Evaluation of Hardness of Bimetallic Weld joint between SA-508Gr3 and SS-304L

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Abstract - *Bimetallic Welds has its importance in the Pressurized Vessels used in Nuclear Power Plants which consists of pressurized water reactors (PWR) and steam generators in Boilers, where metals have to bear high temperature. The main focus of this work is to improve the mechanical properties of weld formed by joining the two dissimilar metals because failure of such metals at weld is very common in power plants and boilers where high temperature start-ups and shut- down are taken very frequently.*

In this work, dissimilar materials carbon steel SA 508 Gr3 and stainless steel type SS304 L was used. Buttering is considered for improving the properties, which is done with stainless steel (Grade-SS309L) and stainless steel (Grade-SS308L) as a filler material. Hardness and impact test were conducted to measure the micro hardness and toughness. The maximum hardness 37.5 and 27.5 were found in the weld joint for buttering and without buttering respectively.

***Key Words*:** Bimetallic Welding, SA-508Gr3, SS-304L, Toughness, Hardness.

1. INTRODUCTION

Dissimilar metal welds composed of low alloy steel, Inconel 82/182weld, and stainless steel were prepared by gas tungsten arc welding and shielded metal arc welding techniques. Microstructures were observed using optical and electron microscopes. Typical dendrite structures were observed in Inconel 82/182 welds. Tensile tests using standard and mini-sized specimens and micro-hardness tests were conducted to measure the variation in strength along the thickness of the weld as well as across the weld. In addition, fracture toughness specimens were taken at the bottom, middle, and top of the welds and tested to evaluate the spatial variation along the thickness. It was found that while the strength is about 50–70MPa greater at the bottom of the weld than at the top of the weld, fracture toughness values at the top of the weld are about 70% greater than those at the bottom of the weld [1].

Residual stresses present in the weld joint are one of the main factors, which cause failures in dissimilar weld joints. A typical dissimilar pipe weld joint, representing a joint used in an Indian Fast Breeder Test Reactor (FBTR) was fabricated between 2.25Cr–1Mo ferritic steel and AISI type316 stainless steel with and without Inconel-82 buttering on the ferritic steel side. Residual stress profiles across these weld joints were determined using the X-ray diffraction (XRD) technique. The Inconel-82 buttering layer employed in the dissimilar weld joint is useful in reducing the residual stresses in the HAZ of the ferritic steel and thus the buttering will be beneficial to avoid/minimize residual stress related failures of dissimilar weld joints [2]. The study of structural changes in laboratory welds of 6Cr-Mo-V 8-3-2 (T25) and X12Cr-Mo-V-Nb 10-1 (P91) steels annealed at temperatures from 600° to 900°C(1112° to 1652°F). Carbon redistribution measurements by the EPMA method were complemented with detailed structural analyses aimed at the phase and chemical compositions of coexisting carbides and carbonitrides. The results of experimental work were compared with thermodynamic and kinetic calculations using the Thermo-Calc and DICTRA software. A very good agreement between the calculations and the experiments was obtained, in particular for the phase composition of individual areas of the weld joints [3].

Power station pipelines and other structural fabrications operating at high temperature are predominantly made of creep-resistant steels. These steels may become martensitic even if the cooling medium was air due to their relatively high Cr, Mo, and V content, which can retard the Bai nitic transformations. These steels must, therefore, be preheated, and filler materials must be carefully selected. In heterogeneous joints, substantial diffusion takes place during high-temperature service conditions. This paper describes the layered formation in the heterogeneous welded joint and reports on the investigation of the consequences of such diffusion. The principal goal of this investigation was to reduce the probability of cracking during service [4].

The welding of 11–12%chromium steels is subject to the traditional concern with ferritic grain growth in the heat-affected zone of ferritic stainless steels. The grain growth could be inhibited if austenite on the ferrite grain boundaries could be stabilized at high temperatures. This article discusses the possibility that diffusion from the weld metal can increase the carbon or nitrogen content of the heat-affected zone, and consequently stabilize grain boundary austenite [5].

Dissimilar metal joints between austenitic stainless steels and carbon steels containing low amounts of carbon are being extensively utilized in many high-temperature applications in energy conversion systems. In steam generating power stations, the parts of boilers that are subjected to lower temperatures as in the primary boiler tubes and heat exchangers are made of ferritic steel for economic reasons. Other parts, such as the final stages of the super heaters and repeaters operating at higher temperatures where increased creep strength and resistance to oxidation are required, are constructed with austenitic stainless steels. Therefore, transition welds are needed between the two classes of materials [6-7].

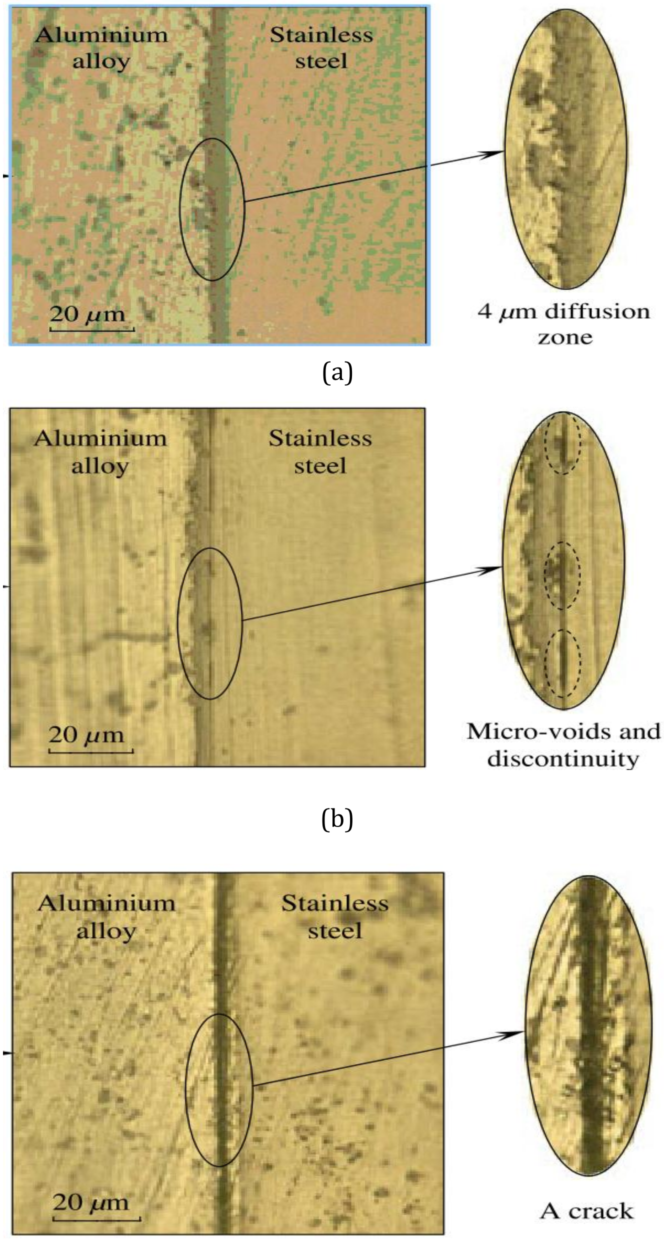


Figure: 1 Optical micrographs of the bimetallic joint interfaces (magnification: 1950x), (a) The best quality joint (T=450^{0}C), (b) The unsatisfactory Joint (T=350^{0}C), (c) The Unsuccessful Joint (T=200^{0}C) [8]

The forge-welding process should be carried out with high temperature, so that the recrystallisation of aluminum alloy can occur, and a high applied pressure is needed for producing a quality joint. The typical optical micrographs of the joint interfaces between AISI 316L stainless steel and 6063 aluminum alloy are given in Fig 1. These two materials were welded completely by forged welding at the process parameters T=450^{0}C provide best quality joint instead of T=350^{0}C and 200^{0}C [8]. There have been several studies on the welding of carbon steels and stainless steels because the failure in bimetallic joints can occur before the components reach their design life [9, 10]. These investigations have shown that large thermal stresses arise in these joints during temperature fluctuations owing to the difference in thermal expansion coefficients [11]. The highest risk zone in the joints is the interfacial region between the weld metal and carbon steel and all of the austenitic-ferritic dissimilar alloy weld failures that have occurred in service [12-14] or in laboratory test programs [15- 16] have been in the ferritic alloy close to the weld. The carbon migration takes place from SA 516 gr. 65 to weld metal when the bimetallic weld samples subjected to thermal loading at temperature 625^{0}C. The ultimate tensile strength and hardness of samples increases by increasing the pre-stress [17-19].Thermal cycling in power plant operation during the numerous startups and shut-downs thus plays a major role in premature service failure of these joints [20-21]. These cyclic stresses superimposed on the residual welding stresses, external loads and internal steam pressures cause the ultimate service failure of the dissimilar joint [22- 25]. At high temperature carbon migration takes place from higher concentration to lower concentration. This carbon migration is also responsible for bimetallic weld join failure [26]. The mechanical properties of welded joint by friction stir welding are largely dependent on the combined effect of both the composition of alloying element and processing parameter [27, 28].

1.1 Circumferential and axial residual stresses of the Bimetallic weld Joint with a buttering layer

Fig. 2 shows the profile of the circumferential residual stresses across the bimetallic weld joint with an Inconel-82 buttering layer. It was found that the circumferential residual stress value varies from 350 MPa tensile at the interface of weld metal and the stainless steel to 200 MPa tensile at the interface of the weld metal and the buttering layer. The circumferential residual stress present in the buttering layer is around160–200 MPa (tensile). The HAZ of the stainless steel has a higher tensile residual stress than that of the HAZ of the ferritic steel.
Fig. 3 shows the profile of the axial residual stresses across the bimetallic weld joint with an Inconel-82 buttering layer. The maximum axial tensile residual stress is at the weld metal with a value around 300 MPa (tensile). The maximum axial compressive residual stress is 260 MPa at the HAZ of the ferritic steel and 230 MPa at the HAZ of the stainless steel [2]

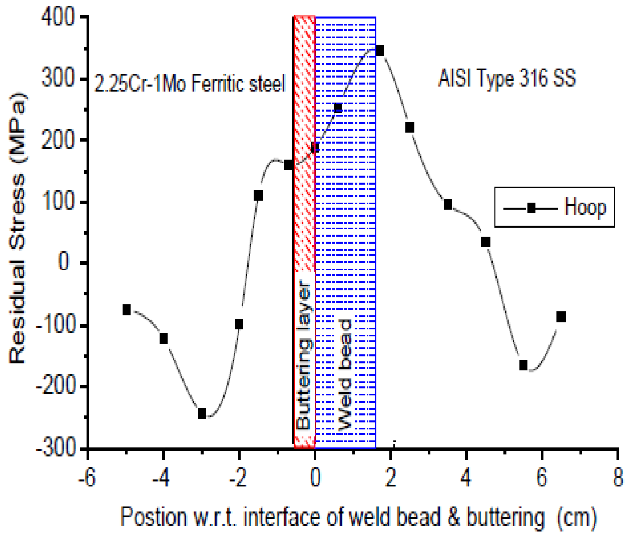


Figure 2:- Circumferential residual stress profile of a bimetallic pipe welded joint with a buttering layer [2]

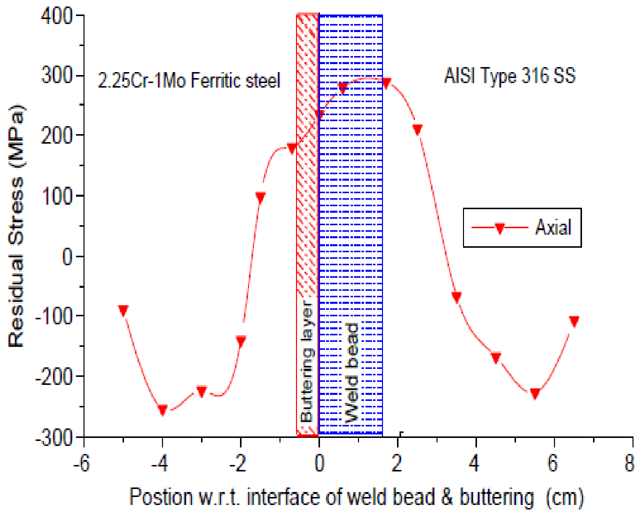


Figure 3:- Axial residual stress profile of a bimetallic pipe welded joint with a buttering layer [2]

1.2 Circumferential and axial residual stresses of the bimetallic weld joint without a buttering layer

Fig. 4 shows the circumferential residual stress profile across the bimetallic welded joint without a buttering layer. The maximum circumferential tensile residual stress is at the middle of the weld metal and the value is around 350 MPa. The maximum circumferential compressive residual stress value in the ferritic steel is 190 MPa and in the stainless steel is about 230 MPa [2].

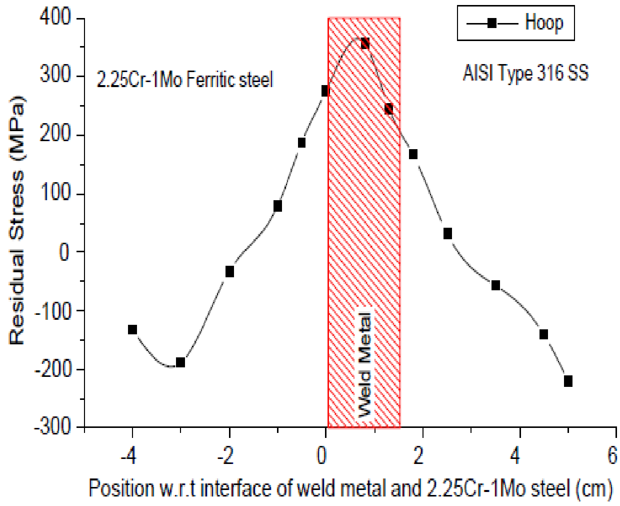


Figure 4:- Circumferential residual stress profile of a bimetallic pipe welded joint without a buttering layer [2]

Fig. 5 shows the axial residual stress profile across the bimetallic welded joint without a buttering layer. The maximum axial tensile residual stress is at the middle of the weld metal and the value is around 300 MPa. The maximum axial compressive residual stress values at the HAZs of the stainless steel and the ferritic steel are around 230 and225 MPa, respectively.

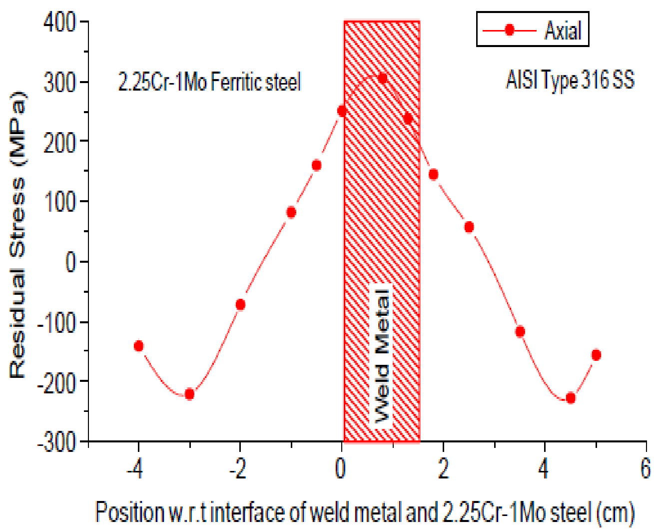


Figure 5:- Axial residual stress profile of a bimetallic pipe welded joint without a buttering layer [2]

1.3 Carbon migration from the ferritic steel

Carbon migration occurs across the weld metal interface from ferritic steel to austenitic stainless steel during elevated temperature exposure. An investigation was carried out involving aging of samples of Alloy 800H/2.25Cr-lMo steel joints, welded with Inconel 82, at 783, 866 and 950 K to various times, and measurement of the carbon concentration profiles using an EPMA[17]. The test data were then used for arriving at a Larson-Miller type equivalency given by

$$P = T(C + \log_{10} t) \quad (1)$$

where P is the equivalency parameter, T is the absolute temperature in Kelvin, C is a constant dependent primarily on the kinetics of carbon migration, and t is the exposure time at the temperature T. Based on these results, it was found that the value of the constant C was 8.4.This is lower compared to a C value of 20, which is often found appropriate to describe creep rupture properties of carbon and low-alloy steels. In similar experiments conducted on Cr-Mo steel/austenitic SS joints welded with Inconel 82, a C value of 15 was found to be appropriate. Evidently, the carbon migration in BMWs depends very much on the chemical compositions of the weld metal and the base metal [26]. The process of carbon migration involves decomposition of carbides in the ferritic steel, followed by diffusion of carbon from the ferritic steel into the weld metal. The driving force is primarily the carbon concentration gradient, or more correctly, the carbon activity gradient between the ferritic steel containing low Cr and the weld metal which is rich in Cr. When carbon diffuses beyond the weld metal/ferritic steel interface, carbide formation and precipitation takes place because of the low solubility and diffusivity of carbon in the weld metal. Based on the width of carburized layers, determined by metallographic etching, a time-temperature relationship similar to that of Larson-Miller equivalency was established.

$$P' = K/T + \log t \quad (2)$$

where P' is the equivalency parameter, K is a material constant determined for each weld joint, T is the absolute temperature, and t is the time of exposure. Equations (1) and (2) were developed using experimental data obtained by EPMA carbon concentration profiles and metallographic measurement of the carbon diffusion layer [29]. From earlier studies, it has become evident that carbon migration in BMWs during service exposure has been regarded as the dominant metallurgical factor responsible for the failure problems. This is reflected by the extensive efforts to understand the kinetics of carbon migration [29, 30].

2. EXPERIMENTAL PROCEDURE

2.1 Base materials

The materials used are carbon steel SA 508 Gr3 that is used in reactor pressure vessel and stainless steel type 304 L that is used in primary boiler tubes. These steels were received in the form of rectangular block

2.2 Buttering and Filler Materials

Buttering was done on SA 508 Gr3 by depositing SS 309L. SS 309L is a highly alloyed austenitic stainless steel used for its excellent oxidation resistance, high temperature strength and creep resistance. The lower nickel content of SS 309L improves resistance to Sulphur attach at high temperatures. It is tough and ductile and can be readily fabricated and machined.

Filler material was used SS 308 L. Weld filler SS 308L has the same composition as type SS 308 except the carbon content has been held to a maximum of 0.30% to reduce the possibility of intergranular carbide precipitation. SS 308L is ideal for welding types 304, 321 and 347 stainless steels. This is a suitable wire for application at cryogenic temperatures.

2.3 Chemical composition

Chemical composition of carbon steel SA 508 Gr3 and stainless steels are given in table 1and 2 respectively.

Table 1:- Chemical composition of SA 508 Gr3 steel

Type of Carbon steel	C	Mn	P	S	Si
SA 508 Gr3	0.19	1.2-1.5	0.006	0.002	0.07-0.1

Table2:- Chemical composition of Stainless steel [11]

Type of Stainless steel	C	Mn	Si	Cr	Ni	P	S
304L (base material)	.03	2	1	18-20	8-12	0.045	0.03
308L (filler material)	.03	2	1	19-21	10-12	0.045	0.03
309 L (buttering material)	.03	2	1	22-24	12- 15	0.045	0.03

2.4 Mechanical and physical properties

Mechanical and physical properties of carbon steel SA 508 Gr3 and stainless steels are given in table 3.

Table 3- Mechanical and physical properties of SS and carbon steel SA 508 Gr3 [11]

Type of steel	Tensile strength (MPa)	Yield strength (MPa)	Elastic modulus (GPa)	Thermal coeff. (10^{-5}m/m°C)	Density (Kg/m^3)
SA 508 Gr3	450–585	240	200	11.7	7.8
304L	480	170	193-200	17.2-18.4	7.8-8.0
308L	618	448-460	190-210	17.2-18.4	7.7-8.03
309L	644	489	190-210	15.0-17.2	7.7-8.03

3. WELDING PROCEDURE

3.1 Gas tungsten arc welding

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, is an arc welding process that uses a non-consumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by a shielding gas (usually an inert gas such as argon), and a filler metal is normally used, though some welds, known as autogenous welds, do not require it. A constant-current welding power supply produces energy which is conducted across the arc through a column of highly ionized gas and metal vapors known as a plasma as shown in fig 6.

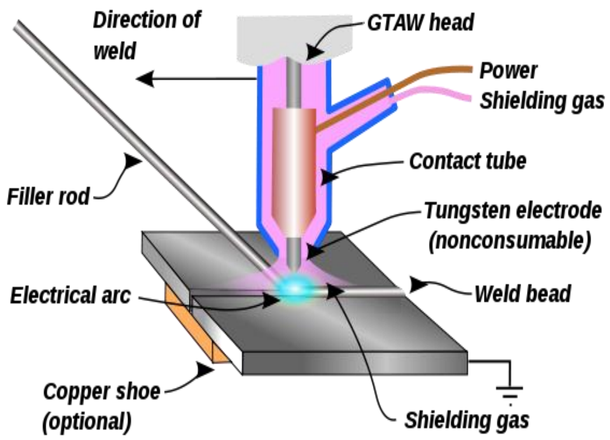


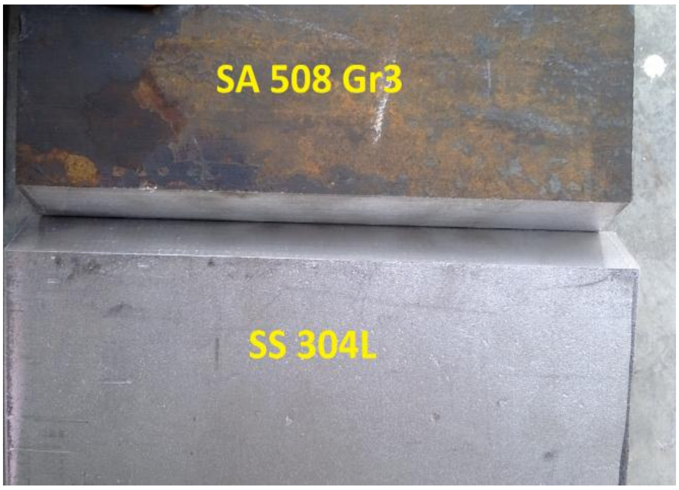
Figure 6: Gas tungsten arc welding

Table 4: Welding Parameters

Type	Current (A)	Voltage (V)	Wire feed (cm/min)	Gas flow rate (liter / minute)
Buttering	190-200	12 - 15	40	10
Welding	230-270	12- 15	40	10

3.2 Sample Preparation

A 25 mm thick plate of SS 304 was welded to a 25 mm thick plate of SA 508 Gr3 by using GTAW process. The plate was shaped to a thickness of 10 mm. The specimen's blanks 150 mm x 20 mm x 10 mm were cut from the welded plate; the weld was in the center of the blank. Total 4 numbers of blanks were obtained from the welded plate. These samples subjected to a Post weld heat treatment for reducing residual stress. The samples before Post weld heat treatment and after Post weld heat treatment are shown in below figures 7-8.

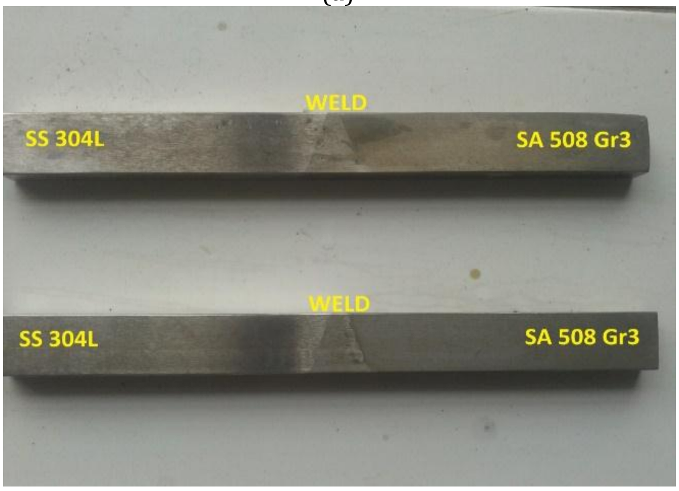


(a)

(b)

Figure 7: (a) plate before welding (200 x 100 x 25 mm), (b) Welded plate (200 x 100 x 25 mm)

(a)



(b)

Figure 8: bimetallic weld samples (150x20x10 mm3) (a) with buttering, (b) without buttering

After that these samples are prepared for tensile test, microstructure and hardness test to find out these properties. For tensile test the flat tensile specimen are and hardness samples are cut from the center contained base metal of both material i.e. carbon steel SA 508 Gr3 and SS 304L and weld metal at the center.

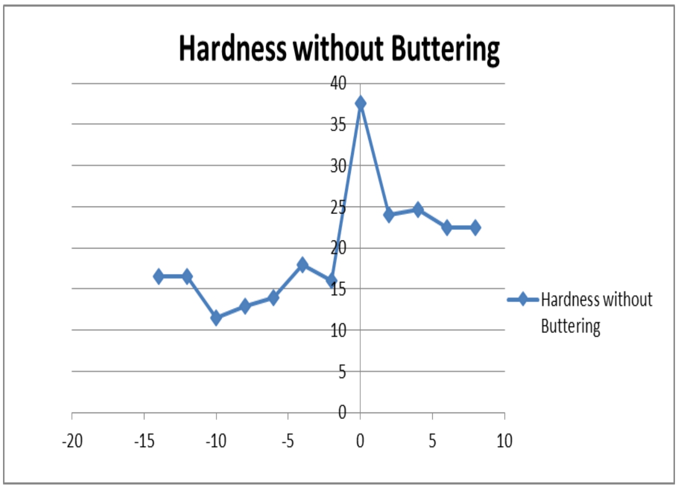
4. RESULT AND DISCUSSION

4.1 Hardness survey

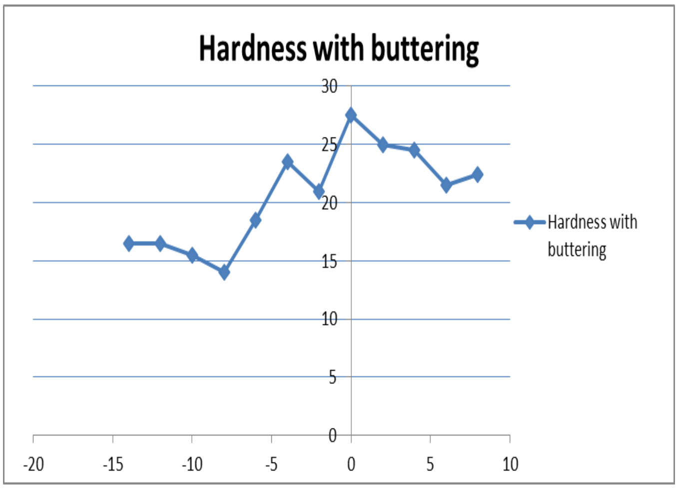
We use ASTM E18 – Standard methods for Rockwell hardness of metallic materials. The hardness distributions across carbon steel base metal, weld metal and SS base metal are shown in table 5.

Table 5: Rockwell hardness result

Position (mm)	Hardness without buttering	Hardness with buttering
-14(SA 508 Gr3)	16.5	16.5
-12	16.5	16.5
-10	11.5	15.5
-8	12.9	14
-6(HAZ)	14	18.5
-4 (HAZ)	18	23.5
-2(interface)	16	21
0 (weld)	37.5	27.5
2 (interface)	24	25
4	24.7	24.5
6	22.5	21.5
8 (SS 304 L)	22.5	22.4



(a)



(b)

Figure 9:- (a) Hardness without buttering, (b) Hardness with buttering

The Rockwell hardness of bimetallic weld samples with buttering and without buttering shown in the following tables 5. In first sample were no buttering was used there is a hardness drop near the SA 508 Gr3 and weld interface because of carbon migration. In carbon migration the carbon migrates from high concentration of carbon to low concentration of carbon, because the concentration of carbon is high as compare to SS 304 L so the carbon migration takes place from SA 508 Gr3 to SS 304 L. This carbon migration can be prevented by applying a layer of 5 to 6 mm thickness of buttering on SA 508 Gr3. The maximum hardness 37.5 and 27.5 were found in the weld joint for buttering and without buttering respectively, whereas minimum hardness were found 16.5 in SA 508Gr3.

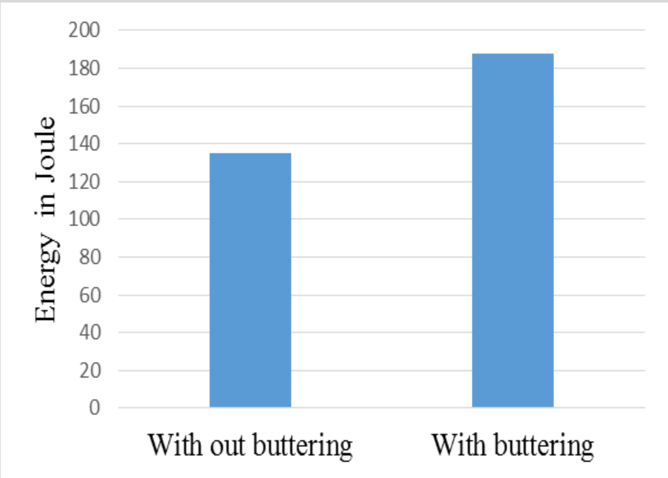
4.2 Charpy Impact test

The Charpy impact test, also known as the Charpy v-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by a material during fracture as shown in table 6.

Figure 10:- Charpy Test Specimen

Table 6: Charpy Test Results

S.No	Dimensions	Energy in joules
With out buttering	55x10x10	135.31
With buttering	55x10x10	187.52



This absorbed energy is a measure of a given material's toughness and acts as a tool to study temperature-dependent ductile-brittle transition. The maximum energy stored in bimetallic welding was 187.52 joules for with buttering, whereas 135.31 joules energy obtained in without buttering.

5. CONCLUSION

In this work, dissimilar materials carbon steel SA 508 Gr3 and stainless steel type SS304 L was used. Buttering is considered for improving the properties, which is done with stainless steel (Grade-SS309L) and stainless steel (Grade-SS308L) as a filler material. The following conclusion can be made.

- To prevent carbon migration the temperature should not be high and also can be prevent by the increasing the thickness of buttering layer on carbon steel.
- The maximum hardness 37.5 and 27.5 were found in the weld joint for buttering and without buttering respectively.
- The maximum energy stored in bimetallic welding was 187.52 joules for with buttering, whereas 135.31 joules obtained in without buttering.

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