bond strength, Mpa | | | | | |

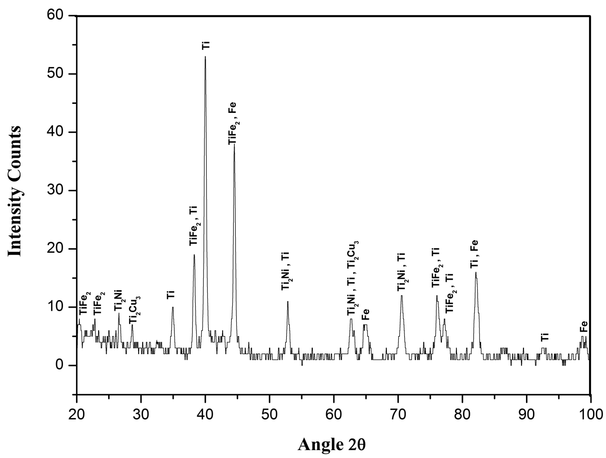


Fig. 12 : X-ray diffraction pattern for the clad joint region

EPMA Quantitative analysis was carried out at four different locations across the interface for the alloying elements such as Ti, Fe, Si, Cr, Mn, Ni, Cu, Nb, Mo and V. The data was plotted and diffusion zone widths were worked out for all the elements. The EPMA data obtained from location 2 for some of the alloying elements is plotted in **Fig. 14** wherein the diffusion distance appears to be 5 to 10 μm. The EPMA data for of Ti and Fe was also plotted and in this case the diffusion distance was found to be 40-75 μm at different locations.

### 3.3 Weld overlay cladding of high strength low alloy steel with austenitic stainless steel - structure and properties

Cut section of weld overlay plate is shown in **Fig. 15** which shows that the thickness of overlay is 15 mm. The low magnification micrograph of the weld overlay clad plate is shown in **Fig. 16a**. The interface between the substrate (base plate) and clad layer is nearly flat. **Fig. 16b** reveals that grain coarsening and decarburization occurred in the base plate near the interface. The clad layer revealed austenite dendritic structure (**Fig. 17a**). The low magnification micrograph of the clad layer (**Fig. 17b**) shows the inter-pass boundaries as the clad layer was built up by multiple passes.

Tensile and notch-tensile tests were conducted for the base plate region as well as interface region. Test specimens from the interface regions were machined such that fracture takes place at the weld overlay-interface. Initially, 18 mm diameter rods were machined in z-direction which were 65 mm long (**Fig. 15** and **18**). Out of this length, 50 mm was of HSLA steel and 15 mm was of 347 SS(2) which were equal to the thickness of the base plate and weld overlay-layer respectively (**Fig. 15**). Therefore, to make the weld overlay-interface as the centre of the test specimens, there was the need to increase the length of the 347 SS(2)-side (which is only 15 mm as seen from **Fig. 15** and **18**) so that grip portion of the test specimens is facilitated. For this, 18 mm diameter rods of 75 mm length were machined from a similar grade stainless steel bar. These rods were welded to the 347 SS(2)-side of the 18 mm diameter rods already machined from the weld overlay plate, by friction welding (portion E in **Fig. 18**) on a continuous drive friction welding machine. Therefore, each rod consisted of two weld interfaces out of which one was of weld overlay i.e., HSLA Vs 347 SS(2) (point B in **Fig. 18**) and other one was of friction welding i.e., 347 SS(2) Vs its equivalent grade (point D in **Fig. 18**). All the specimens were machined from these rods such that the weld overlay-interface (point B in **Fig. 18**) lies at the centre of the test specimen.

The mechanical properties of the base plate as well as interface of the weld overlay clad steel are presented in **Table 5**. All the properties are found to be in order except the CVN energy of the weld overlay-interface (47 joules) which is only 30 % when compared to the CVN energy of the base plate (164 joules). This is attributed to the brittle dendritic microstructure of the interface (**Fig. 17**).

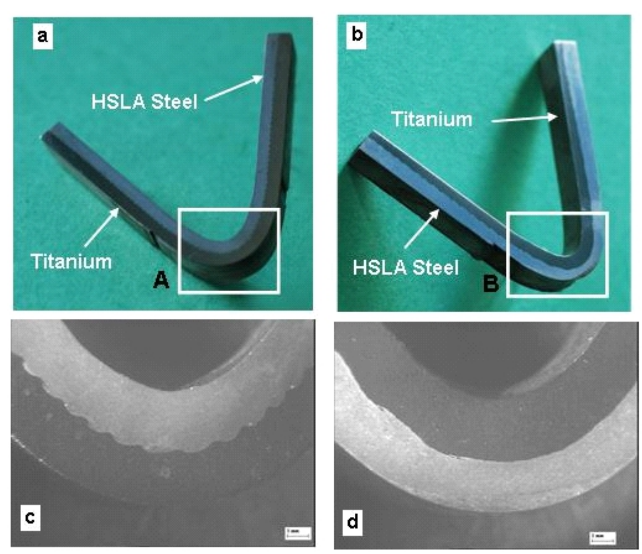


**Fig. 13 : Bend samples (a) Face-bend tested b) Root-bend tested; c) Magnified view of region A and d) Magnified view of region B.**

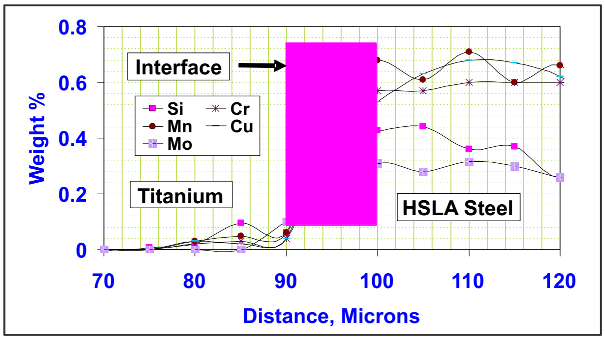


Fig. 14 : EPMA Quantitative analysis

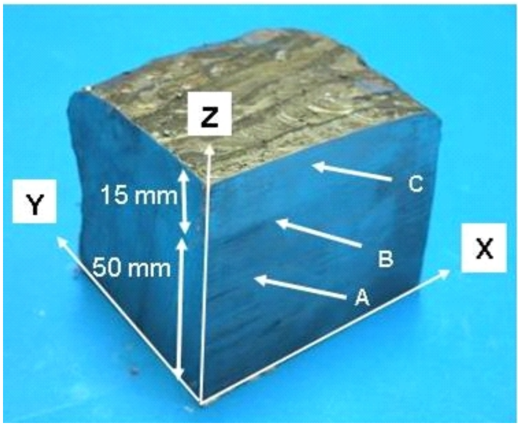


Fig. 15 : Cut section of weld overlay plate :
A - HSLA steel plate; B - Welding overlay interface
C - Clad layer of 347 SS built-up

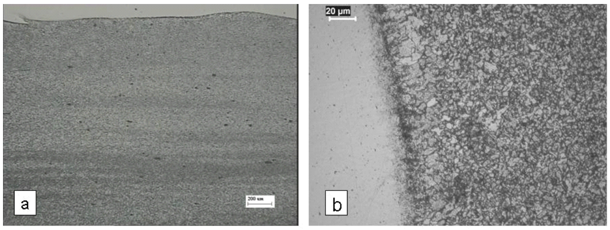


Fig. 16 : Microstructure of weld overlay plate
a) Low magnification micrograph
b) De-carburization and grain coarsening at interface

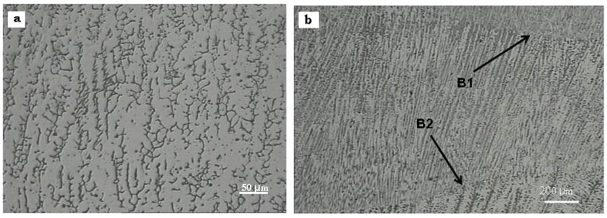


Fig. 17 : Microstructure of the clad layer revealing
(a) Austenite dendrites and
(b) Inter-layer boundaries B1 and
B2 within austenite structure.

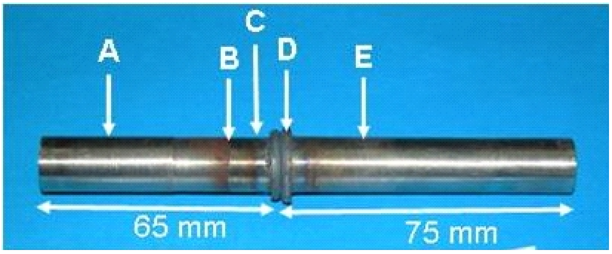


Fig. 18 : 18 mm diameter rod machined from weld overlay plate

A : HSLA steel portion
B : Weld overlay interface between HSLA steel and 347 SS(2)
C : Clad layer of 347 SS(2)
D : Friction welding interface between 347 SS(2) and its equivalent.
E : Stainless steel rod similar to 347 SS(2) grade friction welded on to the weld overlayed material to facilitate grip portion when test specimens is machined out of it.

SEM fractographs of different test specimens are presented in **Figs. 19-20**. Tensile and notch-tensile specimens of the interface failed in ductile mode revealing equiaxed dimples (**Fig. 19**). Shear bond test specimens of the interface as well as shear test specimens of the base plate also revealed the presence of predominantly dimpled rupture. Charpy impact specimens of the interface revealed a mixed mode of failure exhibiting dimpled and quasi cleavage features (**Fig. 20a**) while impact specimens of the base plate failed in ductile mode (**Fig. 20b**).

**Table 5 : Mechanical properties of the weld overlay-clad joint of austenitic stainless steel and HSLA steel**

| Type of test | Base plate | | | At the interface | | |
|---|---|---|---|---|---|---|
| | YS, MPa | UTS, MPa | %El | YS, MPa | UTS, MPa | % El. |
| Tensile | 630 | 713 | 21 | 400 | 592* | 19 |
| Notch-tensile | 926 | 1025 | - | 715 | 953 | - |
| Shear/shear bond strength | 399 Mpa | | | 488 MPa | | |
| CVN at -40°C | 164 J | | | 47 J | | |

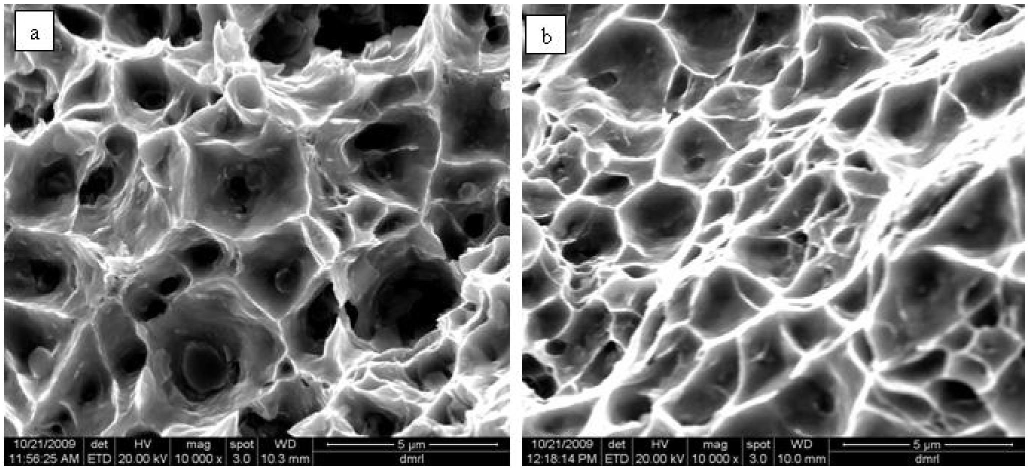


**Fig. 19: Fractographs of a) tensile and b) notch-tensile test specimens of the interface**

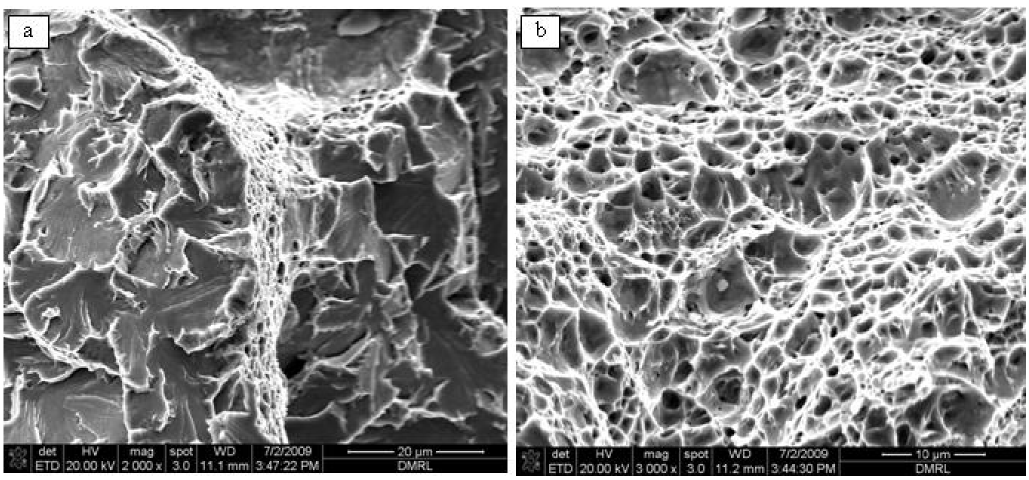


**Fig. 20: Fractographs of impact test specimens of (a) interface and (b) base plate.**

## 4.0 CONCLUSIONS

- Explosive clad joints of HSLA steel + austenitic stainless steel exhibited a bond strength of 491 MPa in as-clad condition and 408 MPa after hot rolling and heat treatment.
- Explosive clad joint of HSLA steel + CP titanium exhibited a bond strength of 356 MPa in as-clad condition as CP titanium possesses lower strength (337 MPa) compared to that of AISI 347 grade austenitic stainless steels (515 Mpa).
- The weld overlay clad joint exhibited a bond strength of 488 MPa which is almost equal to that of explosive clad joints in as-clad condition.
- The clad joints of austenitic stainless steel and CP titanium, with the base plate in heat treated condition, exhibited good formability when three point bend tests were conducted upto 110º and 139º respectively.
- An attempt was also made to reduce the cost of production of explosive clad plates by employing hot rolling process for thickness reduction.
- To facilitate evaluating tensile and impact properties of the weld overlay interface, a novel technique of friction welding was employed.
- From the present work it is concluded that the HSLA steel having yield strength >600 MPa can be successfully cladded to austenitic stainless steel of AISI 347 grade by explosive cladding and weld overlaying techniques. It can also be cladded to CP titanium by explosive cladding

process. All the clad joints meet the required bond strength of 350 MPa for the intended application.

## 5.0 FUTURE SCOPE OF WORK

It has already been mentioned in the Introduction that the base material used in the present investigation (HSLA steel: Yield Strength >600 MPa) has been developed by DMRL specifically for repair/fabrication of underwater vessels by the Indian Navy. In the present investigation, detailed structure-property correlations have been established for different cladding materials such as 347 grade austenitic stainless steel and commercial pure titanium as these cladding materials are only presently used by Indian Navy. Detailed corrosion studies and further microstructural investigation by Transmission Electron Microscopy will further contribute to the Science and Technology of the HSLA steel.

In order to further strengthen the Naval Vessels, DMRL has recently developed high strength version of the HSLA steel. Similar studies such as explosive cladding, weld overlay cladding and corrosion on this new steel will be of interest to the Indian Navy.

## REFERENCES

[1] Narayanadas J (2012); Naval materials for Indian defence applications, IIM Metal News-Special Issue on Defence Materials,15, 2, pp. 20-27.

[2] Malakondaiah G, Srinivas M and Balamuralikrishnan R (2012); High performance steels for Indian defence, IIM Metal News-Special Issue on Defence Materials, 15, 2, pp. 28-31.

[3] ASTM E 8, (2004); Standard test methods for tension testing of metallic materials, Annual book of ASTM standards-2004, ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA.

[4] Crossland B and Bahrani BS, (1981); Fundamentals of explosive welding, Source Book on Innovative Welding Processes, ASM, Metals Park, Ohio, pp. 99-115.

[5] Cowan GR, Bergmann OR and Holtzman AH (1971); Metallurgical Transactions, 2A, pp. 3145 -3155.

[6] Mamalis AG, Szalay A, Vaxevanidis NM and Pantelis DI, (1994); Materials Science and Engineering, A188, 267-275.

[7] Nobili A, Masri T and Lafont M C (1999); in Proc Reactive Metals in Corrosive Applications Conference, ATI Wah Chang, Albany, OR, USA, pp. 89-98.

[8] Kacar R and Acarer M, (2003); Microstructure–property relationship in explosively welded duplex stainless steel–steel, Materials Science and Engineering: A, 363, pp. 290-96.

[9] Nobili A (1998); Stainless Steel World, 10, pp. 33-37.

[10] Holtzmann AH and Cowan GR (1965); American Welding Society, Welding Research Council Bulletin, 104, pp.1-40.

[11] Kamachi MU, Ananda Rao B M, Shanmugam K, Natarajan R and Baldev Raj (2003); Corrosion and microstructural aspects of dissimilar joints of titanium and type 304L stainless steel, Journal of Nuclear Materials, 321, pp. 40-48.

[12] Nizamettin Kahraman, Behcet Gulenc and Fehim Findik, (2005); Joining of titanium/stainless steel by explosive welding and effect on interface, Journal of Materials Processing Technology, 169, pp. 127-133.

[13] Song J, Kostka A, Veehmayer M and Raabe D (2011); Hierarchical microstructure of explosive joints: Example of titanium to steel cladding, Materials Science and Engineering: A, 528, pp. 2641-47.

[14] Venkateswara Rao N, Sarma DS, Nagarjuna S and Madhusudhan Reddy G (2009); Influence of hot rolling and heat treatment on structure and properties of HSLA steel explosively clad with austenitic stainless steels', Material Science and Technology, 25, pp. 1387-1396.