Nat. Volatiles & Essent. Oils, 2021; 8(5): 3111-3132

Study on Effect of Repair Welding Process on Clad Inteface of Austenitic Stainless Steel and Structural Steel

[1]Elangovan S, [2]Pratheesh kumar S, [3]Narasimmavinay N, [4]Arumuga sastha M

[1,2,3,4] Department of Production Engineering, PSG College of Technology, Coimbatore, India-614004
Corresponding author email id: elangosurya@gmail.com

Abstract

Stainless steels are the class of material used for various applications involving corrosive environment where damage to the structure take place through different modes of corrosion. Because of the high cost due to its rich alloying element, it is difficult to use this material in bulk quantity for various structural applications. To solve the above problem metal cladding process is employed to clad a layer of stainless steel with backing structural steel plate. As the surface of stainless steel in the clad will be in contact with the corrosive medium, damage will take place on the surface of the material after being put into any application. Thus, repair welding process will be carried out as a part of maintenance to make the structure suitable for further operation and also for prevention of premature failure. Some work has been by carried out by researchers on the effect of multiple number of repair welding process on cladded stainless steel plate. This work deals with study on effect of Tungsten Inert Gas (TIG) repair welding process on the interface of 316L austenitic stainless steel and IS 2062 structural steel plate cladded by explosive bonding technique. Repair welding is carried out on grooves of 1mm, 1.5mm and 2mm height with various input current values. The welded specimen is evaluated for any debonding at the interface using Ultrasonic Testing and the shear strength of the material is found using shear testing method. Also, the correlation of mechanical property and microstructure is carried out to understand the complete effect of repair welding process on the cladded interface and the threshold factors for repair welding is established.

***Keywords :** Welding; Austenitic Stainless Steel; Structural Steel; Clading; Repair*

I. INTRODUCTION

Stainless steel is a class of material with the presence of wide range of alloying elements contributing to its high strength and excellent corrosion properties. These steels are in high demand for applications predominantly requiring very high resistance to various types of corrosion during its lifetime such as in heat exchangers, boilers, pressure vessels, ship building automotive, chemical and rail coach manufacturing [1]. Austenitic stainless steels are a class of these Corrosion Resistant Alloys (CRAs) exhibiting excellent resistance to corrosion on almost all kinds of environment. These materials are known for its high creep, stress to rupture and tensile strength at elevated temperatures but it can be subjected to pitting and crevice corrosion in warm chloride environments and stress corrosion cracking above temperature of 600C. But the major disadvantage for usage of stainless steel material is its high cost due to presence of various alloying elements in its composition. For this purpose metal cladding process has been developed to produce a layer of CRA on one or both sides of a backing plate. This method allows achieving both the required strength and corrosion resistance for usage of structures in corrosive environment. Explosive cladding is used in this work to clad 316L austenitic stainless steel to IS 2062 structural steel. This method is used because of its capability to clad a wide range of materials more efficiently by forming a metallurgically sound bond between the flyer and the backing plate. This combination of 316L- IS 2062 clad plate can be used in a way that corrosive medium will be in contact with Stainless steel surface while the backing steel provides the required structural property for the clad plate. During service this stainless-steel clad material will undergo wear due to various types of corrosion. Thus the material has to be repaired properly for further use in such environments so that premature catastrophic failure can be prevented. Welding is considered as a widely acceptable repair process for filling the damaged portion with suitable kind of material for its proper functioning. In particular Tungsten Inert Gas (TIG) welding is preferred over other welding processes for stainless steel because of their high controllability, superior mechanical and corrosive properties [1]. Since welding involves providing a large amount of heat as input to the material, the base properties of the material tend to get affected. For instance, in this combination of clad steel, austenitic stainless steel has a linear thermal coefficient of expansion about 1.5 times than that of mild steel. Thus upon repair welding process, the stainless steel clad layer tries to expand more when compared with that of backing steel thereby creating a disturbance in the interface. Proper welding parameters have to be employed to reduce the effect of repair process on the clad interface. This work involves study on effect of TIG welding repair process on Cladded 316L stainless steel and IS 2062 structural steel interface. The effect of current and heat input on the repair welding of material is studied and evaluation of bond through Ultrasonic testing, shear testing and microstructure is carried out.

Stainless steel is used in various applications for its excellent resistance to corrosion because of the presence of high chromium content in its composition. The cladded combination of stainless steel with backing structural steel can be used in applications demanding both mechanical and corrosive properties such as ship hulls, boilers, heat exchangers etc to reduce the cost due to high expenses involved in using stainless steel structures. The exposure of this material to harsh environment like chlorides for a long time will result in corrosion on stainless steel surface. Thus repair welding is essential to make the structure suitable for further operation. Because of high heat input in repair welding process, changes in microstructural and mechanical properties occur due to the disturbance in clad interface. This work attempts to study the behavior of interface of an Austenitic Stainless Steel (316L) and Structural Steel (IS 2062) clad plate when subjected to a repair welding process.

The goals of this experiment are to use an explosive welding technique to clad AISI 316L Austenitic stainless steel and IS 2062 structural steel. Ultrasonic examination of the claded plate to look for debonding at the clad contact. To select the welding settings to be utilised for experiments and to perform TIG welding on the grooves machined on the weld coupon. Destructive and non-destructive testing, as well as microstructure studies are used to investigate the weld samples to create a link between the amount of heat applied and the strength of the interface connection. In order to achieve the objective of this research literature reviews carried out are summarised as follows. Jiang et al. [2] attempted to study the effect of multiple weld repairs on Q345R and 06Cr19Ni10 austenitic stainless steel-cladplate by means of TIG welding process. A martensitic diffusion layer is reported to be observed due to diffusion of elements like C, Cr, Ni and Fe. Also, the hardness of the diffusion layer is reported to be increased due to increased number of weld repairs and void formation is seen in third and fourth repair welding process. From the analysis, it is proposed that the clad plate should not be repaired more than two times. Kacar and Acarer [3] investigated the properties of explosively cladded 316L stainless steel DIN-P355GH grade vessel steel plate. The microhardness, tensile shear strength and impact toughness of the clad plate was found to be significantly higher than acceptable value. It was thus concluded that 316L stainless steel can be explosively cladded to ferritic base plate. AghaAli et al. [4] studied the effect of multiple repair welds using SMAW on 316L austenitic stainless steel. It was found that the heat input provided during repeated repair welding reduces the amount of ferrite content in the microstructure resulting in reduction of hardness in Heat Affected Zone (HAZ). Tensile properties of the material do not get affected much whereas the impact toughness tends to drop considerably on increasing the number of weld repairs. Thus, it has been proposed that in chloride environment the number of weld repairs cannot exceed two beyond which pitting corrosion of material takes place. Gurudev Singh and Aman Bansal [5] attempted to optimize the Tungsten Inert Gas (TIG) welding process parameters for 316 Austenitic Stainless Steel. Welding current, voltage and gas flow rate were evaluated against properties such as tensile strength, impact force and hardness. An L9 orthogonal array was used to design the experiments with Argon as shielding gas and an optimal parameter combination was found as: Current - 135 A, Voltage - 35 V, Gas flow rate – 10 litres/minute. Ping Zhu et al. [6] investigated on microstructure and pitting corrosion behavior on TIG welded 316L austenitic stainless-steel joint with 316L filler wire. It was found that Weld zone (WZ) exhibited a duplex structure whereas base metal and HAZ represent a fully austenitic structure. From the immersion test in 6% $FeCl_3$ solution, it was noted that weld metal do not undergo obvious corrosion and the pitting potential of HAZ was much lower than that of WZ and base metal. Halil İbrahim Kurt and Ramazan Samur [7] conducted a study on evaluating the microstructure, tensile strength and hardness on 316L stainless steel jointed by TIG welding process with 308 filler wire. The hardness value was found to be increased in the weld zone with the carbide precipitates and was higher than HAZ. Also, from the fracture analysis it was reported that the fracture observed to have originated from a crack in HAZ was ductile in nature. Bharath et al. [8] tried to optimize the TIG welded joint characteristics of 316 Stainless steel using Taguchi technique. For a sample of 3mm thickness, L27 Orthogonal Array was used to optimize five factors with each factor being kept at three different levels. From the Analysis of Variance (ANOVA) it has been reported that the current (96.75%) has highest influence on tensile strength and weld speed (46.51%) has most influence on bend strength of material. Also, it was found that root gap has small influence on both tensile and bends strength. Anawa et al. [9] investigated the weldability of 316 austenitic stainless steel using automated Tungsten Inert Gas (TIG) process with various set of parameters. The effect of welding current and gas flow rate on tensile and impact strength of material was considered. From the work it was concluded that the current has direct effect on impact strength and inverse effect on tensile strength of material. Also, the gas flow rate has a direct effect on both tensile and impact strength of material. Kunjanpaa [10] investigated on various defects rising from TIG welding of austenitic stainless-steel sheet and the effect of welding parameters on such formation. Various kinds of defects such as cracks, ripples, undercuts etc were seen due to welding process. It was found that increasing the value of current increases the number and size of defects. Also, low or high weld speed results in formation of defects such as ripples, cavities etc. Defects like undercuts are found to be formed due to pressure of arc in the melt flow of the weld. Zina Dhib et al. [11] worked on studying the effect of welding process on microstructural and mechanical properties of hot roll bonded stainless steel-clad plate. The material combination used in this work is ASTM A283 low carbon steel cladded with 316 austenitic stainless steel. It was found that the hardness of welded clad plates was higher than parent material due to deformation hardening in cladding process. The tensile strength of the material was found to be satisfactory along with no signs of fracture from bend test. The impact toughness of clad plate was found to be higher than that of base metal due to high toughness of stainless-steel material.

II.MATERIALS AND METHODS

Based on the experimental objectives the following methodology is adopted to carry out this work. The methodology flow chart is shown in Fig. 1.

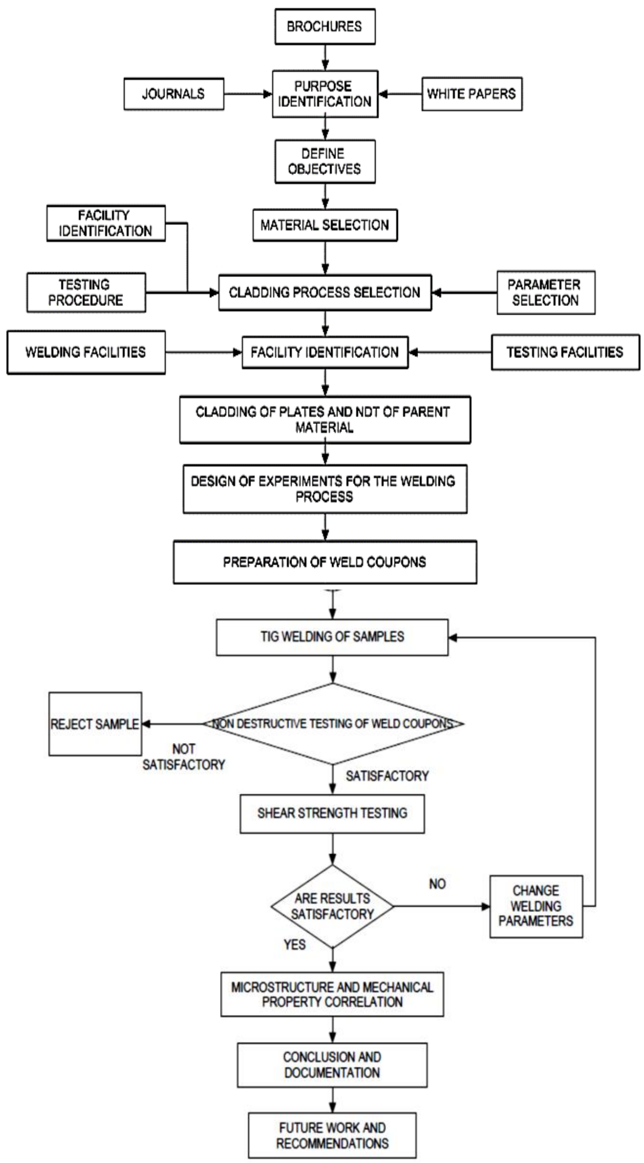


Fig. 1 Methodology

A. Metal Cladding Process

Cladding is a process of joining two dissimilar materials in order to obtain combined properties for several demanding applications such as shipbuilding, pressure vessels, heat exchangers etc. Cladding of materials can be obtained through hot roll bonding, explosive cladding and weld overlay process. In this work, a clad combination of 316L austenitic stainless steel (3mm thick) and IS 2062 (12mm) structural steel is obtained by means of explosion cladding process. This type of cladded combination of stainless steel and structural steel is used in applications requiring a combination of both strength and corrosion resistance. Explosion cladding or welding or bonding process is used because of its ability to clad a wide variety of material combination. It involves the formation of metallurgically bonded interface due to a controlled progressive detonation of the clad layer by means of explosives on to a backing substrate. The wavy interface formed between the two materials due to impact created from high velocities in the range of 250 to 500 m/s [12] is responsible for its high bond strength. Also, the removal of oxides present between the material interface produces a highly clean bond. The interface produced through this process is stronger enough to be used in applications requiring corrosive and structural properties and the failure usually takes place in the weaker of two metals rather than the bond interface. The schematic of explosion cladding process is shown in the Fig. 2 [13].

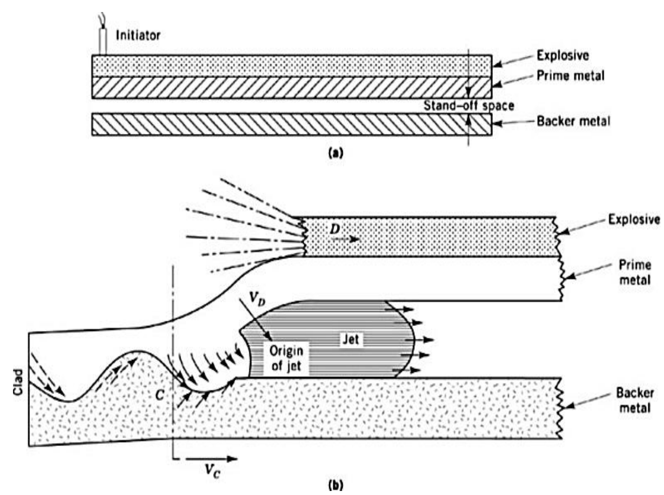


Fig. 2 Explosion cladding process [13]

B. Parent Material Cladding

The material used in this work is 316L austenitic stainless steel and IS 2062 structural steel. The chemical compositions of material used in this work are shown in Table 1 and 2.

Table 1 316L austenitic stainless-steel composition

Material	C	Cr	Ni	Mo	Si	Fe
316L	0.02	17	11.9	2.5	1	Remaining

Table 2 IS 2062 structural steel material composition

Material	C	Mn	P	S	Si	Fe
IS 2062	0.23	1.5	0.045	0.045	0.40	Remaining

Cladding of metals was performed using explosive welding setup with following parameters.
1.Plate Dimension (mm) : 310 x 320 x 12 (IS 2062)
: 310 x 320 x 3 (316L)
2.Standoff distance (mm) : 8
3.Explosive layer (mm) : 20
After explosive cladding the material was stress relieved at 610˚C.

Parent metal used in this work (i.e) clad plate is subjected to welding procedure. It is important to examine the parent metal before welding process to ascertain that the considered material will meet the requirements for an application. These results will help the design engineer to select a particular material for a specific application considering the factor of safety. This testing is important in welding to create joints that are stronger than parent metal. The comparative studies are made in the subsequent chapters.

Ultrasonic testing was carried out on these plates to determine the condition of the clad interface before subjecting it to a welding process. A flat bottom hole of 3mm diameter is drilled on the stainless steel side for a depth of 3mm as per ASME BPVC Section:V Article:4 [14] at a distance of 25.4mm from the edges and the plate was preserved by applying oil to avoid rusting of carbon steel. The pulse echo method of testing was followed and a Trans-receiver probe was used for the same. The probe was calibrated against a V2 block (MS block 25mm thick). The testing was carried out to determine the following:

1.The clad interface position from the carbon steel side.
2.To observe any debonding in the clad interface.
3.To find any other defects in the parent material.

The following were the results obtained from ultrasonic testing of the plate.

1.The clad interface cannot be distinguished as the velocity of propagation is not largely varied in the two materials
2.The plate is completely integral i.e., there are no instances of debonding in the clad interface as found in Fig. 3.

Fig. 3 Instance of artificial debonding

3.The plate has a defect a distance of 75mm from the scanning side which is causing a complete loss of backwall. The defect is a line defect of length 13mm, the exact orientation of the defect has to be found by radiography testing only. The instance of backwall loss is shown in Fig. 4.

Fig. 4 Instance of backwall loss due to subsurface defect

III.EXPERIMENTAL WORK AND TESTING

The experimental study aims to develop a relationship between the effect of heat input in repair welding on the clad interface for a given groove depth with the help of an experimental procedure. The details of each stage of sample preparation and experimental design are described in the following section.

A. Sample Preparation

The clad steel plates of dimension 310mm x 320mm each was procured for experimental purpose. To carry out welding and subsequent tests, weld coupons of dimension 90mm x 50mm were required. A cutting scheme was planned to incorporate the cutting losses and the plate was cut into small coupons using plasma cutting as shown in Fig. 5 with the parameter setting as shown in Table 3.

Table 3 Plasma cutting parameter

Parameters	Values
Current	125 A
Travel speed	10mm/sec

The cutting was started from the stainless-steel side because it was harder than the carbon steel. The cut plates had a slight taper because of improper plate clamping and the built-up edge on the carbon steel side was removed by subsequent machining as shown in Fig. 6.

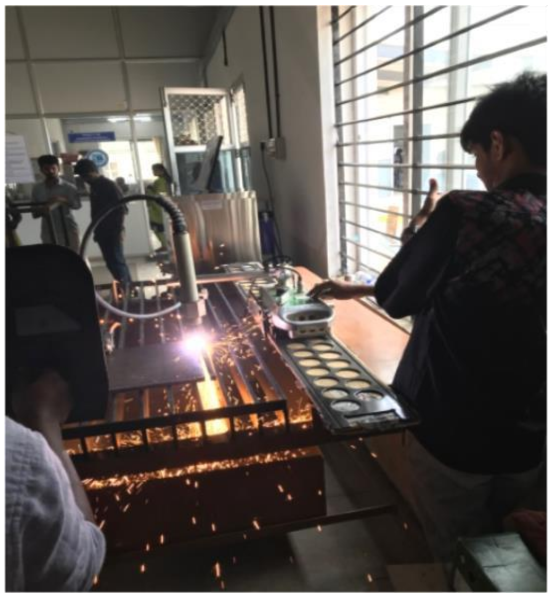


Fig. 5 Plasma cutting machine

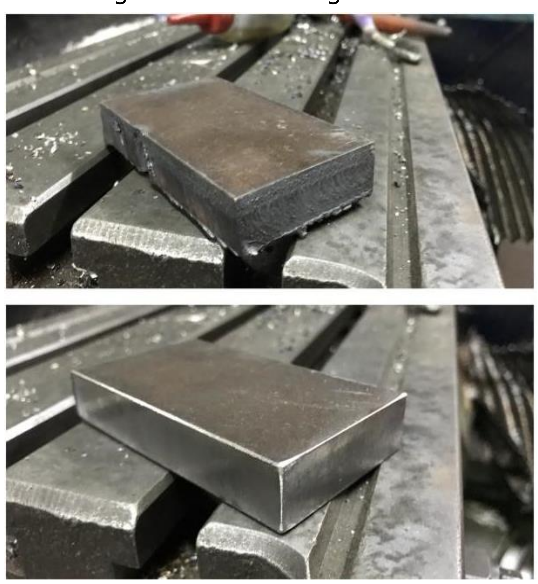


Fig. 6 Weld coupons before and after edge preparation

Repair welding is usually carried out on the surface affected by corrosion. To understand the effects of repair process, grooves were machined on the stainless-steel side for different depths using end milling process. The specimen with groove preparation is shown in Fig.7.

Fig. 7 Grooves machined using end mill cutter

B. Experimental Design

The repair welding process was conducted by creating a groove of 50 mm x 3 mm (L x W) on the sample of dimension 90 mm x 50 mm x 15 mm. The groove depth is varied with different dimensions of 1 mm, 1.5 mm and 2 mm. Welding process was carried out with 309L filler material with a wire diameter of 0.8 mm. The parameters and their values are shown in Table 4.

Table 4 Experimental design for repair welding process

Sample	Groove Depth(mm)	Current(A)	Heat Input (KJ/mm)
A1,A2	1	150	5.0
A3,A4	1	170	6.5
A5,A6	1	190	8.1
B1,B2	1.5	150	5.0
B3,B4	1.5	170	6.5
B5,B6	1.5	190	8.1
C1,C2	2	150	5.0
C3,C4	2	170	6.5
C5,C6	2	190	8.1

C. TIG Welding

A Gantry type automated Tungsten Inert Gas Welding was used to repair the coupons as shown in Fig. 8. The plates were clamped using C clamp and aligned perfectly to the direction of nozzle movement. The welding parameters are shown in Table 5 and the welding setup, camera vision and welded specimen are shown in Fig. 9, 10 and 11 respectively.

Table 5 Welding parameter setting

Welding Parameter	Setting value
Welding current	150, 170, 190 A
Welding speed	80 mm/min
Cold wire feed	120, 130 mm/min
Arc length	4 mm
Welding gas	98% Ar and 2% CO_2
Gas flow rate	25 lpm
Filler wire	309 L (0.8 mm diameter)

Fig. 8 Gantry type welding machine

Fig.9 Experimental setup for welding

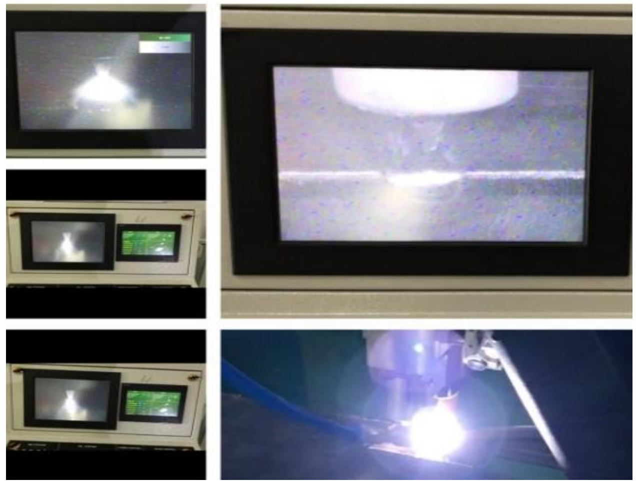


Fig. 10 TIG welding camera vision

Fig. 11 Welded coupon

D. Non-destructive Testing

The welded coupons were subjected to Non-Destructive Testing to examine the quality of the weld and interface. The coupons were visually inspected first and then followed by ultrasonic testing.

i. Visual Inspection

Weld coupons were visually inspected to identify the defects. All the 18 samples were inspected and some of the common defects found on the welded samples are listed below.

1.Side Wall Lack of Fusion (SWLOF) - This is a condition where the groove's side wall does not melt during welding. The possible reasons may be the faster welding speed or slow wire feed rate.

2.Under fill – This is a condition where the groove is not completely filled. A low wire feed rate or poor alignment of the weld nozzle to the groove may cause this type of problem.

3.Under cut - This is a condition where the parent material melts but does not fuse with the filler material. A low current setting is the possible reason for occurrence of this kind of defect in the weld zone.

4.Tungsten inclusion - Tungsten gets added to the weld pool due to improper dressing of the electrode.

ii. Ultrasonic Testing

Ultrasonic testing of the weld coupons was carried out using a 90° Trans Receiver (T/R) probe (longitudinal wave) and a 45° Trans receiver probe (shear wave). The specification of probe setting for both 90° and 45° probe is shown in Table 6 and 7 respectively.

Table 6 Specification for 90° T/R Probe setting

Parameter	Setting value
Ultrasound velocity	5930 m/s
Probe delay	9.960 µs
Pulser	Spike
Receiving	RF Mode
Range	20 mm
Gate details	Level: 7 % FSHLogic: Negative
Detecting mode	Edge - high peak (amplitude)
Gain	59.7 dB
Standard	V2 block (MS block 25mm thick)

Table 7 Specification for 45° T/R Probe setting

Parameter	Setting value
Receiving	Dual mode
Pulser	Square
Gate level	20 % FSH
Gain	40.4 dB
Standard	1.5 mm side drill hole of V2 block taken from 8 mm and 20 mm depth

Representation of the reference faces A and B for ultrasonic testing are indicated in Fig. 12 and faces C and D represents the exact opposite side of faces A and B respectively.

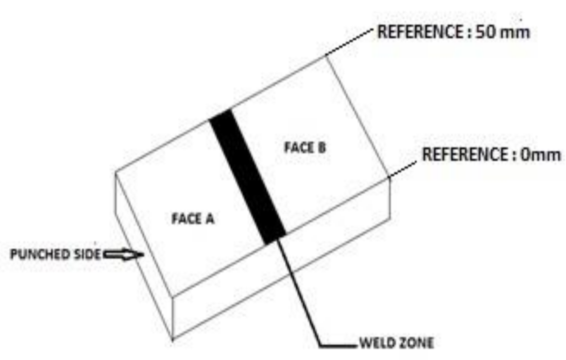


Fig. 12 Face representation for ultrasonic testing

E. Destructive Testing

This is a type of destructive testing where the load is applied on the material parallel to the bond interface and the failure occurs along the interface direction. Shear test was carried out as per ASTM A264 standard to determine the tensile shear strength of the clad plate material [15]. In this testing, sample dimensions of 64.5mm x 25.4mm x 15mm were used with the clad metal width being 4.5mm. As per standard the criterion for evaluation is that the minimum required shear strength of the clad plate should be 140 MPa. The specimen dimension and the loading setup are shown in Fig. 13 [14].

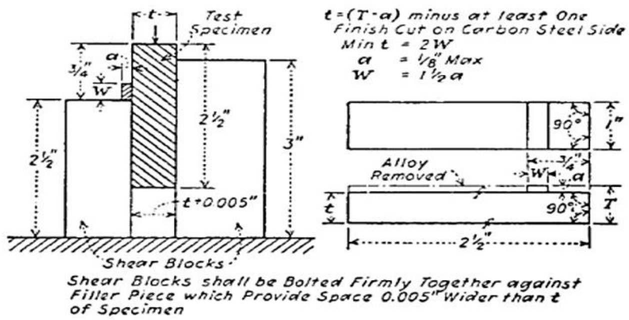


Fig. 13 Shear test specimen in accordance with ASTM A264 [14]

A fixture is designed and fabricated to carry out the shear tests of the clad specimen as per ASTM A264 standards. The fixture setup used for testing is shown in Fig. 14.

Fig. 14 Setup for Shear testing

***F.** Microstructural Sample Preparation*

The samples for microscopy were cut using band saw machine. The length of specimen was approximated to blackened area around the weld. The samples cut had lay pattern of the band saw which was removed using a hand grinder. The samples were then polished using emery sheets of grades 180 to 2000 to obtain a unidirectionally polished surface. Disk polishing was carried out with alumina paste to attain mirror like finish. The samples after polishing were etched using Nital for 5 sec to expose the microstructure of carbon steel and then etched with Aquaregia to expose the microstructure of austenitic stainless steel. The microstructures of the samples are photographed under an optical microscope with a fixed magnification of 200X to draw a comparative study between the variables and their effect on clad interface [15].

IV. RESULTS AND DISCUSSION

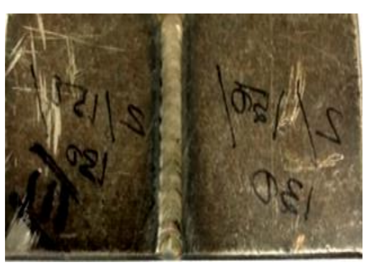
A. Non-Destructive Testing Results

The results observed from the examination of welded specimen are shown in Table 8.

Table 8 Non-Destructive Test Results

Spe. ID	**Weld coupon**	**NDT Indications**	**Acceptance**
A1		1. Under fill - 20 to 46 mm at Face A 2. SWLOF - 36 to 39 mm at Face A	Visual rejection
A2		90° Probe: 1. Back wall shift up to 13.97 mm detected for full length 45° Probe: 1. Minute SWLOF detected	Accepted
A3		90° Probe: 1. Non recordable deviation noted from 22 - 30 mm 45° Probe: Non recordable deviation : 17% Full Screen Height (FSH) from 16 - 18 mm	Accepted

A4		1. Intermittent weld deposition throughout the weld 2. SWLOF 8 - 45 mm at Face A	Visual rejection
A5		1. Under fill 15 - 17 mm at Face A 2. Point defect at 21 mm 3. SWLOF 27 - 30 mm and 35 - 40 mm at Face A	Visual rejection
A6		90° Probe: 1. Back wall shift up to 14.17 mm detected from 45 - 49 mm 45° Probe: 1.Non recordable indication from 25 - 40 mm	Accepted
B1		1. SWLOF from 19 - 24 mm at Face B 2. Under fill from 5 - 40 mm at Face B	Visual rejection
B2		90° Probe: 1. Back wall shift up to 14.45 mm for entire weld length 45° Probe: 1. All indication below 40% FSH (recordable but not significant)	Accepted
B3		90° Probe: 1. Back wall shift up to 13.36 mm at 27 mm 2. Back wall shift up to 14.4 mm from 0 - 25 mm 45° Probe:	Accepted

		1. Point indication at 17 mm	
B4		1. SWLOF from 12 - 15 mm, 18 - 31 mm and 36 - 42 mm at Face A	Visual rejection
B5		90° Probe: 1. No significant defect 45° Probe: 1. Pointed indication at 34 mm (non recordable) at Face D	Accepted
B6		1. Slight under fill from 10 - 47 mm	Visual rejection
C1		1. Intermittent weld deposition throughout the weld 2. Under cut at 14 mm and 21 mm at Face A 3. SWLOF at 35 mm at Face A	Visual rejection
C2		90° Probe: 1. Back wall shift 12.8 mm from 0 - 5 mm and 23 mm at Face B 45° Probe: 1. Pointed indication (non recordable) at 20 mm	Accepted

C3		1. Blow hole at 18 mm and 30 mm 2. Under fill from 15 - 20 mm at Face B	Visual rejection
C4		90° Probe: 1. Back wall shift of 13.46 - 13.6 mm from 25 - 49 mm 45° Probe: 1. Internal defect (continuous) from 8 to 18 mm @ Face D	Accepted
C5		90° Probe: 1. No significant defect 45° Probe: 1. Internal defect location at 34 mm (non recordable)	Accepted
C6		1. Blow holes at 5 mm and 15 mm	Visual rejection

From the above observation it can be seen that defects such as Side Wall Lack of Fusion (SWLOF) and Underfill are mostly responsible for rejection of welded specimen. The improper values of welding speed and wire feed rate used might be the possible reasons for indication of such defects [17]. A total of nine samples were found to satisfy the requirements of Ultrasonic Testing and are subjected destructive testing for evaluating the interface shear strength.

B. Shear testing results

i. Parent Material Shear Testing

ii. The explosively cladded 316L austenitic stainless steel and IS 2062 structural steel plate is subjected to shear test to determine the interface bond shear strength. This shear strength is *compared with a repair welded clad plate specimen. The interface bond strength obtained from the test is shown in the Table 9.*

Table 9 Parent material shear strength

Maximum Shear Load (N)	**Shear Strength (MPa)**
55000	470.2

iii. Weld Specimen Testing

Testing was carried out on nine samples which satisfied the required criteria from ultrasonic testing. These shear strength values were used in comparison to study the effect of repair welding on the clad interface. The test specimen used is shown in Fig. 15. The results obtained from the test are shown in Table 10. It was observed from the table that specimen A2 has the maximum shear load of 70.8 kN.

Fig. 16 Specimen before and after testing

Table 10 Shear strength of tested weld Specimen

Specimen ID	**Maximum Shear Load (kN)**	**Shear Strength (MPa)**
A2	70.8	550
A3	66	512.5
A6	57	440.85
B2	66.480	521.45
B3	62.4	504.81
B5	54.680	423.49
C2	63.7	509.85
C4	58.48	452.559
C5	60.140	486.313

C. Effect of Heat Input on Bond Strength

The shear test results were plotted to determine the effect of welding heat input on the interface bond strength for a repair groove depth. The results are shown in Fig. 16.

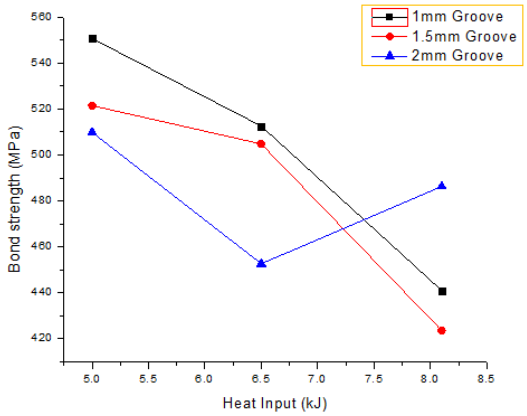
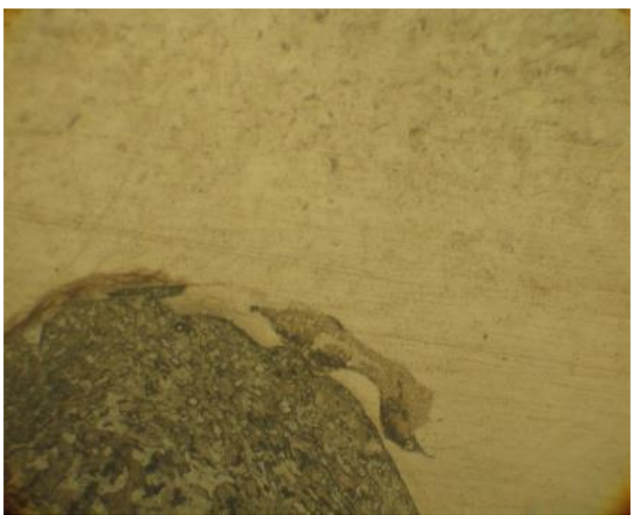


Fig. 16 Heat input vs Bond strength Relationship

The plot clearly shows that the increase in value of heat input results in decrease in the interface bond shear strength. The primary reason for the drop in interface shear strength is that as the heat input increases the effect of welding reaches the interface i.e. remelting of the clad interface takes place resulting in the formation of coarse grains at the wavy interface. As the grains get coarse, propagation of cracks in easier thus causing earlier failure in the product [18]. The progressive coarsening of the interface grains is shown in Fig. 17.



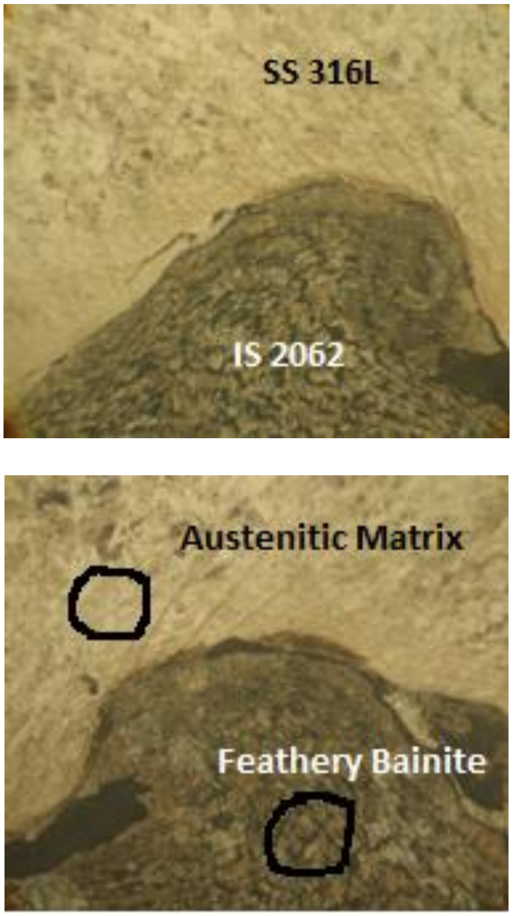


Fig. 17 Progressive coarsening of clad interface

The Fig. 17 also clearly shows the metallurgical aspects of the material. The stainless steel is austenitic based while the low carbon steel is characterized by formation of feathery bainite on the ferrite matrix.

The weld interface is shown in Fig. 18. The weld zone is clearly distinguished from the parent material by the dendritic structures, followed by the coarse grained heat affected zone and unaffected parent material with grains.

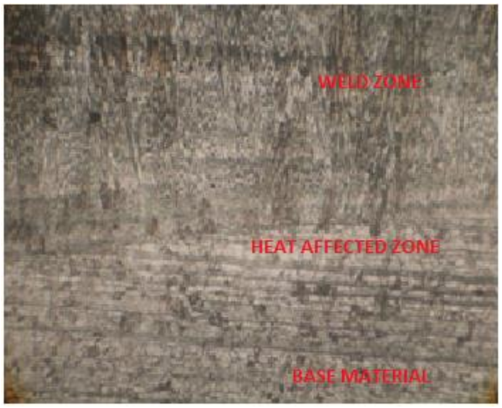


Fig. 18 Various Zones at Weld interface

D. Effect of Groove Depth on Bond Strength

The shear test results were plotted to determine the effect of repair groove depth on for a provided heat input on interface bond shear strength. The results are shown in Fig. 19.

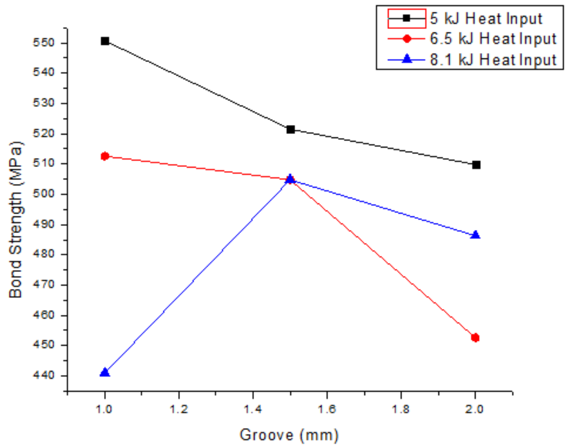
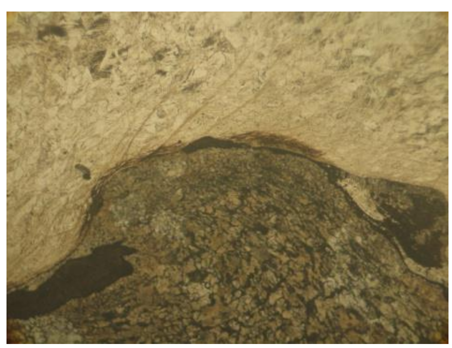


Fig. 19 Groove depth vs Bond strength Relationship

The above plot clearly shows a drop in bond strength as the groove depth increases for a fixed heat input. It can be seen that as the depth of groove increases, the base of groove comes in close proximity with the clad interface. Thus a small heat input provided results in remelting and coarsening of grain structure at the clad interface [19] [20]. The microstructural images supporting the above claim are shown in Fig. 20.



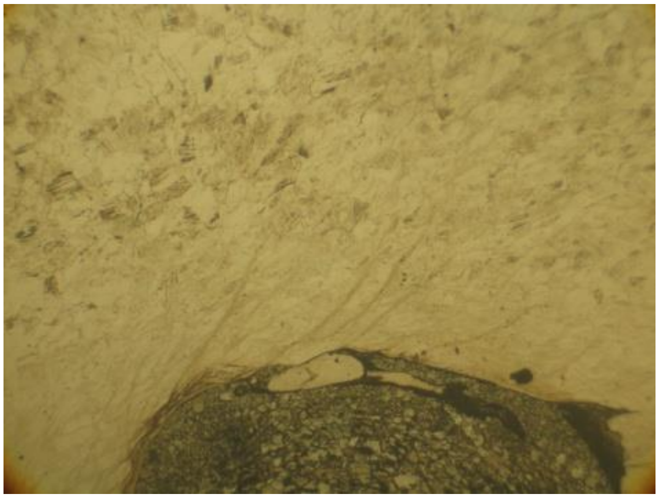


Fig. 20 Clad interface changes for a given heat input

V. CONCLUSION

1. The clad interface is always wavy in nature characterized by fine grains at the interface.
2. The damage of the clad interface on repair welding is inevitable even for the smallest of the damage on the stainless-steel surface.
3. The shear strength of the repair welded clad plate gets reduced below the value of parent clad material for higher heat input irrespective of groove depth. Thus, heat input is an important criterion for a proper repair welding process.
4. The effects observed in 75% damage of the plate is similar to that of the 50% damage except that the grain size has been increased significantly resulting in reduced interface shear strength. Thus, it is clear that the threshold of repair welding is well below 50% damage of the plate.

REFERENCE

1. D. Devakumar, D.B Jebaraj, “Research on Gas Tungsten Arc Welding of Stainless steel – An overview”, International journal of Scientific & Engineering Research, Volume 5, Issue 1, 2014.
2. Wenchun Jiang, Yun Luo, Guodong Zhang, Wanchuck Woo, S.T. Tu, “Experimental to study the effect of multiple weld-repairs on microstructure, hardness and residual stress for a stainless steel clad plate”, Materials and Design 51 (2013), pp. 1052-1059.
3. Ramazan Kacar, Mustafa Acarer, “An investigation on the explosive cladding of 316L stainless steel-din-P355GH steel”, Journal of Materials Processing Technology 152 (2004), pp. 91-96.
4. Iman AghaAli, Mansour Farzam, Mohammad Ali Golozar, Iman Danaee, “The effect of repeated repair welding on mechanical and corrosion properties of stainless steel 316L”, Materials and Design 54 (2014), pp. 331-341.
5. Gurudev Singh, Aman Bansal, “Parametric optimization of TIG welding on stainless steel 316”, An International journal of engineering sciences, 2016.

6. Ping Zhu, Xinyuan Cao, Wei Wang, Jiancang Zhao, Yonghao Lu, Tetsuo Shoji, "An investigation on microstructure and pitting corrosion behaviour of 316L stainless steel weld joint", Journal of Material Research, 2017.
7. Halil Ibrahim Kurt, Ramazan Samur, "Study on Microstructure, Tensile Test and Hardness 316 Stainless steel jointed by TIG welding", International Journal of Advances in Engineering, Science and Technology, Volume 3 No. 1, 2013.
8. P. Bharath, V. G. Sridhar, M. Senthil Kumar, "Optimization of 316 Stainless Steel Weld Joint Characteristics using Taguchi Technique", 12th Global Congress on Manufacturing and Management, GCMM 2014.
9. E.M. Anawa, M.F. Bograrah, S.B. Salem, "Investigation of the Weldability of Austenitic Stainless steel", Materials Sciences and Applications, 2014, pp. 639-648.
10. V.P. Kunjanpaa, "Weld defects in austenitic stainless steel sheets – Effect of Welding Parameters", Welding Research Supplement, 1983.
11. Zina Dhib, Noamen Guermazi, Ahmed Ktari, Monique Gasperini, Nader Haddar "Mechanical bonding properties and interfacial morphologies of A283/316 clad composite, Journal of Material Science and Engineering, 2017.
12. John G Banker and Edward G Reineke, "Explosive Welding", ASM Handbook vol.6 Welding, Brazing and Soldering, 1993.
13. Bergmann, "Metallic Coatings Explosively Clad Metals", John Wiley & Sons, 2000.
14. ASME BVPC.V (2017) – Article 4, Ultrasonic examination methods for welds
15. Standard Specification for Stainless Chromium – Nickel Steel – Clad Plate, ASTM A 264 – 03.