

Study of Corrosion Behavior of Tig and Mig Welded Joints of Ferritic Stainless Steel (FSS) (Aisi-430) in Different Environments

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ABSTRACT: In the present study corrosion behaviour of FSS (AISI 430) weldment welded by TIG and MIG welding process using austenitic filler metal/electrode have been investigated. For analyzing the corrosion behavior of welded joints, Weight loss method and Potentiodynamic Scanning (PDS) methods have been used. Weight loss method and PDS method have been found to show similar behaviour of the corrosion rate of TIG/MIG welded joints of AISI 430 FSS in different environments. Corrosion behavior of TIG/MIG welded FSS 430 has been found to be the highest in acidic medium (H₂SO₄, HCl), less in marine (3.5% NaCl) and least in basic (NaOH) media. Corrosion due to sensitization was observed in acidic medium.

KEYWORDS: Ferritic stainless steel, TIG/MIG welding, corrosion behavior, corrosion rate, Weight loss method, Potentiodynamic Scanning (PDS)

I. INTRODUCTION

Ferritic stainless steels are iron-chromium alloys with body-centred cubic crystal structure having chromium content usually in the range of 11–30 %. In ferritic stainless steels the predominant metallurgical phase present is ferrite. These steels are Fe-Cr-C alloys with sufficient chromium or chromium plus other ferrite stabilizer, such as niobium, molybdenum, or titanium, and are used to inhibit the formation of austenite on heating [1]. They are used in a variety of applications where corrosion resistance rather than mechanical properties, is the primary service requirement. It is used under less severe corrosive atmospheres for chemical processing equipment, furnace parts, heat exchangers, oil burner parts, petroleum roller equipment, protection tubes, recuperators, rubber plant machinery, scientific apparatus, storage vessels, tubing, television cones, electrical appliances, solar water heaters, air conditioners, kitchenware, household appliances, decorative trims, parts for washing machines [2]. Ferritic stainless steels can be welded by SMAW, GTAW, GMAW and SAW processes. The filler metal can be used made of matching composition or austenitic stainless steel and nickel alloys.

Mainly TIG/MIG welding with appropriate filler material/electrode is used for joining of ferritic stainless steel (FSS) plates for various industrial applications. These welded plates have been exposed to different environment like acidic (H₂SO₄, HCl), basic (NaOH) and NaCl (salt/marine). Although some researchers have worked on the corrosion behaviour of AISI 430 in different environments, sufficient information of the corrosion behaviour of FSS welded joint is not available in the literature [2-5], Hence, further investigation in the corrosion behaviour of the various welded joints of the ferritic stainless steels are required. Thus, there is a scope of study of corrosion behaviour of TIG/MIG welded joints in different corrosive media. The main objective of this work was to experimentally evaluate

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corrosion behaviour of AISI 430 ferritic stainless steel (FSS) welds prepared by TIG/MIG welding processes with Austenitic filler wire/electrode under various corrosive media like H₂SO₄, HCl, NaCl and NaOH of varying strength.

II. MATERIALS AND WELDING METHODS

II.I Materials:

The material used in this study was 3 mm thick cold rolled, annealed AISI 430 ferritic stainless steel. The chemical analysis of the base metal was obtained by spectrometer (Model: Spectromax max imf 14) as shown in Table 1.

Table 1: Chemical Composition of Base metal (wt. %)

Elements	Cr	Ni	C	Si	Mn	S	P	Fe
Base metal	16.37	-	0.0337	0.3132	0.4918	0.0123	0.0213	Bal.

Filler metals/ Electrode used for TIG/MIG welding of AISI 430 ferritic stainless steel is a metal core wire of ER309L, whose composition is given in Table 2. The chemical analysis of the filler metal/electrode was obtained by spectrometer (Model: Spectromax max imf 14) analysis.

Table 2: Chemical composition of austenitic stainless steel filler material (wt. %)

Filler material	Cr	Ni	C	Si	Mn	S	P	Cu
ER309L	23-25	12-14	0.03	0.30-0.65	1.0-2.5	0.03	0.03	0.75

II.II TIG welded joint:

TIG welding was done using tungsten electrode and austenitic filler wire ER309L of diameter 1.2 mm. The polarity used during welding was direct current with electrode negative (DCEN). Welding was done in a single pass with current 64-65 A and voltage 10-11 V. The shielding gas used was pure argon with flow rate 6 L/min. A set of preliminary trials were performed in order to optimize the experimental welding parameters to ensure weld quality. The optimum welding condition and process parameters are given in Table 3.

Table 3: Welding conditions and process parameter for TIG

	TIG Welding
Welding Machine	KEMPPI
Base Material	AISI 430 ferritic stainless steel
Plate Thickness (mm)	3mm
Filler wire	ER309L
Electrode diameter (mm)	1.2

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Welding Current (amps)	64-65
Welding voltage (volts)	10-11
Welding Speed	55 mm/min
Polarity	DCEN

II.III MIG welded joint:

GMAW welding was done using consumable electrode ER309L of diameter 1.2 mm. The polarity used during welding was direct current with electrode positive (DCEP). Welding was done in a single pass with current 160-170 A and voltage 16.1-16.3 V. The electrode feed rate used was 4.9 m/min. The shielding gas used was pure argon with flow rate 6 L/min. A set of preliminary trials were performed in order to optimize the experimental welding parameters to ensure good weld quality. The optimum welding condition and process parameters are given in Table 4.

Table 4: Welding conditions and process parameter for MIG

	MIG Welding
Welding Machine	KEMPPI
Base Material	AISI 430 ferritic stainless steel
Plate Thickness (mm)	3mm
Electrode	ER309L
Electrode diameter (mm)	1.2
Welding Current (amps)	160-170
Welding voltage (volts)	16.1-16.3
Welding Speed	300 mm/min
Polarity	DCEP

III. EXPERIMENTAL RESULTS

III.I Weight loss measurement tests

The samples for weight loss tests were prepared in accordance to the procedure recommended by ASTM G1. The samples were cut from the welded plate to a square size of $2.5 \times 2.5 \times 0.3 \text{ cm}^3$ with surface area of 15.5 cm^2 , as shown in Fig 1. The surface area of the both type (TIG welded plate and MIG welded) plate were kept same i.e. 15.5 cm^2 for comparative study of corrosion rate. The samples were mechanically abraded with a series of emery papers. They were rinsed in acetone and distilled water to remove dirt, oils, and possible product formed on the surface of the samples.

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Polished and pre-weighed samples were exposed to 0.3M, 0.5M, 0.7M, 1M, H₂SO₄, 0.5M, 1M, 1.5M, 2M HCl, 0.001M, 0.003M, 0.01M, 0.03M NaOH, and 3.5% NaCl, solution at room temperature. The all solutions were made in 250 ml of distilled water. The weight loss experiment lasted for 14 days and weight losses measurements were carried out at one day intervals. The corrosion rate was calculated in milli meters per year (mm/y) from the mass loss data.

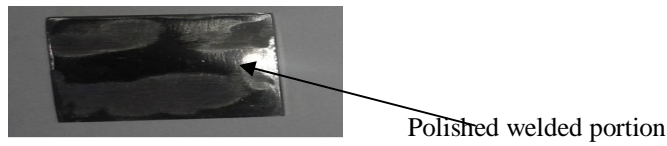


Fig. 1: TIG/MIG welded Sample for corrosion study

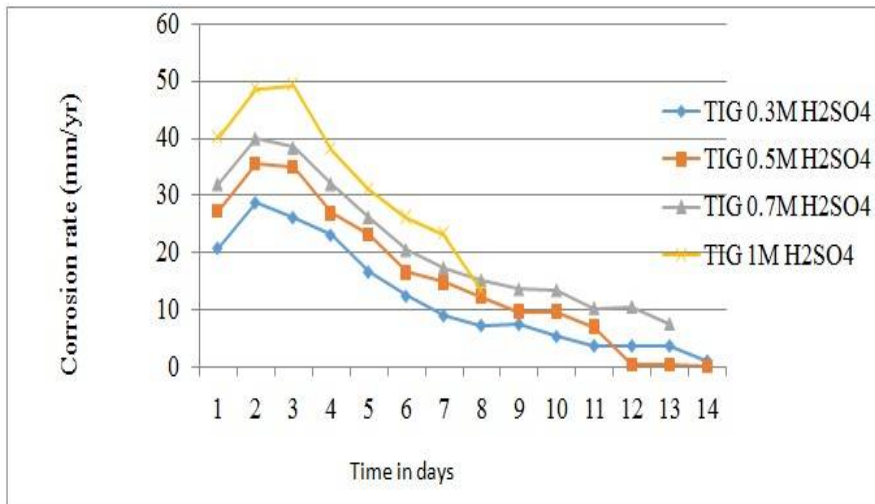


Fig. 2: Corrosion- time graphs of TIG test samples in H₂SO₄ Solutions

From Fig 2, it could be found out that rate of corrosion was high in H₂SO₄ for TIG welded FSS plate. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on the concentration, then after that rate of corrosion decreased to a constant value in all cases due to the creation of a passive layer on the sample. More rate of corrosion was observed for higher concentration of solutions.

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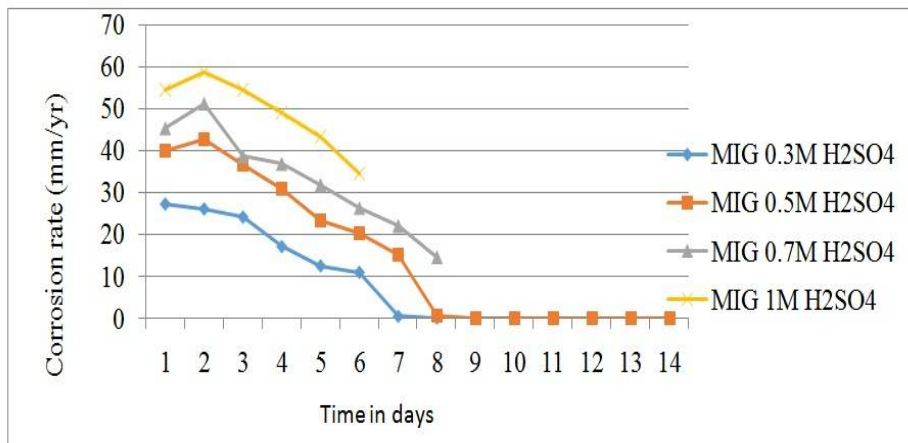


Fig .3: Corrosion- time graphs of MIG test samples in H₂SO₄ Solutions

From Fig 3, it could be found out that rate of corrosion was high in H₂SO₄ for MIG welded FSS plate. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on the concentration, then after that rate of corrosion decreased to a constant value in all cases due to the creation of a passive layer on the sample. More rate of corrosion was observed for higher concentration of solutions.

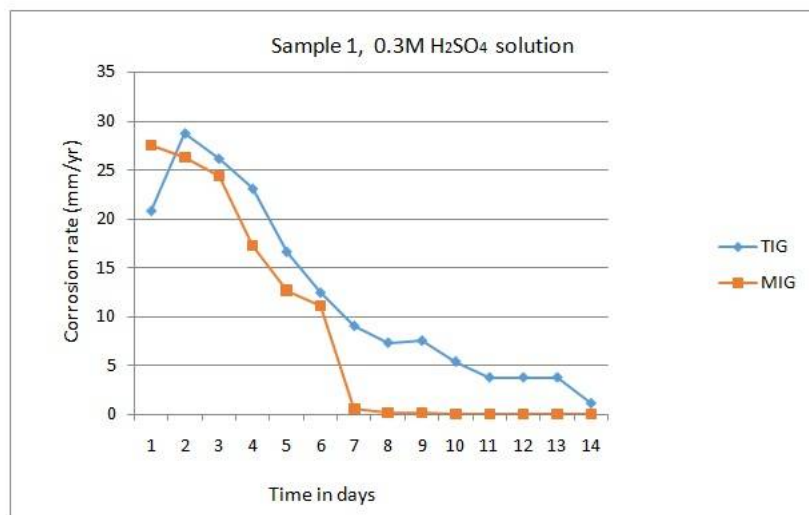


Fig .4: Corrosion- time graphs of TIG/MIG test samples in 0.3M H₂SO₄ Solutions

From Fig 4, it could be found out that rate of corrosion was high in 0.3 M H₂SO₄ for TIG welded FSS plate than MIG welded plate. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on welding method used, then after that rate of corrosion decreased to a constant value in both cases due to the creation of a passive layer on the sample.

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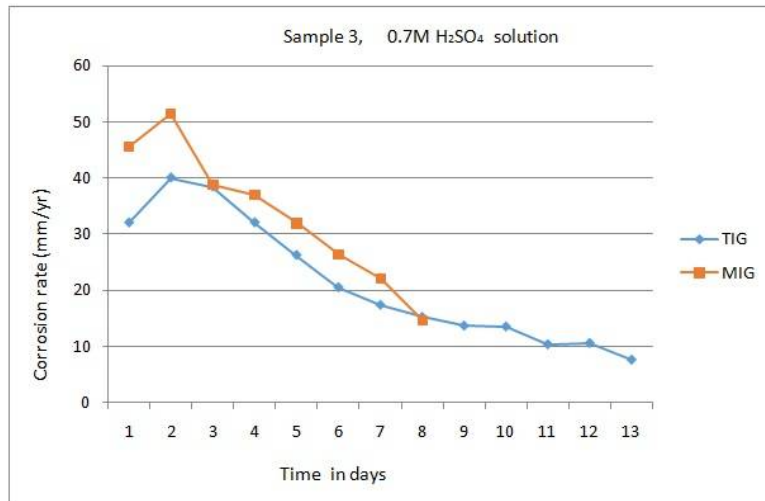


Fig .5: Corrosion- time graphs of TIG/MIG test samples in 0.7M H₂SO₄ Solutions

From Fig 5, it could be found out that rate of corrosion was high in 0.7 M H₂SO₄ for MIG welded FSS plate than TIG welded plate. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on welding method used, then after that rate of corrosion decreased to a constant value in both cases due to the creation of a passive layer on the sample.



Fig .6: State of welded joint exposed to 0.5 M H₂SO₄.

From Fig 6, it could be found out that rate of corrosion is very high in heat affected zone rather than the weld metal zone. Sensitization in HAZ just after the weld metal zone was observed. Failure of specimen took place just after the weld metal zone due to sensitization.



Fig. 7: State of welded joint exposed to 1M H₂SO₄.

From Fig 7, it could be found out that rate of corrosion is very high in heat affected zone rather than the weld metal zone. Sensitization in HAZ just after the weldmetal zone was observed. Failure of specimen took place just after the weld metal zone due to sensitization.

III.I.I Corrosion behaviour of TIG/MIG welded joint in H₂SO₄

From Fig 2 to 7, it could be found out that rate of corrosion was high in H₂SO₄ for TIG/MIG welded FSS plate. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on the concentration, then after that rate of corrosion decreased to a constant value in all cases due to the creation of a passive layer on the sample. More rate of corrosion was observed for higher concentration of solutions. It has been observed that rate of corrosion is very high in heat affected zone rather than the weld metal zone [Fig 6, 7]. Sensitization in HAZ just after the weldmetal zone was observed. Failure of specimen took place just after the weld metal zone due to sensitization. MIG welded plates got separated earlier than TIG welded plates in higher concentration of solutions

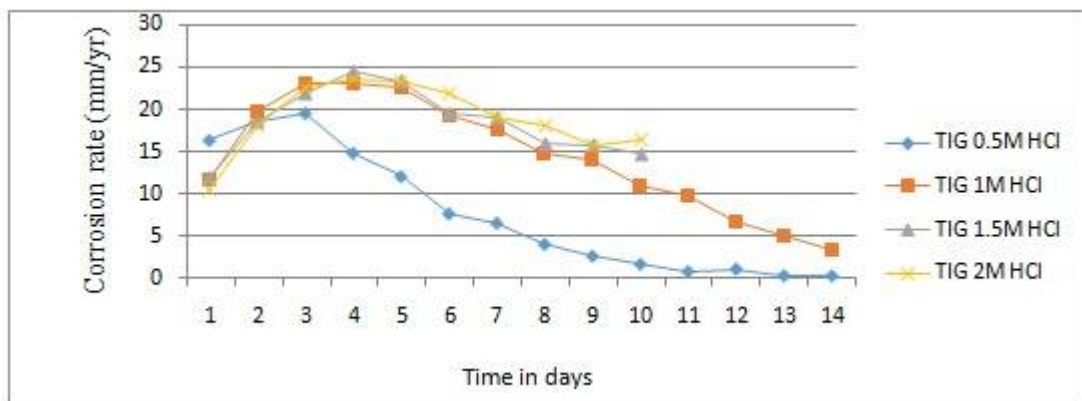


Fig 8: Corrosion- time graphs of TIG test samples in HCl Solutions

From Fig 8, it could be found out that rate of corrosion was high in HCl for TIG welded FSS plate. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on the concentration, then after that rate of corrosion decreased to a constant value in all cases due to the creation of a passive layer on the sample. More rate of corrosion was observed for higher concentration of solutions.

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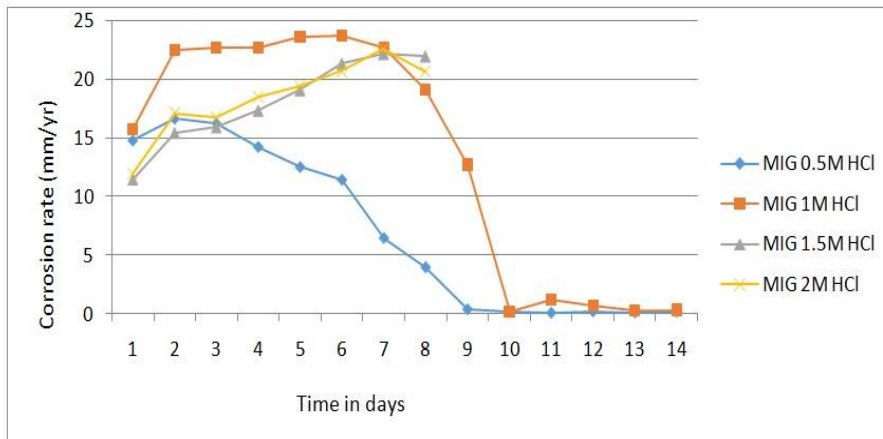


Fig 9: Corrosion- time graphs of MIG test samples in HCl Solutions

From Fig 9, it could be found out that rate of corrosion was high in HCl for MIG welded FSS plate. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on the concentration, then after that rate of corrosion decreased to a constant value in all cases due to the creation of a passive layer on the sample. More rate of corrosion was observed for higher concentration of solutions.

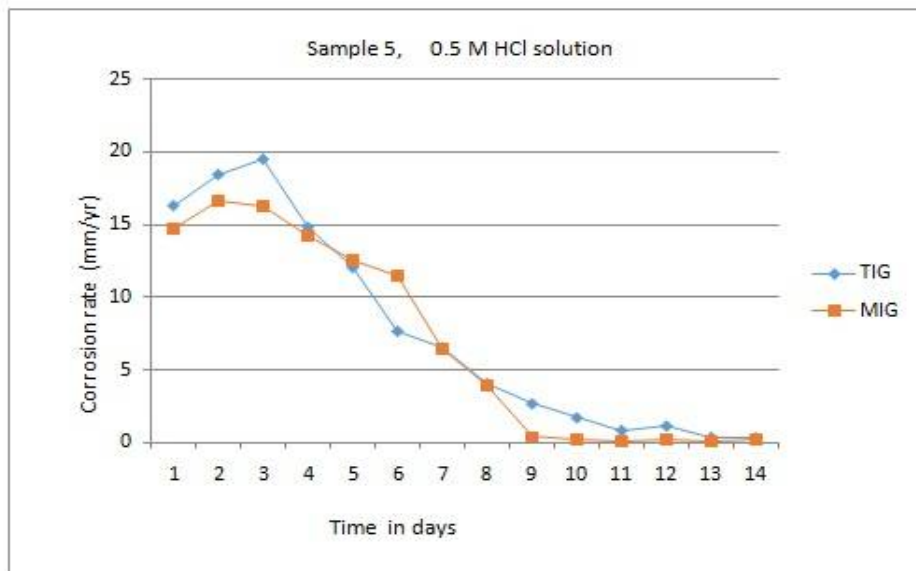


Fig 10: Corrosion- time graphs of TIG/MIG test samples in 0.5M HCl Solutions

From Fig 10, it could be found out that rate of corrosion was high in 0.5 M HCl for TIG/MIG welded plate. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on welding method used, then after that rate of corrosion decreased to a constant value in both cases due to the creation of a passive layer on the sample.

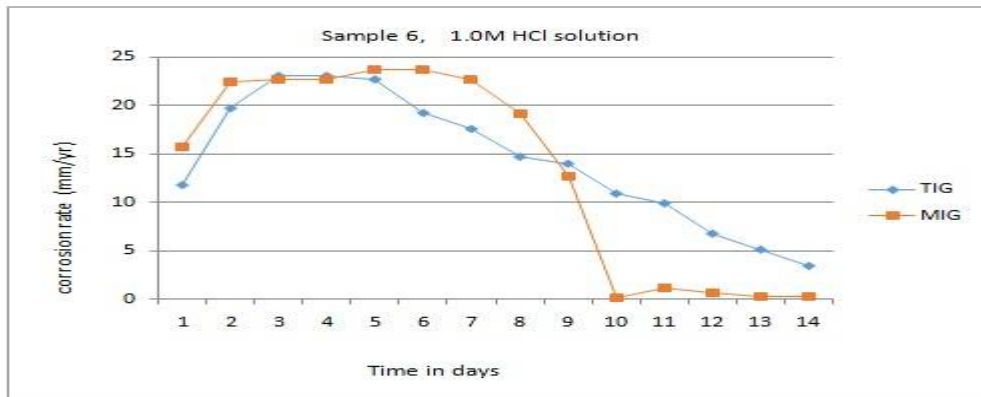


Fig 11: Corrosion- time graphs of TIG/MIG test samples in 1.0M HCl Solutions

From Fig 11, it could be found out that rate of corrosion was high in 1 M HCl for TIG/MIG welded plate. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on welding method used, then after that rate of corrosion decreased to a constant value in both cases due to the creation of a passive layer on the sample.

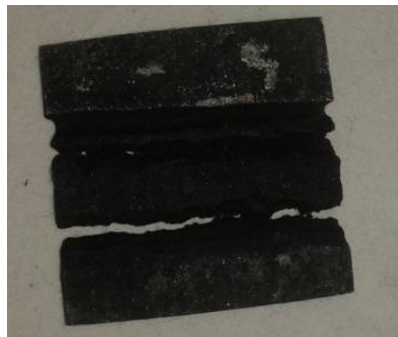


Fig 12: State of welded joint exposed to 1M HCl.

From Fig 12, it could be found out that rate of corrosion is very high in heat affected zone rather than the weld metal zone. Sensitization in HAZ just after the weld metal zone was observed. Failure of specimen took place just after the weld metal zone due to sensitization.

III.I.II Corrosive behaviour of TIG/MIG welded joint in HCl

From Fig. 8 to 12, it could be found out that rate of corrosion was high in HCl for TIG/MIG welded FSS plate but it was less than that of H_2SO_4 solution. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on the concentration, then after that rate of corrosion decreased to a constant value in all cases due to the creation of a passive layer on the sample. More rate of corrosion was observed for higher concentration of solutions. It was found to be very high in heat affected zone rather than the weld metal zone [Fig 12]. In FSS sensitization take place just after the fusion zone in heat affected zone. Failure of the specimen took place just after the weld metal zone due to sensitization. MIG welded plate got separated earlier than TIG welded plate in higher concentration of solution.

III.I.III Corrosion behaviour of TIG/MIG welded joint in H_2SO_4 and HCl

- In acidic medium (H_2SO_4/HCl) the rate of corrosion was found to be high and it was more in the case of H_2SO_4 than HCl. There was a gradual increase in corrosion rate for the first 3 or 4 days depending on its

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concentration, after that rate of corrosion was decreased to a constant value in all cases due to the creation of a passive layer on the sample.

- Total weight loss in welded sample after two week was about 6 to 10 gm depending on the concentration of the acidic medium from its initial weight of 13.2 gm. More rate of corrosion was observed in higher concentration of solutions.
- Corrosion rate was higher in the heat affected region than the fusion zone, [Fig 6, 7, 12]
- More corrosion attack was found just after the fusion zone due to the sensitization. The weld got separated after 8 days in higher concentration of acidic solution. It was caused by intergranular corrosion (IGC), which occurs due to the presence of chromium depleted zones at the grain boundaries. Due to sensitization, weld decay/knife line attack occurs close to the weld metal.
- MIG welded plate got separated faster than TIG welded plate in higher concentration of H₂SO₄/HCl, hence it can be concluded that weld decay was higher in MIG welded plate than TIG welded plate.
- It was observed that there was a difference between weld decay of TIG/MIG welded plates, it could be due to the difference in microstructure in heat affected region of TIG/MIG welded plates.
- It was observed that TIG welded plate lost more mass in two week than the MIG welded plate, hence overall corrosion rate was found to be higher in TIG welded plate than MIG welded plate in acidic media.
- It was observed that TIG welded plate was more resistant to IGC caused by weld decay than MIG welded plate in various acidic media but the overall corrosion rate of TIG welded plate was higher than the MIG welded plate.

III.IV Corrosion behaviour of TIG/MIG welded joint in NaOH and 3.5%NaCl

Corrosion was negligible in comparison to the acidic media from weight loss method. Even after two weeks, there was no weight loss in case of NaOH and NaCl mediums. It was only a short term corrosion prediction. The corrosion behaviour of TIG/MIG welded FSS plate with this information could not be generalised, for predicting long term corrosion behaviour. To confirm this, PDS tests must be performed.

III.II Potentiodynamic Scanning (PDS) experiments

The test samples of size 2.5 × 2.5 × 0.3 cm were metallographically polished to 600 grit surface finish using SiC emery paper. It was then subjected to Potentiodynamic scanning (PDS) test in 0.2M, 0.3M, 0.5M, 0.7M, H₂SO₄, 0.2M, 0.3M, 0.5M HCl, 0.003M, 0.01M, 0.03M NaOH, and 3.5% NaCl; The test was carried out in the standard three electrode flat corrosion cell using graphite as the counter electrode, silver-silver chloride as the reference electrode. The polished specimens were mounted in the corrosion testing cell to expose a surface area of 12 cm² to the test solution. The corrosion cell was electrically connected to computer controlled potentiostat (Model: CHI660B). The polarization was performed potentiodynamically by starting at a positive potential or initial potential (1.2V) and then moving to the negative or final potential (-1.2V) with the scan rate of 0.002 V/sec. The results of PDS test data are shown and compared in the Fig 13 to 19.

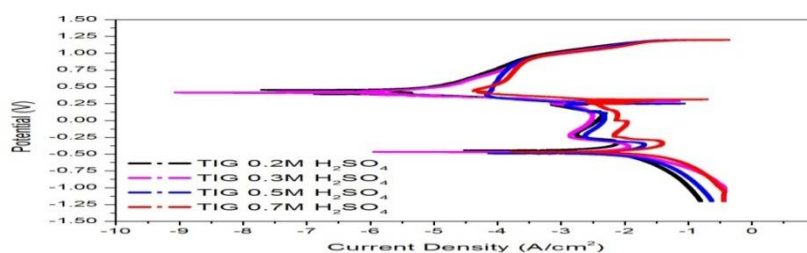


Fig. 13: PDS - TIG samples in H₂SO₄ Solutions

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From Figure 13, it could be observed that more than one anodic peaks are occurring in the PDS plot, hence the PDS plot equipment is providing corrosion current and corrosion rate with respect to the second or third anodic peak and hence, those values can be ignored. Manual methods must be applied for finding the corrosion current density and corrosion rate. Actual corrosion current and corrosion rate is difficult to determine using manual methods hence a range of corrosion current density was found out with respect to the OCP (Open circuit potential) of samples, anodic, cathodic tafel region and using this corrosion current density, a range of corrosion rate can be calculated, and these values are given in table 5.

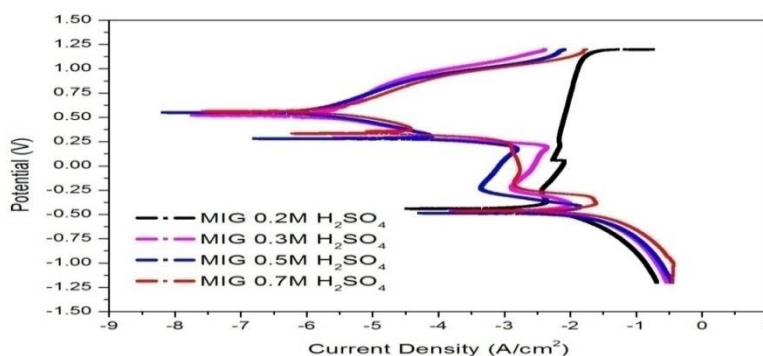


Fig. 14: PDS - MIG samples in H₂SO₄ Solutions

From Figure 14, it could be observed that more than one anodic peaks are occurring in the PDS plot, hence the PDS plot equipment is providing corrosion current and corrosion rate with respect to the second or third anodic peak and hence, those values can be ignored. Manual methods must be applied for finding the corrosion current density and corrosion rate. Actual corrosion current and corrosion rate is difficult to determine using manual methods hence a range of corrosion current density was found out with respect to the OCP (Open circuit potential) of samples, anodic, cathodic tafel region and using this corrosion current density, a range of corrosion rate can be calculated, and these values are given in table 5.

Table 5: PDS Corrosion rate – TIG/MIG samples in H₂SO₄ Solution.

Solution	TIG Sample		MIG Sample	
	$i_{corr.}$ (A/cm ²)	Corr. rate (mpy)	$i_{corr.}$ (A/cm ²)	Corr. rate (mpy)
0.2M H ₂ SO ₄	$8 \times 10^{-4} - 2 \times 10^{-3}$	370-926	7.515×10^{-4}	347.2
0.3M H ₂ SO ₄	$10^{-3} - 3 \times 10^{-3}$	463-1400	$8 \times 10^{-4} - 2 \times 10^{-3}$	370-926
0.5M H ₂ SO ₄	$10^{-3} - 3 \times 10^{-3}$	463-1400	$9 \times 10^{-4} - 2 \times 10^{-3}$	420-926
0.7M H ₂ SO ₄	$2 \times 10^{-3} - 4 \times 10^{-3}$	926-1800	$10^{-3} - 3 \times 10^{-3}$	463-1400

III.II.I Corrosion behaviour of TIG/MIG welded joints in H₂SO₄

From Table 5 and Figure 13 and 14, it could be found out that rate of corrosion was very high in H₂SO₄ for TIG/MIG welded FSS plate. Rate of corrosion was found to be of the order of 347-1800 mpy depending on the concentration of the solution. It has been observed that rate of corrosion is increasing with the concentration of the solution and TIG welded plate is more corrosive than the MIG welded plate in H₂SO₄.

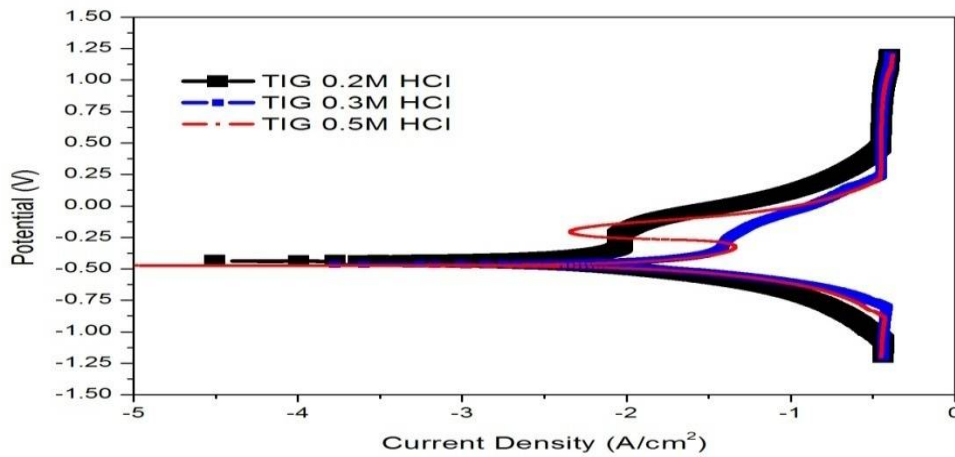


Fig. 15: PDS –TIG samples in HCl Solutions

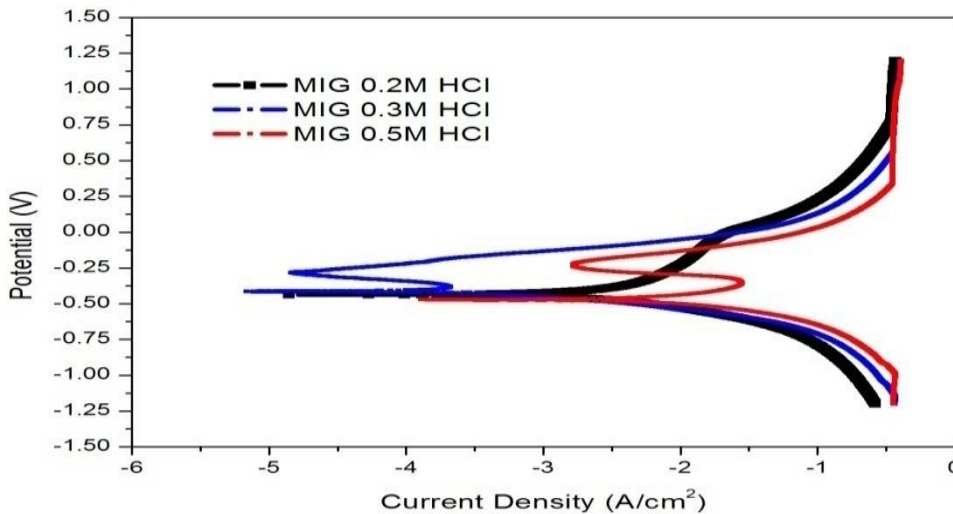


Fig. 16: PDS-MIG samples in HCl Solutions

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From Figure 16, it could be observed that a sharp passivation curve is occurring in the PDS plot (MIG 0.3M HCl) , hence the PDS plot equipment is providing corrosion current and corrosion rate with respect to the passivation curve and hence, these values can be ignored. Manual methods must be applied for finding the corrosion current density and corrosion rate. Actual corrosion current and corrosion rate are difficult to determine using manual methods, hence a range of corrosion current density was found out with respect to the OCP (Open circuit potential) of samples, anodic, cathodic tafel region and using this corrosion current density, a range of corrosion rate can be calculated and that value is given in Table 6 for MIG sample exposed to 0.3M HCl

Table 6: PDS Corrosion rate – TIG/MIG samples in HCl Solution.

Solution	TIG Sample		MIG Sample	
	$i_{corr.}$ (A/cm ²)	Corr. rate (mpy)	$i_{corr.}$ (A/cm ²)	Corr. rate (mpy)
0.2 M Hcl	6.239×10^{-4}	288.2	2.78×10^{-4}	128.6
0.3 M Hcl	1.375×10^{-3}	635.3	$4 \times 10^{-4} - 10^{-3}$	185-463
0.5 M Hcl	1.85×10^{-3}	856.2	1.791×10^{-3}	827.1

III.II.II Corrosive behaviour of TIG/MIG welded joints in HCl

From Table 6 and Figure 15 and 16, it could be found out that rate of corrosion was very high in HCl for TIG/MIG welded FSS plate but it was less than that of the H₂SO₄ solution. Rate of corrosion was found to be of the order of 128-827 mpy depending on the concentration of the solution. It has been observed that rate of corrosion is increasing with the concentration of the solution and TIG welded plate is more corrosive than the MIG welded plate in HCl.

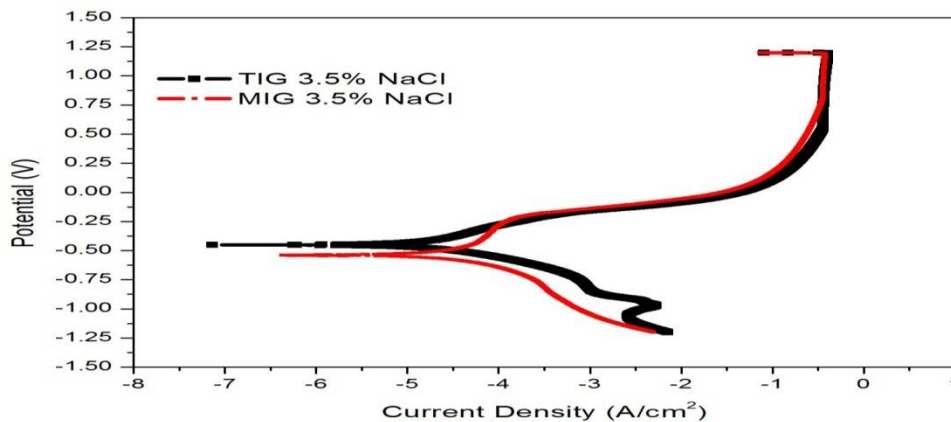


Fig. 17: PDS – TIG/MIG samples in 3.5% NaCl Solutions

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Table 7: PDS Corrosion rate – TIG/MIG samples in 3.5% NaCl Solution.

Solution	TIG Sample		MIG Sample	
	$i_{corr.}$ (A/cm ²)	Corr. rate (mpy)	$i_{corr.}$ (A/cm ²)	Corr. rate (mpy)
3.5% NaCl	2.009×10^{-6}	0.9282	3.185×10^{-6}	1.471

III.II.III Corrosion behaviour of TIG/MIG welded joints in 3.5% NaCl

From Table 7 and Figure 17, it could be found out that rate of corrosion was low in 3.5% NaCl for TIG/MIG welded FSS plate. Rate of corrosion was found to be of the order of 0.8 to 1 mpy depending on the type of welded joint used.

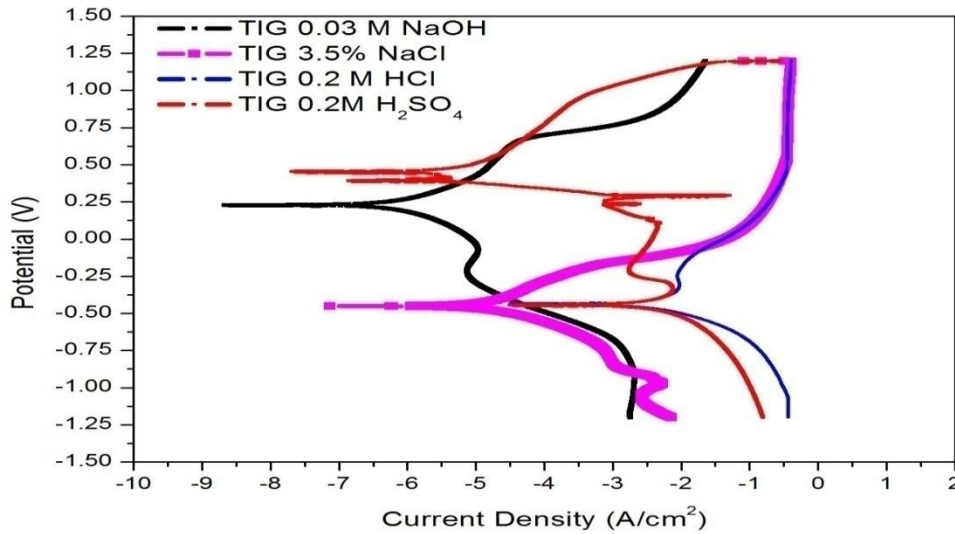


Fig. 18: PDS – TIG samples in different Solutions

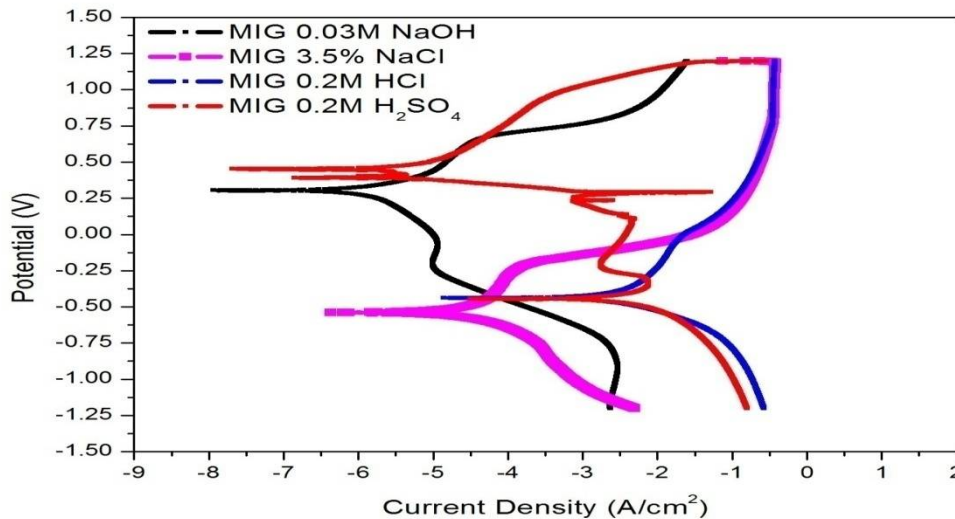


Fig.19: PDS – MIG samples in different Solutions

III.IV Corrosion behaviour of TIG/MIG welded joint in different environments.

From Figure 18 and 19, it could be found out that corrosion rate of TIG/MIG welded AISI 430 FSS plate was very high in acidic medium (H_2SO_4 , HCl) and less in marine (3.5% NaCl) and least in the case of diluted basic medium (NaOH). Corrosion current density represents the rate of corrosion in a particular medium, if corrosion current density is high then corrosion rate is also high in that medium. Corrosion current density in acidic medium was found to be of order 2×10^{-3} Amp/cm², in marine medium of the order of 2×10^{-6} Amp/cm², and in basic medium of the order of 2×10^{-7} Amp/cm².

IV. CONCLUSIONS

- Weight loss method and PDS method gives similar behaviour for the corrosion rate of TIG/MIG welded joints of FSS in different environments.
- Corrosion rate of TIG/MIG welded FSS 430 is highest in acidic medium (H_2SO_4 , HCl) of the order of 128 to 1800 mpy depending on the concentration of the acidic medium. Corrosion rate increases with the increasing concentration of the acidic medium (H_2SO_4 , HCl). Corrosion rate is higher in H_2SO_4 solution than HCl solution of same concentration.
- Corrosion rate of TIG welded sample is more than MIG welded sample in acidic medium. MIG welded weld metal position getting separated from the base plate faster than TIG welded plate. It could be due to higher IGC caused by weld decay/knife line attack in MIG welded weldment.
- Corrosion rate of TIG/MIG welded FSS 430 is less in marine (3.5% NaCl) of the order of 0.8 to 1.5 mpy.
- Corrosion rate of MIG welded sample is more than TIG welded sample in marine (3.5% NaCl) medium.
- Corrosion rate of TIG/MIG welded FSS 430 is least in basic (NaOH) of the order of 0.04 to 0.7 mpy.

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