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Sensitization and Corrosion of 409M Ferritic Stainless Steel by Different Welding Processes

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Abstract: The aim of this research work was to analyze the sensitization due to the effect of welding (Shielded Metal Arc Welding, Gas Tungsten Arc Welding & Gas Metal Arc Welding) heat in heat affected zone area in terms of metallurgical properties, mechanical properties and corrosion of base metal comparatively. Also the effect of different chemicals / acidic environments on tensile properties was investigated. The plates of 3 mm thickness of 409M Ferritic Stainless Steel welded at constant current of 90A by three different welding processes with the same filler metal. The microstructure observation was made after Marble reagent chemical etched. Then tensile properties were investigated and comparative analysis done between the tensile properties i.e. before and after the chemical exposure given to it with the parent metal. After completion of experimental work it is found that SMAW, GMAW and GTAW have affected the microstructure of 409M Ferritic Stainless Steel. Due to the acidic environments/ Chemical exposures the strength and ductility of the metal affects. But comparatively GTAW has shown better process than GMAW and SMAW for welding of 409M Ferritic Stainless Steel. It should be used with caution in sulphuric acid environments than chloride environments to resist corrosion.

***Index Terms*: 409M FSS, Sensitization, Corrosion, SMAW, GMAW and GTAW**

I. INTRODUCTION

Ferritic Stainless Steels (FSS) constitute approximately one-half of the AISI type 400 series stainless steels. These steels contain 10.5% to 30% of Cr along with other alloying elements, notably molybdenum [3]. These steels exhibit good ductility, formability, and moderately better yield strength relative to those of the austenitic grades, but the high temperature strength is somewhat poor. Due to the crystal structure, the toughness is low at cryogenic temperature [2]. These grades provide a saving of approximately 1.5 percent over the austenitic grades in material cost and are, as such, attractive alternative to the austenitic variety. [1].Ferritic stainless steel is a candidate material in less severe corrosion atmosphere for chemical processing equipment, furnace parts, heat exchangers, petroleum refining equipment, recuperators, storage vessels, electrical appliances, solar water heaters, and household appliances . They are particularly more appropriate in caustic and chloride environments [2]. The ferritic grade of stainless steel is not commonly used for structural engineering purpose because their fabrication is associated with several challenges principal among which is the deterioration in after-weld properties following conventional fusion welding process. However, in the recent past, the austenitic variety is becoming quite expensive on the account of the increasing cost of nickel; a major alloying element. Therefore, there is a renewed interest in the FSS though the challenges of acceptable weldability have yet to be fully addressed. Different welding techniques have been explored to improve weldability of the ferrites and it emerged that low heat input provides a promise [1]. However, despite these economic and metallurgical attributes, ferritic stainless steel is less used in engineering application. This is because fusion welding of ferritic stainless steel particularly the first generation group AISI 430 is associated with many problems. These problems are grain coarsening in both fusion zone and HAZ coupled with formation of grain boundary martensite in the weld, and these result in lower ductility and toughness in the weldment.

II. EXPERIMENTAL ANALYSIS

Experimental analysis consists of welding procedure for GTAW, SMAW and GMAW and preparation of samples for the microstructural test, Mechanical Properties test and corrosion test.

Welding Procedure

In order to analyze the sensitization gas tungsten arc welding, gas metal arc welding and shielded metal arc welding techniques were used for welding on 409M ferritic stainless steel plate. The sheet of size (3mm X 1200mm X 312 mm) were brought from the supplier is shown in the Fig.1&2 In this investigation, the sheet of 3mm thickness AISI 409M grade ferritic stainless steel were cut into the required plate of dimensions (72mm X 312mm) by hydraulic shearing machine. The six plates were cut for the three different welding techniques with the (72mm X 312mm) dimensions.

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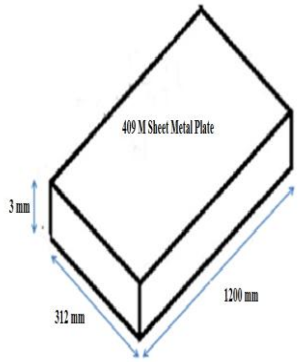


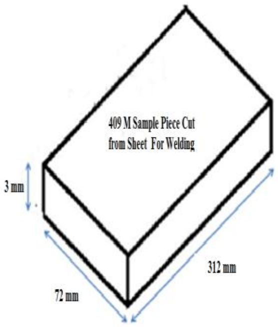


Fig. 1 Sheet Metal Dimensions **Fig. 2Weld Plate dimensions**

Preparation of Welding Sample

Weld plate were cut by using the power hack saw machine with the continuous coolant at M/s. ARUN Engineering Works, MIDC , Hingna , Nagpur. The plates were prepared for the welding by providing the V-groove between both plates for V-butt joints. V-groove prepare on the grinder machine at M/s. Hari Om Engineering Works with reference of book of welding Technology by G.D. Garg. The root gap is maintained 1.5 mm, root face of 1 mm and 30^o-60^o were made on each plate for welding V-groove butt joint [4]. As the dimension were checked by vernier caliper.

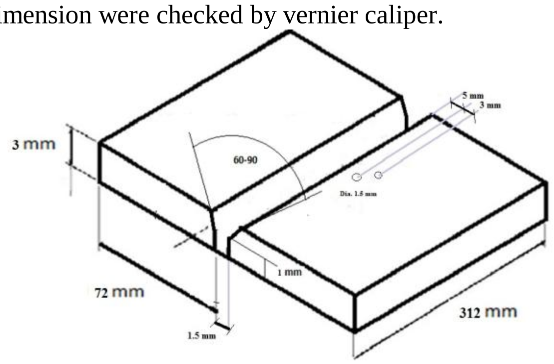


Fig.3 welding plate specification

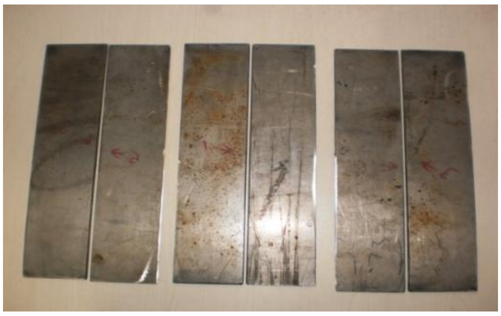


Fig.4 Actual images of plates

SMAW	GMAW	GTAW
		

Fig.5 Visual Heat Affected Zone after welding Processes

III. MICROSTRUCTURE TEST

Three samples were cut from the welding plates prepare by SMAW, GTAW and SMAW by using hack saw with continuous cooling. Samples are extracted from the one end of the plate. Separate sample was prepared of each welding for the microstructure observation and that will compare with the parent material microstructure sample and the changes in the welded samples were observed and compared with each other. The samples were prepared for observing the microstructures at weld zone and heat affected zone, heat affected zone, heat affected zone and base metal.

Fig.6 cut samples for Microstructure Test

The surface of the base material is prepared for the comparison of the microstructures. Fig. 6 clearly shows the welded portion of SMAW, GTAW and GMAW. The microstructure preparation and microstructure observation has done at M/s. Quality Heat Treatment, Hingna MIDC Nagpur. The 409M ferritic stainless steel has three major constituents, which are ferrite and pearlite and which separate it from the other steel is chromium which is more than11 %. The light colored region of the microstructure is the ferrite. The grain boundaries between the ferrite grains can be seen quite clearly. The dark regions are the pearlite. It is made up from a fine mixture of ferrite and iron carbide, which can be seen as a "wormy" texture. There are small spots within the ferrite grains. These are inclusions or impurities such as oxides and sulphides.

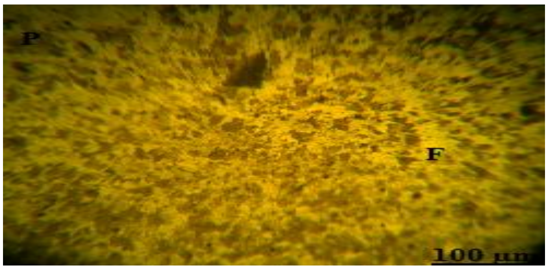


Fig .7 Microstructure of parent material 409M (100X)

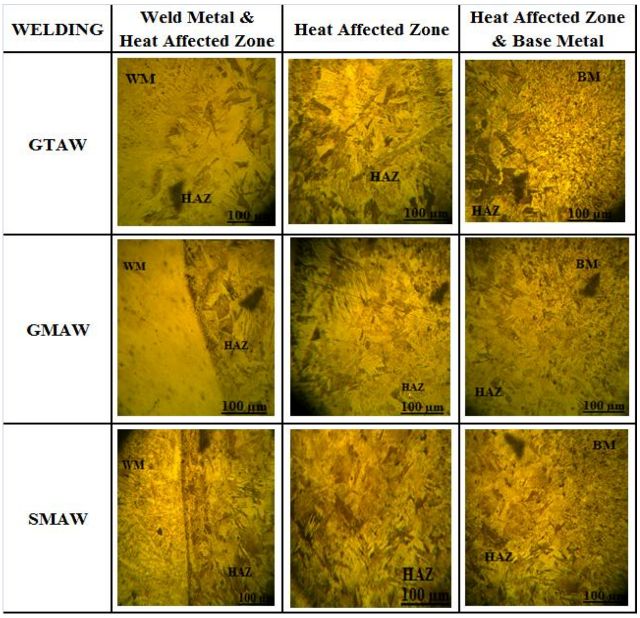


Fig.8 Transverse section Microstructure of 409M FSS after GTAW, GMAW & SMAW

1. Microstructure of Weld Metal Zone

It consist ferrite structure and pearlite in dendritic form. It has interdendritic casting structure in the weld metal zone. The grain structure of the welded region is observed coarser than grain structure of the parent metal. GTAW welding shows more interdendritic casting structure than the GMAW & SMAW.

2. Microstructure of Heat Affected Zone

The heat affected zone contains the coarser grain ferrite structure. In this zone, it is observed that the smaller grains are coagulated to form new grains, hence grain growth is there.

3. Microstructure of Base Metal

The microstructure of the base metal is as similar as the parent metal. In each welding the microstructure of the base metal is shown as same.

IV. TENSILE TEST

The tensile test has performed in MIA Lab, Nagpur. The total 26 samples were prepared for the tensile testing; it includes 2 parent metal tensile test samples and 24 samples for the welded tensile specimen. Tensile testing was done before and after the chemical exposure test to know the corrosion effects on tensile strength and ductility due to the different acidic/ chemical exposures. First the parent metal tensile testing was carried out followed by tensile testing before and after the chemical exposures tests, 8 samples from each welding i.e. SMAW, GMAW & GTAW. Out of these 24 samples; 6 samples were used for tensile test before chemical exposure and the remaining 18 samples were used after chemical exposure for doing the tensile test. The 6 samples those were used before chemical exposure contains 2 samples of each welding and 18 samples those were used after chemical exposure contains 6 samples of each welding for three different chemical exposures.

A. *Tensile test of Parent Metal*

The strength and the ductility of materials are determined from the tensile test. Samples for testing are taken parallel to the rolling direction of the plate and 90^0 the rolling direction, and these types of tests are called longitudinal and transverse tensile strength respectively. The ultimate tensile strength is calculated by dividing the load (max) by original area and it is the maximum stress in the stress-strain curve. The ductility of the materials is evaluated by percentage elongation (% E) and percentage reduction in area (% RA). A standard gauge length (GL) is marked on the samples before application of load and after testing increase in gauge length is measured. The %E is the ratio of increase in GL by the original GL (dl/L). In order to obtain the parent metal tensile strength and ductility 2 tensile samples get prepared with the standard dimensions and tested by using Universal Testing Machine at MIA Lab, Nagpur. Fig. 8.21 shows the parent metal tensile samples after tensile testing below.

Fig.9 Parent metal Tensile Specimen after testing

B. Tensile test before chemical exposure

The tensile test has performed in MIA Lab, Nagpur. Out of 24 welded tensile samples; 6 samples were used for the tensile testing before chemical exposure. These 6 tensile samples include 2 samples of each welding i.e. SMAW, GMAW & GTAW. These samples get tested just after the welding. To test the effect of various chemical exposures on the tensile strength and ductility, it is necessary to compare these tensile specimens with the parent metal. So the 2 samples of each welding get tested before the chemical exposure test

(a) (b)

Fig.10 Tensile Specimens before Chemical exposure a) Sample before tensile test b) Sample after tensile test

C. Tensile test after chemical exposure

This tensile test followed by the tensile testing before the chemical exposure. Out of 24 welded tensile samples; 18 samples were used for the tensile testing after chemical exposure. These 18 tensile samples include 6 samples of each welding i.e. SMAW, GMAW & GTAW. Three different chemical exposures given to the tensile welded samples are:

1. Copper-Copper Sulphate (16 % Sulphuric acid solution)

The solution contains dissolve 100 g of copper sulphate ($CuSO_4$. $5H_2O$) in 700 ml of distilled water, and 100 ml of sulphuric acid (H_2SO_4, reagent grade sp. Gr. 1.84) and dilute to 1000 ml with distilled water). 16 % Sulphuric acid test is a 24-h test in a boiling solution containing 16% sulphuric acid and 6% copper sulphate with the test specimen embedded in metallic copper shot or grindings, which detects the intergranular attack associated with the precipitation of chromium rich carbides.

2. 0.5 M Sulphuric acid with 0.01 M NH_4SCN:

The solution consists of 0.5 M H_2SO_4 + 0.01 M NH_4SCN. In this solution 27.15 ml concentrated H2SO4 dissolve in 1000 ml distilled water and 0.76 gm of ammonium sinite get mix with it. This test is conducted for 6-h in the boiling solution

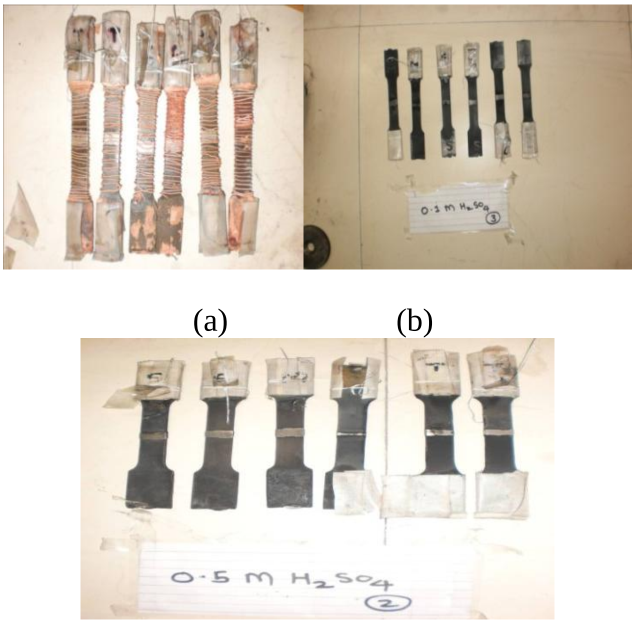
3. 0.1 M Sulphuric acid with 0.01 M NH_4SCN:

The solution consists of 0.1 M H_2SO_4 + 0.01 M NH_4SCN. In this solution 5.43 ml concentrated H2SO4 dissolve in 1000 ml distilled water and 0.76 gm of ammonium sinite get mix with it. This test is conducted for 6-h in the boiling solution.

The welded tensile specimens dipped into the three flask containing three different solutions mentioned above. The test was conducted in the corrosion laboratory of VNIT, Nagpur. Fig.11 shows the 6 samples of GTAW, 6 of SMAW & 6 of GMAW respectively. Total 18 samples get exposed to the chemicals for checking the tensile strength and ductility. The tensile samples of parent metal and samples before chemical exposure get compared with the samples of the chemical exposure. Fig.12 shows the experimental arrangement for these three different chemical exposures. After chemical exposure testing the colour of the samples get changes due to the effect of the acidic environment/ chemical solutions. Fig 13 shows the effect of the chemicals on the welded tensile samples due to Cu-Cu Sulphate solution, 0.1 M H_2SO_4 + 0.01 M NH_4SCN solution and 0.5 M H_2SO_4 + 0.01 M NH_4SCN solution respectively.

Fig.11 Welded tensile samples of GTAW, SMAW & GMAW for chemical exposure

Fig. 12 Experimental set-up for 3 different chemical exposures of tensile samples



(a) (b)

(c)

Fig.13Welded tensile samples after chemical exposure (a) Cu-Cu Sulphate Samples (b) 0.1 M H_2SO_4 samples (c) 0.5 M H_2SO_4 samples

After completing the chemical exposure the samples get tested on the universal testing machine of 100 KN. Fig.14, Fig.15, & Fig.16 shows the tensile samples after tensile testing of 3 different chemical exposures.

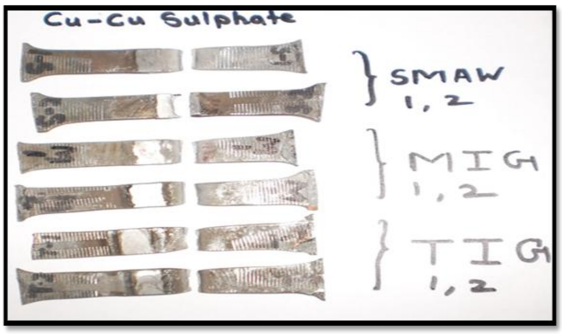


Fig. 14 Tensile tested sample of Cu-Cu Sulphate solution

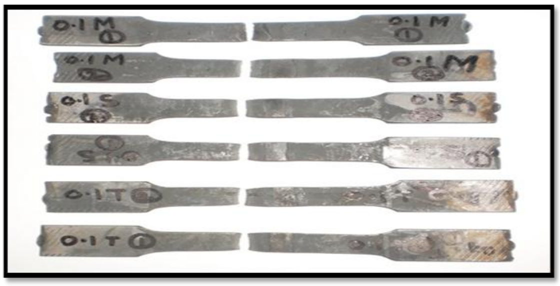


Fig. 15 Tensile tested sample of 0.1 M H_2SO_4 solution

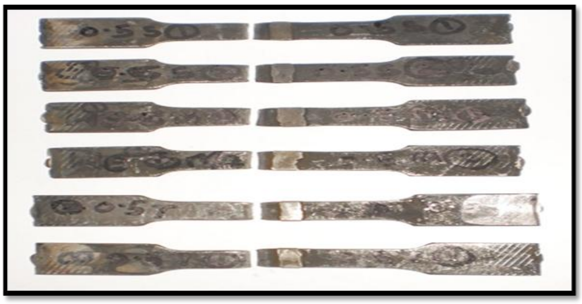


Fig. 16 Tensile tested sample of 0.5 M H_2SO_4 solution

V. CORROSION TEST

The corrosion test has performed in VNIT, Nagpur to estimate the corrosion rate of metal. The sample for corrosion test cut with Wire EDM followed by solution annealing at 1050°C in a furnace, soldering, pasting and surface finish.

Ferritic stainless steel, 409M samples in plate form (10mm wide and 10mm long) used for this investigation were Mounted in araldite resin and connected with a flexible wire connection, ground and polished to fine diamond (1µm), cleaned and rinsed/degreased in an ultrasonic bath using acetone. The samples were immediately kept in a desiccator for subsequent corrosion experimental studies. Potentiostatic polarization experiments were performed using each of the flat plate specimens in turns, in which 1 cm^2 surface area of the specimen was exposed to the test solution at room temperature. The experiments were performed using a polarisation cell of three – electrode system consisting of a reference electrode (silver chloride electrode– SCE), a working electrode (WE); and two carbon rod counter electrodes (CE). The potentiodynamic studies were made at a scan rate of 0.00166V/s from -0.6 to +1 V and the corrosion currents were recorded. The experiments were conducted in two different concentrations of 0.1M sulphuric acid (H_2SO_4) and 3% sodium chloride environments. Table 8.5 shows the different chemicals used for testing the corrosion rate of the parent material.

Table.1 Different chemicals used for corrosion test

Sr. No.	Concentrations used
1	0.1 M Sulphuric Acid (0.1 M H_2SO_4)
2	3% Sodium Chloride (3% NaCl)

The polarization cell was connected to a potentiostat and interfaced with a computer for data acquisition and analysis. The two tests were performed for two different concentrations. Fig. 8.29 shows the experimental set-up for the potentiondynamic measuring instrument for parent 409M samples.

Fig. 17 Experimental set-up for corrosion test of parent metal 409M FSS

VI. RESULTS AND DISCUSSION

A. Microstructural Results

The microstructure after welding is observed as below:

- The size of the grains in the weld metal region is finer (due to high fusion temperature) compared to HAZ.
- Heat affected zones contains the coarser grained ferrite microstructure in all the welding processes.
- In Heat affected zone region, the smaller grains are coagulated to form new grains; hence grain growth is there due to the welding heat.
- The welded region has the interdendritic casting structure mostly in TGAW, then in SMAW and less in GMAW.

B. Tensile Test Results

Tensile testing was done of the different samples i.e. of parent metal tensile testing, tensile testing before chemical exposure and tensile testing after chemical exposure. Finally the results were obtained by the comparative analysis between the samples before chemical exposure and after chemical exposure with the parent metal tensile piece results. The results of these tensile testing is given in the tabular form below.

Parent Metal Tensile Result

The two samples of the parent metal were tested to get the tensile strength and the percentage elongation. Tensile strength of the parent metal and the percentage of elongation are shown in the Table 2

Table.2 Result of Tensile Strength of Parent Metal

Sample No.	Specimen used	Specimen Thickness (mm)	Specimen Width (mm)	Tensile Strength (MPa)	Percentage Elongation (%E)
1	Parent	3.18	12.72	544.65	22.40
2	Parent	3.01	12.74	554.36	24.40

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Tensile Results before Chemical Exposure

The results of the six tensile samples including 2 samples of each welding are shown in the table below before chemical exposure testing. Tensile strength and the percentage elongation of the welded samples are shown in the Table 3.

Table 3: Tensile Results before Chemical Exposure

Sr. No	Sample No.	Welding tech. used	Specimen Thickness (mm)	Specimen Width (mm)	Tensile Strength (MPa)	Percentage Elongation (%E)
1	1	GTAW	2.70	12.78	557.22	21.92
2	2	GTAW	2.94	12.39	477.15	17.92
3	1	GMAW	3.15	12.64	509.29	17.30
4	2	GMAW	3.16	12.54	513.24	16.00
5	1	SMAW	3.20	12.76	506.39	17.20
6	2	SMAW	2.93	12.72	523.46	19.20

Tensile Results after Chemical Exposure

The results of the 18 tensile samples including 6 samples of each welding get exposed to the three different chemical solutions. Tensile strength and the percentage elongation of the welded samples are shown in the Table 4.

Table4: Tensile Results after Chemical Exposure

Sr. No	Chemical Solution used	Sample No.	Welding tech. used	Specimen Thickness (mm)	Specimen Width (mm)	Tensile Strength (MPa)	Percentage Elongation(%E)
1	Cu-Cu Sulphate	1	GTAW	3.20	12.46	487.58	18.20
2		2	GTAW	3.28	12.74	524.04	14.50
3		1	GMAW	2.82	11.92	490.92	12.80
4		2	GMAW	2.80	12.18	496.18	11.60
5		1	SMAW	3.18	12.70	478.33	13.70
6		2	SMAW	3.18	12.65	526.47	15.20
7	0.1 M H_2SO_4	1	GTAW	3.22	12.35	515.96	13.40
8		2	GTAW	3.28	12.35	492.92	19.30
9		1	GMAW	3.30	12.55	479.47	13.20
10		2	GMAW	3.15	12.80	494.04	10.60
11		1	SMAW	3.15	12.44	499.10	16.60
12		2	SMAW	3.15	12.60	488.28	13.40
13	0.5 M H_2SO_4	1	GTAW	2.75	11.76	473.09	13.90
14		2	GTAW	2.78	12.10	463.73	10.30
15		1	GMAW	3.15	12.74	324.44	07.00
16		2	GMAW	3.14	12.24	460.57	13.10
17		1	SMAW	2.78	12.15	488.45	13.60
18		2	SMAW	2.78	12.30	424.68	09.80

Result of Comparative Analysis with Parent Metal

For the comparative analysis of the tensile properties like tensile strength and ductility; between the tensile samples before and after chemical exposure compared with the parent metal. The different chemical solutions used for exposure are Cu-Cu sulphate solution, 0.1 M H_2SO_4 and 0.5 M H_2SO_4. Their results were calculated by taking the average of two specimens in each condition i.e. before and after the chemical exposure and the results are given in the Table 5.

Table5: Comparative analysis of Tensile Results

Base Metal : i) Tensile Strength = 549 MPa ii) Elongation % = 23.40								
Welding Technique used	**Results before Chemical Exposure**		**Results after Chemical Exposure (three different chemical solutions used)**					
			Cu-Cu Sulphate		0.1 M H_2SO_4		0.5 M H_2SO_4	
	Tensile Strength MPa	Elongation %	Tensile Strength MPa	Elongation %	Tensile Strength MPa	Elongation %	Tensile Strength MPa	Elongation %
GTAW	517	19.92	506	16.35	505	16.35	468	12.10
GMAW	511	16.65	494	12.20	487	11.90	393	10.05
SMAW	514	18.20	502	14.45	494	15.00	457	11.70

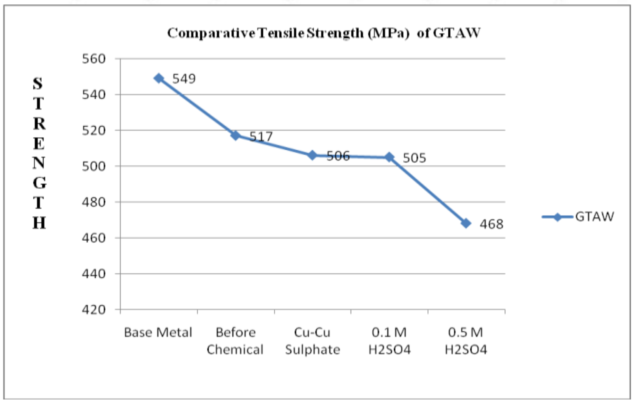

Fig.18 GTAW comparative Tensile Strength before & after Chemical exposure

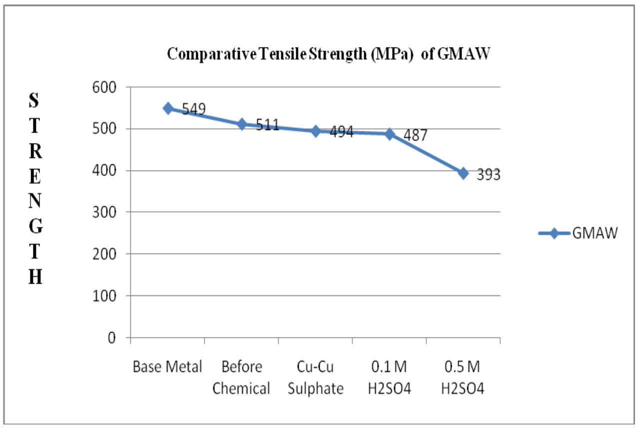

Fig.19 GMAW comparative Tensile Strength before & after Chemical exposure

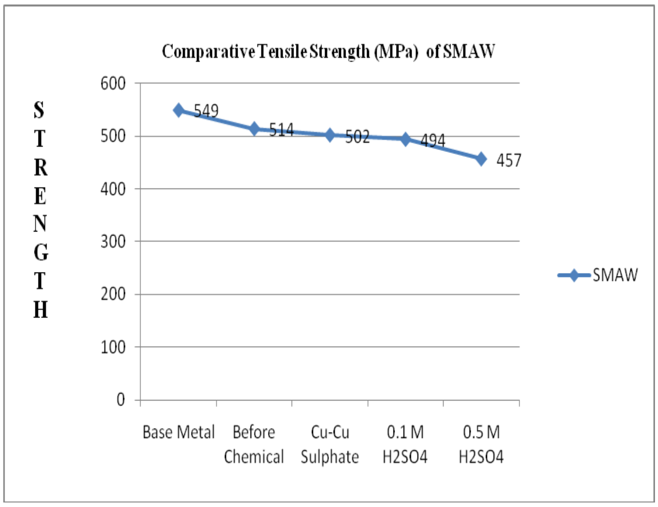

Fig.20 SMAW comparative Tensile Strength before & after Chemical exposure

C. Corrosion Results

Corrosion behavior of 409M Ferritic stainless steel was evaluated with chloride acid environment and Sulphuric acid environments. The experiment was performed at the ambient temperature using potentiodynamic polarization measurement. Tafel traditional technique was used to estimate the corrosion rate of the sample tested. The results are as follows in the tabular form

Table6: Comparative Results of Corrosion Rate

Sr. No	Test Environment	βa (mv)	βc (mv)	Io(Amp/cm^2)	Eo (Volts)	Corrosion Rate(MPY)
1	3 % Nacl	102.11	107.84	2.3075E-6	0.45424	0.893
2	0.1 MH_2SO_4	154.37	176.92	0.0018711	0.53915	724.13

The result shows that the 0.1 M H_2SO_4 has more corrosion rate i.e. of 724.13 MPY than the 3 % Nacl which is having the corrosion rate 0.893 MPY. Appreciable corrosion resistance of the tested 409M Ferritic stainless steel specimen was exhibited in the 3% Nacl test environments than the 0.1 M $H_2SO_{4\ acid}$ environments, While the 0.1 M H_2SO_4, shifted the polarization behavior into the active corrosion reactions. So the Ferritic Stainless steel 409M should be used with caution in the sulphuric acid environments. The polarization curve for 3% Nacl & 0.1 M H_2SO_4 acidic environments is shown in the Fig.9.7 & Fig.9.8 respectively below.

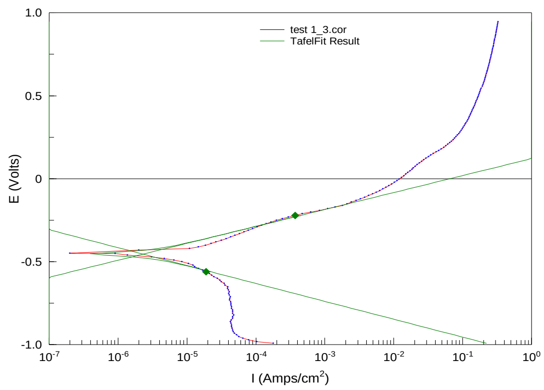

Fig.21 Polarization Curve of FSS in 3% Nacl

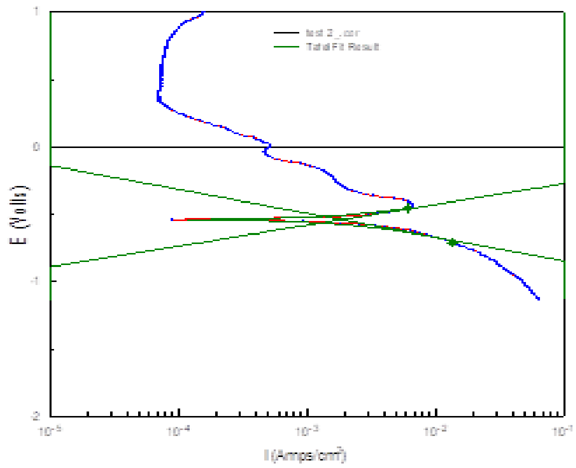

Fig.22 Polarization Curve of FSS in 0.1 M H_2SO_4

VII. CONCLUSIONS & FUTURE SCOPE

1. Among the three welded joints, the joints fabricated by GTAW process exhibited higher strength values and there is a slight increase in the strength value which is approximately 0.6 % compared to the SMAW joints and 1.2% compared to the GMAW joints before the chemical exposure.
2. Among the three welded joints, the joints fabricated by GTAW exhibited higher ductility values and the improvement in the ductility is approximately 8.63% compared to the SMAW & 16.41% compared to the GMAW joints respectively.
3. The corrosion result shows that the 0.1 M H2SO4 has more corrosion rate i.e. of 724.13 MPY than the 3 % Nacl which is having the corrosion rate 0.893 MPY.
4. Appreciable corrosion resistance of the tested 409M Ferritic stainless steel specimen was exhibited in the 3% Nacl test environments.
5. Ferritic Stainless steel 409M should be used with caution in the sulphuric acid environments.
6. In future, the corrosion rate of the metal can be determined with the different acidic environments.

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