

WEAR AND CORROSION STUDIES ON FERRITIC STAINLESS STEEL (SS 409M)

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Abstract

The wear and corrosion behavior of SS 409M have been evaluated and compared with Mild steel ferritic stainless steel SS 430, and austenitic stainless steel SS 304. The SS 409M is a utility grade ferritic stainless steel, and has a very low Ni percentage less than 0.30%. Annealed SS 409M contains ferrite and low percentage of tempered martensite whereas normalized SS 409M has low ferrite and higher percentage of tempered martensite. The manufacturing cost for this steel is low as compared to other grades of stainless steel but it has high strength with excellent corrosion resistance, abrasion resistance and can be easily fabricated. Thus SS 409M has been found to be a suitable material for replacing mild steel in structural applications. SS 409M has also got good wear resistance and this can be considered as an alternate material for mild steel in the railway wagons, track armor, and chemical tanks. The dry wear test has been carried out using the pin on disc machine for all the specimens. The results show that 409M has higher wear resistance as compared to mild steel and SS 430. The corrosion test has been carried out using the potentiostat for SS 409M both in annealed and in the normalized condition and the results are compared with SS 430 and SS 304. SS 304 and SS 430 stainless steels show excellent corrosion resistance while SS 409M both in annealed and in normalized condition reveal higher corrosion resistance than mild steel. Results are discussed with published work on these steels.

Keywords: SS 409M, SS 409M, SS 430, SS 304

I. INTRODUCTION

The steels which do not undergo rust or stain formation is known as stainless steel. Steels having chromium content more than ~12% Cr, are referred to as stainless steel. For the formation of stable passive film 12% of chromium is required, this film forms spontaneously on its surfaces and protects it against corrosion. Higher amount of Cr strengthens the passive film and further helps in passivation. Cr is a strong ferrite stabilizer and it suppresses the ferrite-austenite phase transformation. Nickel favors the rate of formation of passive film. When Ni is added in sufficient quantity, it stabilizes the austenite phase. It imparts toughness, ductility and ease of weldability. Since Ni is expensive Steel Authority of India(SAIL) developed stainless steel called 409M with optimal level of Ni and Cr content. These elements provide necessary corrosion resistance and are less expensive when compared to other grades of stainless steel. Because of low cost and ease of fabrication, 409M steels find many structural applications in rail wagons and military hardware.SAIL(INDIA) has introduced 409M grades stainless steel. It was first used in coal handling area in thermal power plants. Since then for thermal plants 409M grades has been used extensively. It finds major applications in liner plate bunkers in various

thermal power plants. The development of 409M, a utility grade ferritic stainless steel, has proven to be a major step forward in continuing battle against corrosion[1,2],With chromium content of 10.8-12.5%, 409M accounts for high strength, excellent corrosion resistance, abrasion resistance and weldability at lesser cost. The corrosion resistance of 409M in chemical and marine environment is much higher than that of mild steel. This means that structures manufactured using 409M have longer life than mild steel or alloy steel.

1.1 Microstructure

1.1.1 Chemical Compositions of SS 409M, SS 430, and SS 304

Table 1.1 Chemical compositions of SS 409M, SS 430, and SS 304

Elements	409M(Annealed) (%)	409M(Normalized) (%)	SS 430 (%)	SS 304 (%)
C (max)	0.018	0.025	0.055	0.035
Mn(max)	0.82	0.85	0.48	1.63
Si (max)	0.42	0.59	0.40	0.47

S (max)	0.014	0.015	0.007	0.010
P (max)	0.030	0.024	0.0034	0.030
Cr	11.12	11.35	16.36	17.62
Ni	0.30	0.40	0.11	8.02
N (max)	0.017	0.020	0.027	0.065

Materials obtained from Steel Authority of India Limited, Salem steel plant (INDIA) were in the form of rolled coil. In 409M (Annealed and normalized) there is slight variation of composition in ferritic stainless steel since it is obtained from two different coils.

1.1.2 Optical Microscopy

Samples of 409M (both annealed and normalized), SS 430, SS 304 and mild steel were chosen for microstructure studies. Metallography specimens[3], were cut using EDM machine. The extracted specimens were prepared by following the standard metallographic procedure discussed below.

(1) **Grinding:** Rough Grinding is done with belt grinder to improve the flatness of the sample. The rough grinding is continued until the surface is flat and free of nicks, burrs, and scratches due to hacksaw or cut of wheel.

(2) **Intermediate Polishing:** Polishing is done to remove scratches from the surface of the specimen. The sample is polished on series of emery papers containing finer abrasives like 120, 240, 400, 500, 800 grit papers. Intermediate Polishing operations using emery paper are usually done dry. The specimen is rotated progressively by 90° between successive polishing in emery paper.

(3) **Disc polishing:** Disc polishing is further done to make the surface totally scratch free and to impart mirror finish. It is polished with diamond abrasive of 9 μ, 1 μ and ½ μ charge cloth with diamond paste. The specimen is then cleaned using acetone and dried using a hot air dryer. Now the specimen is viewed in the microscope to confirm the surface finish and re-polishing is done if necessary. The finished mounts are preserved carefully for viewing the micrographs.

(4) **Etching:** The purpose of etching is to make visible the structural characteristics of this steel. The etching process must be such that different phases of the microstructure may be clearly differentiated. This is accomplished by the use of an appropriate reagent which subjects the polished surface to preferential chemical attack. Etchant is applied on the surface of the specimen to reveal the grain boundaries. The specimens were etched using Aqua regia.

1.1.3 Etching Details

The etchants used are Aqua regia, Nitric Acid (30ml), Hydrochloric acid (70ml). The etching time takes about 10-15 seconds. After etching the specimen is cleaned immediately in running water followed by swabbing with acetone. Then it is dried under infra red lamp for few minutes[4]. After preparing the metallographic specimen, the specimen is observed under Leica make optical microscope at different magnifications such as 100X, 200X and 500X.

1.2 Wear Characterization

The experimental procedure used for studying the dry sliding wear was done using pin on disc apparatus.

1.2.1 Specimen Preparation

The wear specimens of dimensions (10mmX10mmX8mm) were cut in the EDM machine. Since minimum height requirement is 40 mm, wear specimen is attached with the mild steel rod to match this 40 mm height. The grinding of end faces of the pins is done using emery papers of five different grades 220, 400, 600, 800 and 1000 in the same order. Grinding was followed by polishing with 1/0, 2/0, 3/0 and 4/0 grades polishing papers.

1.2.2 Experimental Set Up

Dry sliding wear tests for the SS409M cylindrical specimens were conducted using a pin- on -disc machine (Wear and Friction Monitor Tester TR-201 made by M/S DUCOM, Bangalore, INDIA) conforming to ASTM G 99 standard. Wear tests were performed on the pin specimens that has flat surfaces in the contact regions and the rounded corner. The pin was held stationary against the counter face of a rotating disc made of carbon steel (EN-31) at minimum of 50mm diameter and a maximum of 100mm diameter. The composition of the material of the steel disc is given in Table 2.2.

Table 1.2 Chemical composition (wt %) of the En-31 carbon steel disc

C	Si	Mn	S	P
0.42 (max)	0.05- 0.35	0.40- 0.70	0.05(max)	0.05 (max)

A pin- on -disc machine was used to investigate the dry sliding wear characteristics of the SS 409M samples as per ASTM G99 standard. Both the pin and the counter face were cleaned with acetone before experimentation. The experiments were conducted to study the effect of sliding speed, applied load, sliding distance on wear behavior of SS 409M. The tests were conducted with the load ranging from 2kg to 4kg at different sliding speed and different sliding distances were considered at constant sliding speed and applied load. All these tests were conducted at room temperature. During the test, the pin was pressed against the counterpart rotating against an EN 32 steel disc having hardness of 65 HRC by applying load. After running through a fixed sliding distance, the specimen were removed, cleaned with acetone, dried and weighed to determine the weight loss due to wear. The difference in the weight measured before and after test gives the wear of the specimen. The wear of the stainless steel was studied as a function of the volume percentage, sliding distance, applied load and the sliding velocity.

1.2.3 Wear Rate

The wear rate data for the coated as well as uncoated specimens were plotted with respect to sliding distance to establish the wear kinetics. The specific wear rates for the

coated and uncoated material were obtained by $W = \delta w / L \rho F$ where W denotes specific wear rates in Bowden (B) ($1B=10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$) [Recommendation from IRG OECD meeting with about 30 participants to introduce a new unit for wear rate: Bowden (B) equal to $10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$], δw is the weight loss measured in g, L is the sliding distance in m, ρ the density of the worn material in g/mm^3 and F the applied load in N[5].

1.2.4 Wear Volume

The wear volume loss was also calculated from the weight loss and density of the coatings as well as substrate material for all the investigated cases. These data were reported in the form of plots showing the cumulative wear volume loss V_s sliding distance for all the cases. Bar charts were also drawn to show net Volume = mass / density.

$$\text{Wear Volume Loss} = (\delta w / 9.81) / \rho$$

where δw is the weight loss in, g
 ρ is the density of material, g/mm^3

1.2.5 Coefficient Of Friction

The coefficient of friction (μ) determined from the frictional force and the normal load has been plotted against the sliding time to give the friction behavior of the coated as well as the uncoated material. The coefficient of friction (μ) was calculated as below: $\mu = \text{Frictional Force (N)} / \text{Applied Normal Load(N)}$.

2.3 Corrosion Test

Mild steel, SS 409M, SS 430 and SS 304 of dimension $10\text{mm} \times 10\text{mm} \times 8 \text{ mm}$ were used to study the corrosion in 3 wt % NaCl solution. The samples were polished successively using emery sheets of 120, 320, 1000 and 2000 grades and then cleaned with acetone. Polarization tests were carried out using potentiostat of model Gamry600 framework using an inbuilt Echem software corrosion rate and current values obtained. Electrochemical impedance spectroscopy is used to analyse the corrosion in 3 wt % NaCl solution further. This test was carried out at open circuit potential. Nyquist and Bode plot was obtained from this test.

2.4 Scanning Electron Microscopy (SEM)

The SEM provides the highly magnified image of the surface of the material. The resolution of the SEM can approach a few nm and it can operate at magnifications that are easily adjusted from 10 to 100000 X. The specimens after the wear and corrosion test were cleaned with acetone and then dried. SEM characterization was done at 25kV accelerating voltage[6,7]. Samples were loaded on the specimen table in the SEM chamber and the necessary vacuum was created using rotary and mechanical pumps. SEM micrographs were taken for all the samples after wear and corrosion test at different magnifications such as 100x, 200x and 500x in secondary electron (SE) mode.

3. RESULTS AND DISCUSSION

3.1 Optical Microscope Results

The microstructure of the specimens using optical microscope is shown in the Figure 3.1 Microstructure of mild steel which has ferrite and pearlite structures, in the Figure 3.2 Microstructure of 409M (Annealed) has ferrite and low tempered martensite, in the Figure 3.3 Microstructure of SS 409M (Normalized) has ferrite and more tempered martensite when compare with 409M (Annealed), in the Figure 3.4 Microstructure of SS 430 as an ferritic stainless steel has ferrite structure, in the Figure 3.5 Microstructure of SS 304 is an austenitic stainless steel has twine structure.

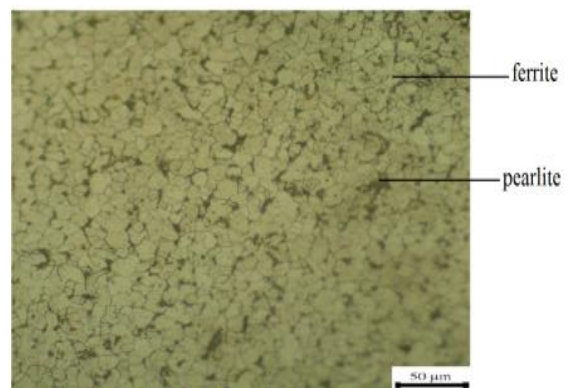


Fig3.1 Microstructure of mild steel



Fig3.2 Microstructure of 409M (Annealed)



Fig 3.3 Microstructure of SS 409M (Normalized)

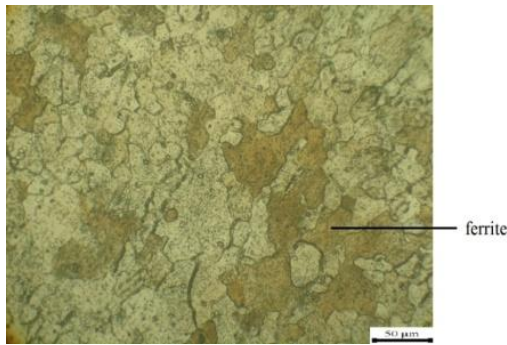


Fig 3.4 Microstructure of SS 430

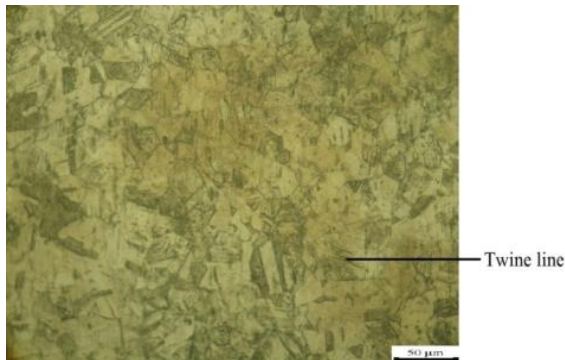


Fig 3.5 Microstructure of SS 304

3.2 Wear Behaviour

The wear test for 409M (Annealed and Normalized), mild steel, SS 430 and SS 304 are carried out using Pin On Disc machine. The test was conducted using 2kg, 3kg, 4kg at a speed of 500 rpm for 10, 15 and 20 minutes of time period respectively [8]. The wear rate and volume of mild steel for different loads and at various times are given in the Figure 3.1. Figure 3.2 gives the result for SS 409M (Annealed), Figure 3.3 for SS (Normalized), Figure 3.4 provides the results for SS 430 steel and Figure 3.5 provides the results for SS 304.

3.2.1 The Variations of Wear Volume Loss with Sliding Distance at 2kg, 3kg and 4 kg load for Different Steels are shown in Figure 3.1, Figure 3.2 and Figure 3.3 respectively.

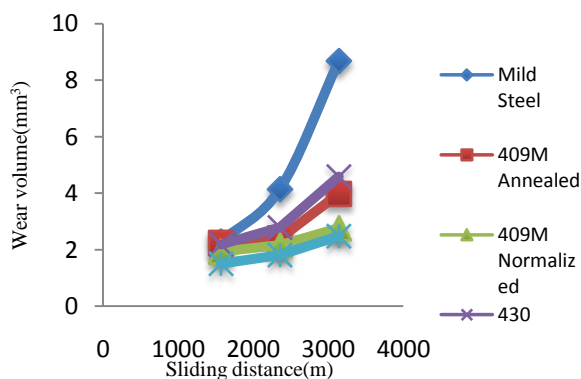


Fig 3.1 Variations of wear volume loss Vs sliding distance at 2Kg load

The higher wear volume of mild steel, SS 409M (Annealed), SS 409M (Normalized), SS 430 and SS 304 at 2kg load for 20 minutes is 8.6798 mm³, 3.9743 mm³, 2.7650 mm³, 4.5913 mm³ and 2.4767 mm³ respectively. Mild steel has higher wear volume loss which results in lower wear resistance. SS 409M (Annealed) and SS 409M (Normalized) have lower wear volume loss compared with mild steel and SS 430. In comparison with all these materials SS 304 has lower wear volume loss which results in superior wear resistance.

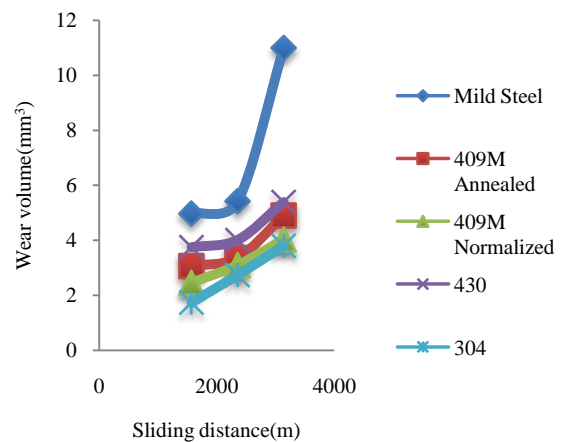


Fig 3.2 Variations of wear volume loss Vs sliding distance at 3Kg load

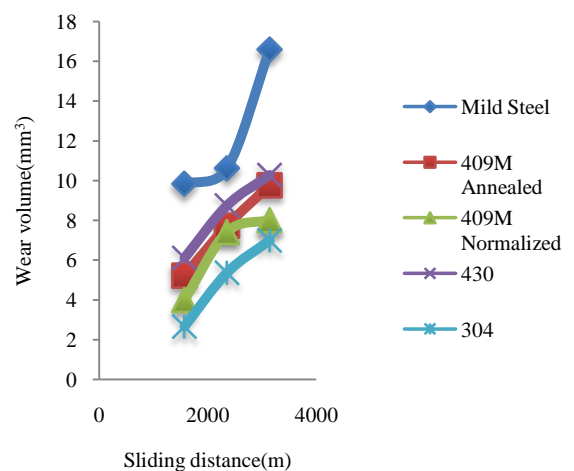


Fig 3.3 Variations of wear volume loss Vs sliding distance at 4Kg load

The higher wear volume of mild steel, SS 409M (Annealed), SS 409M (Normalized), SS 430 and SS 304 at 4kg load for 20 minutes is 16.5870 mm³, 9.7692 mm³, 8.0172 mm³, 10.2800 mm³ and 6.9960 mm³ respectively. Mild steel has higher wear volume loss, which results in lower wear resistance. SS 409M (Annealed) and SS 409M (Normalized) have lower wear volume loss compared with Mild steel and SS 430. When wear loss is compared with 409M (Annealed and Normalized) 409M Normalized has lower wear loss. Compared with all these materials SS 304 has lower wear volume loss, which results in superior wear resistance.

3.2.2 The variation of Wear Rate with Load at a Sliding Distance of 1570.80m, 2356.19m and 3141.59m for Different Materials are shown in the Figure 3.4, Figure 3.5 and Figure 3.6 respectively.

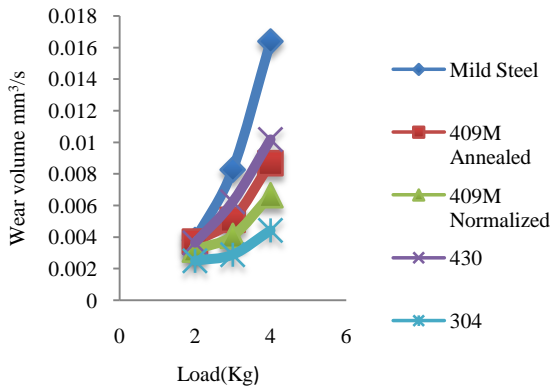


Fig 3.4 Variations of wear rate Vs load at sliding distance of 1570.80m

The higher wear rate of mild steel, SS 409M (Annealed), SS 409M(Normalized), SS 430 and SS 304 at 1570.80m travel distance for 4kg load is 0.0163980 mm³/s, 0.0407 mm³/s, 0.006671 mm³/s, 0.010190 mm³/s and 0.004400 mm³/s respectively. Mild steel has higher wear rate which results in lower wear resistance. SS 409M (Annealed) and SS 409M(Normalized) have lower wear rate compare with Mild steel and SS 430. When wear rate is compared with 409M (Annealed and Normalized) 409M Normalized have lower wear rate. In comparison with all these materials SS 304 has lower wear rate which results in superior wear resistance.

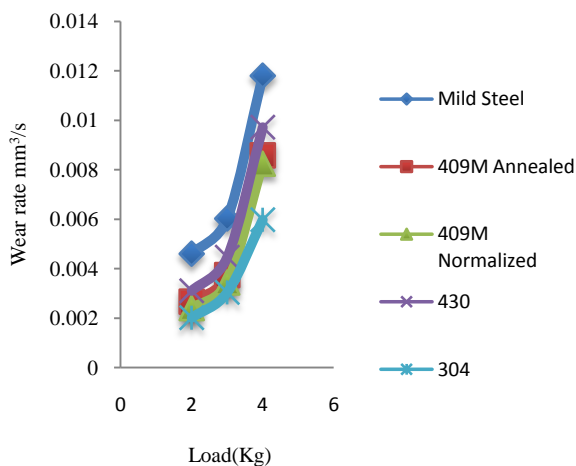


Fig 3.5 Variations of wear rate Vs load at sliding distance of 2356.19m

The higher wear rate of mild steel, SS 409M (Annealed), SS 409M(Normalized), SS 430 and SS 304 at 2356.19m travel distance for 4kg load is 0.0118000 mm³/s, 0.0085800 mm³/s, 0.008242 mm³/s, 0.0097263 mm³/s and 0.005971 mm³/s respectively. Mild steel has higher wear rate, which

result in lower wear resistance. SS 409M (Annealed) and SS 409M(Normalized) have lower wear rate compare with Mild steel and SS 430. When wear rate is compare with 409M(Annealed and Normalized) 409M Normalized have lower wear rate. In comparison with all these materials SS 304 has lower wear rate, which results in superior wear resistance.

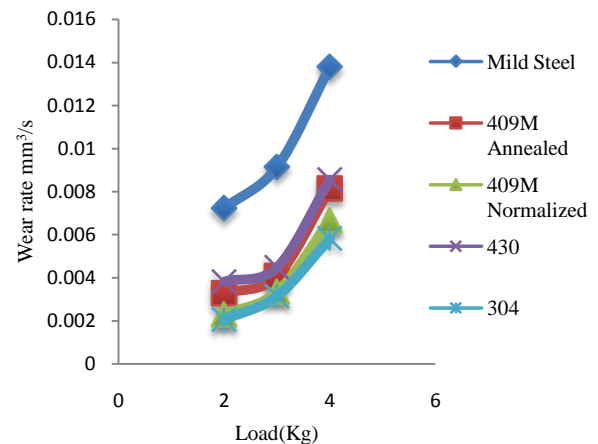


Fig 3.6 Variations of wear rate with load at sliding distance of 3141.59m

The higher wear rate of mild steel, SS 409M (Annealed), SS 409M(Normalized), SS 430 and SS 304 at 3141.51m travel distance for 4kg load is 0.013160 mm³/s, 0.0081420 mm³/s, 0.006681 mm³/s, 0.0085667 mm³/s and 0.005830 mm³/s respectively. Mild steel has higher wear rate, which result in lower wear resistance. SS 409M (Annealed) and SS 409M(Normalized) have lower wear rate compare with Mild steel and SS 430. When wear rate is compare with 409M(Annealed and Normalized) 409M Normalized have lower wear rate in In comparison with all these materials SS 304 has lower wear rate, which results in superior wear resistance.

3.3 SEM Images after Wear Test

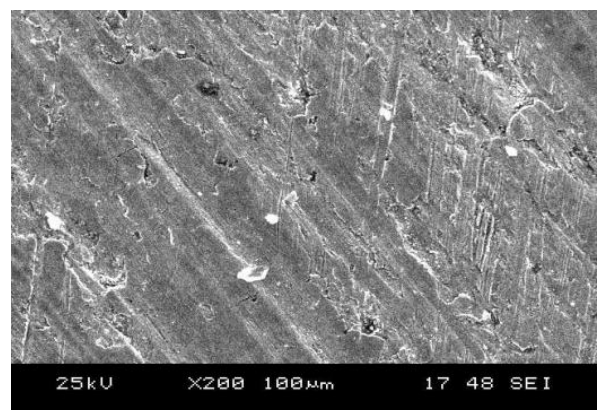


Fig3.7 SEM Image of Mild Steel after Wear test

The SEM Image of Mild Steel after wear test at 4 kg load at a speed of 500rpm and for 20 minutes time period is shown in the Figure 3.7. Wear track formation on the surface can be seen.

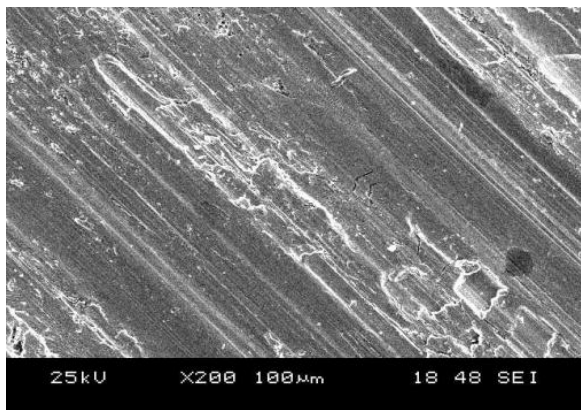


Fig 3.8 SEM Image of 409M (Annealed) after Wear test

The SEM Image of 409M (Annealed) after wear test at 4 kg load, speed of 500rpm and for 20 minutes time period is shown in the Figure 3.8. Uniform wear track formation on the surface can be seen.

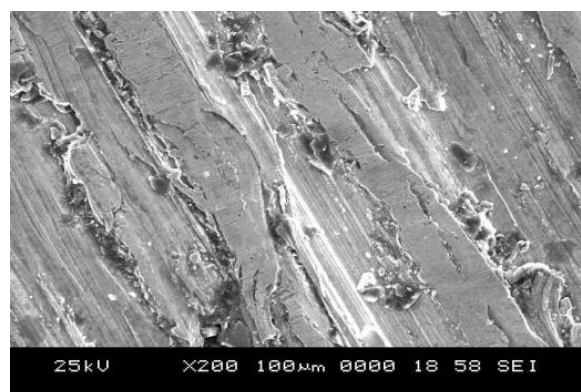


Fig 3.9 SEM Image of 409M (Normalized) after Wear test

The SEM Image of 409M (Normalized) after wear test at 4 kg load, speed of 500rpm and for 20 minutes time period is shown in the Figure 3.9. Wear track formation on the surface can be seen.

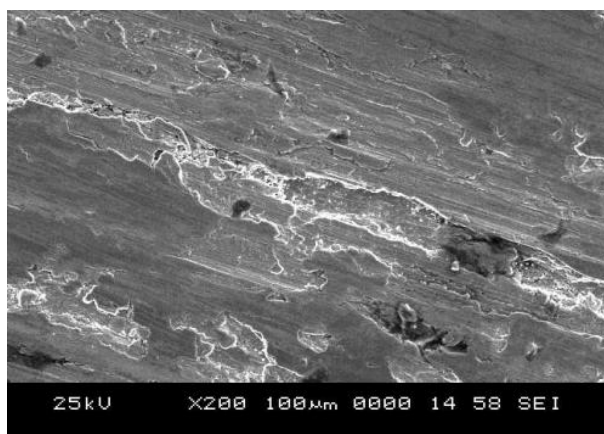


Fig3.10 SEM Image of 430 after Wear test

The SEM Image of 430 after wear test at 4 kg load, speed of 500rpm and for 20 minutes time period is shown in the Figure 3.10. Wear track formation on the surface can be seen.

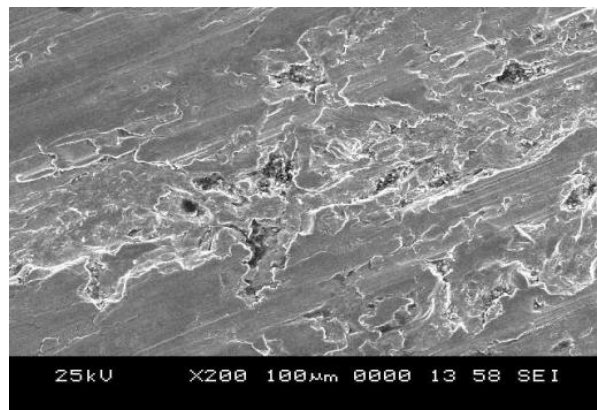


Fig3.11 SEM Image of 304 after Wear test

The SEM Image of 304 after wear test at 4 kg load, speed of 500rpm and for 20 minutes time period is shown in Figure 3.16. Wear track formation on the surface can be seen.

3.4 Corrosion Test

The corrosion test for 409M (Annealed and Normalized), mild steel, SS 430 and SS 304 is carried out using Potentiostat in 3 wt % of NaCl solution. Polarization curve is generated using Gamry600 framework using inbuilt Echem software. This was carried out in open circuit potential[9]

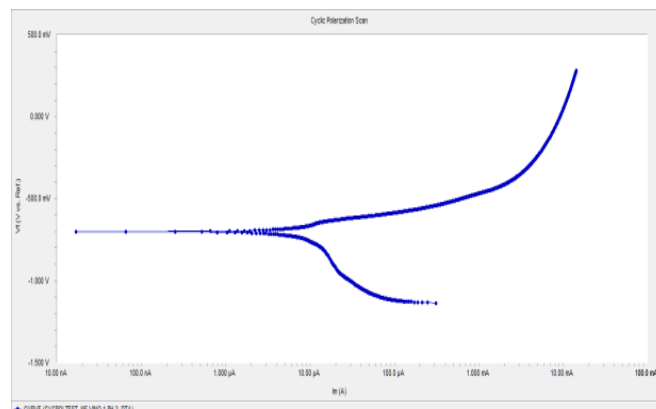


Fig 3.11 Polarization curve of Mild steel

The Polarization curve of Mild steel is shown in Figure 3.17. In this curve mild steel does not exhibit passivation , only dissolution of electrons takes place.

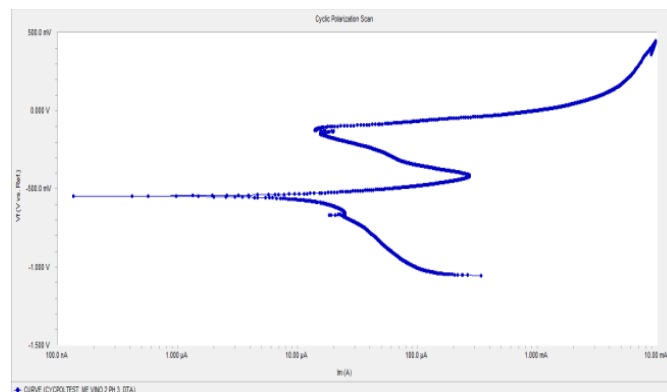


Fig 3.12 Polarization curve of SS 409M (Annealed)

The Polarization curve of SS 409M (Annealed) is shown in the Figure 3.12. In this curve SS 409M (Annealed) exhibits passivation from (-400mV to -50mV).

The Polarization curve of SS 304 is shown in Figure 3.15. In this curve SS 304 exhibits passivation from (-250mV to 250mV).

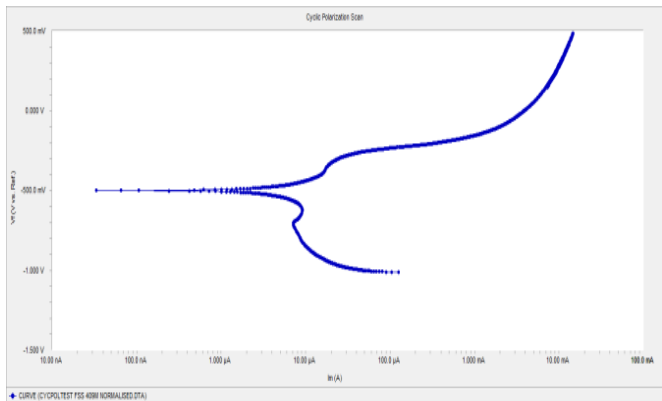


Fig 3.13 Polarization curve of SS 409M (Normalized)

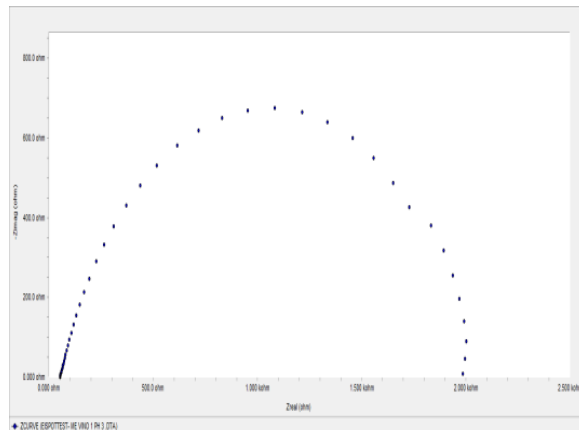


Fig 3.16 NYQUIST PLOT for Mild steel

The Polarization curve of SS 409M (Normalized) is shown in Figure 3.19, in this curve SS 409M (Normalized) exhibits less passivation.

The NYQUIST PLOT for Mild steel is shown in Figure 3.16. In this curve Mild steel exhibit the R polarization values of 2 kohm. This results in lower corrosion resistance.

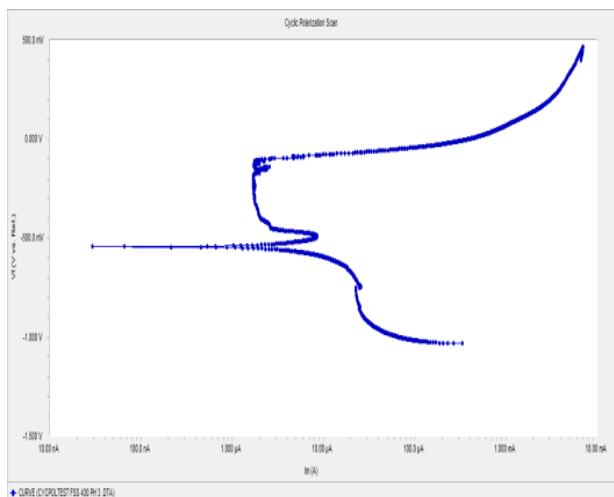


Fig 3.14 Polarization curve of SS 430

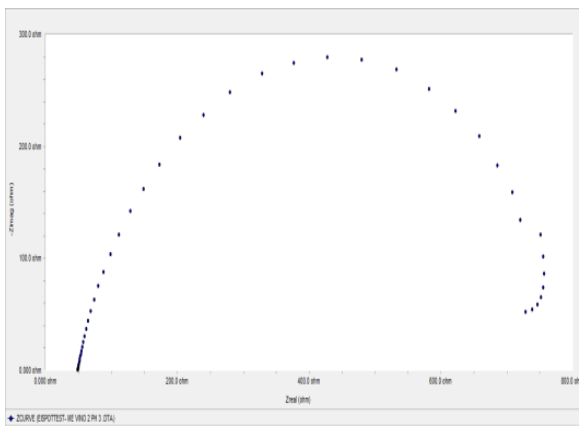


Fig 3.17 NYQUIST PLOT for SS 409M (Annealed)

The Polarization curve of SS 430 is shown in the Figure 3.20. In this curve SS 430 exhibits passivation from (-500mV to 0.00mV).

The NYQUIST PLOT for SS 409M (Annealed) is shown in Figure 3.17. In this curve SS 409M (Annealed) exhibits the R polarization values of 8kohm. This results in higher corrosion resistance than mild steel.

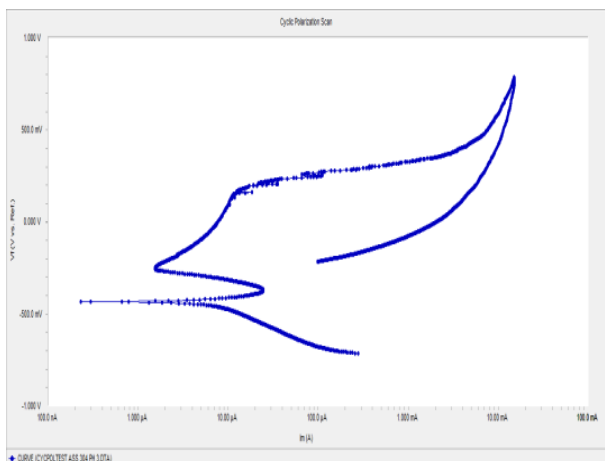


Fig 3.15 Polarization curve of SS 304

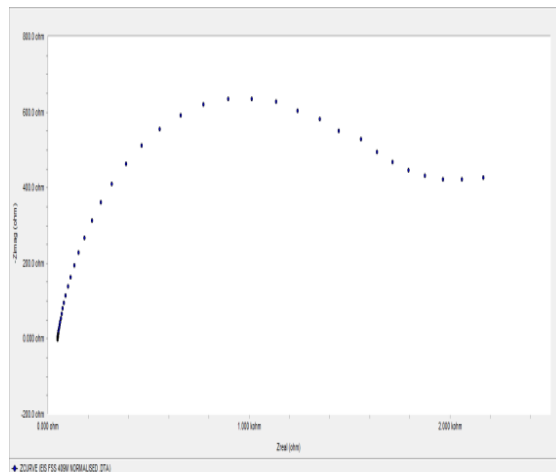


Fig 3.18 NYQUIST PLOT for SS 409M (Normalized)

The NYQUIST PLOT for SS 409M (Normalized) is shown in Figure 3.18. In this curve SS 409M (Annealed) exhibits the R polarization values ends at some infinite point. This results in higher corrosion resistance.

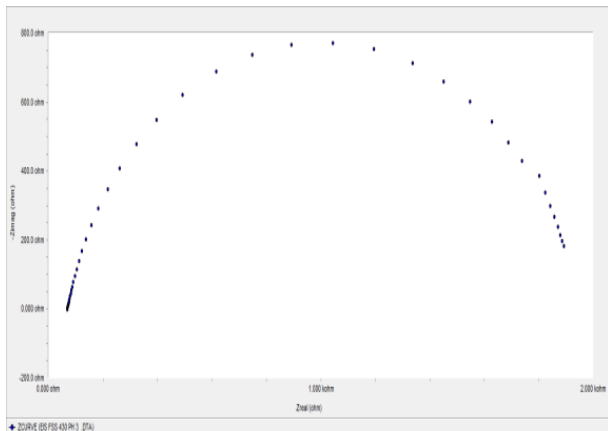


Fig3.19 NYQUIST PLOT for SS 430

The NYQUIST PLOT for SS 430 is shown in Figure 3.19. In this curve SS 430 exhibits the R polarization values ends at some infinite point. This results in higher corrosion resistance when compared with mild steel, SS 409M (Annealed), and SS 409M (Normalized).

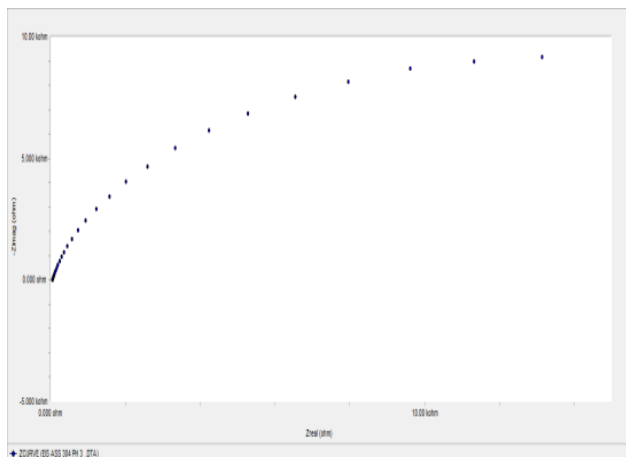


Fig 3.20 NYQUIST PLOT for SS 304

The NYQUIST PLOT for SS 304 is shown in Figure 3.26. In this curve SS 304 exhibits the R polarization values ends at some infinite point. This results in higher corrosion resistance when compared with mild steel, SS 409M (Annealed), SS 409M (Normalized) and SS 304.

3.4.1 Electrochemical Tests carried out using 3 pH NaCl Solution

Table 3.21 Result of electrochemical test in 3 wt % of NaCl solution

Material	icorr (µA/cm ²)	Ecorr (mV)	Corrosion Rate (mpy)
Mild Steel	25.60	-701.0	19.72
SS 409M	13.20	-545.0	8.031

(Annealed)			
SS 409M (Normalized)	15.80	-498.0	11.42
SS 430	7.860	-433.0	4.727
SS 304	1.890	-543.0	1.646

The corrosion rate of SS 409M in annealed and normalized is 8.031mpy and 11.42mpy respectively. From these values 409M (Annealed) has lower corrosion rate than 409M (Normalized). SS 409M has lower corrosion rate than mild steel. The corrosion rate of SS 304 is 1.66mpy which shows superior corrosion resistance than all the materials.

3.4.2 SEM Images after Corrosion Test

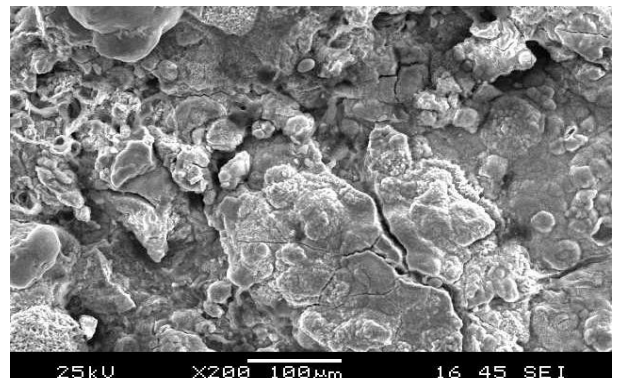


Fig 3.21 SEM Image of Mild Steel after corrosion test

The SEM Image of Mild Steel after corrosion test is shown in the Figure 3.21. We could also see the cracks along the grain boundaries that result in poor corrosion resistance.

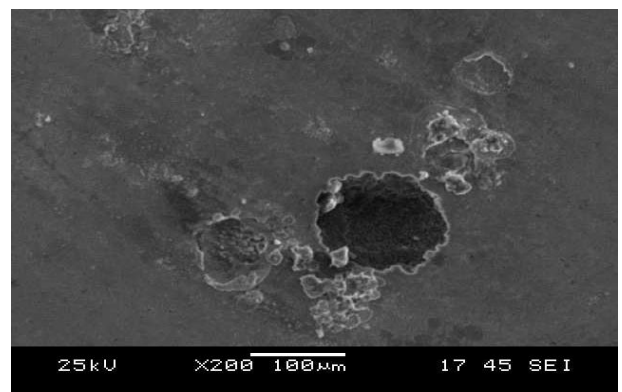


Fig 3.22 SEM Image of 409M (Annealed) after corrosion test

The SEM Image of 409M (Annealed) after corrosion test is shown in Figure 3.22. The image indicates the pit formation clearly, we could also see the dissolutions surrounding the pit.

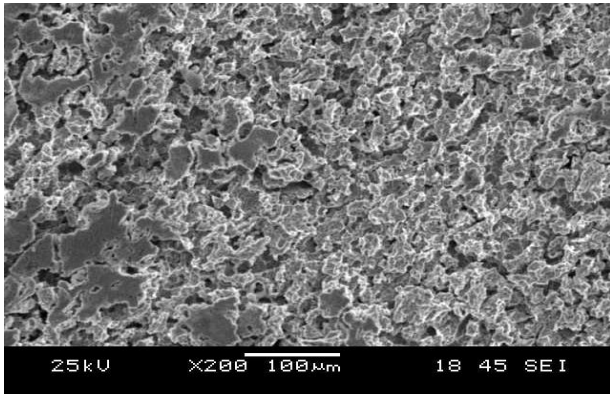


Fig 3.23 SEM Image of 409M (Normalized) after corrosion test

The SEM image of SS 409M (Normalized) after corrosion test is shown in Figure 3.23. Corrosion has been uniform throughout the surface.

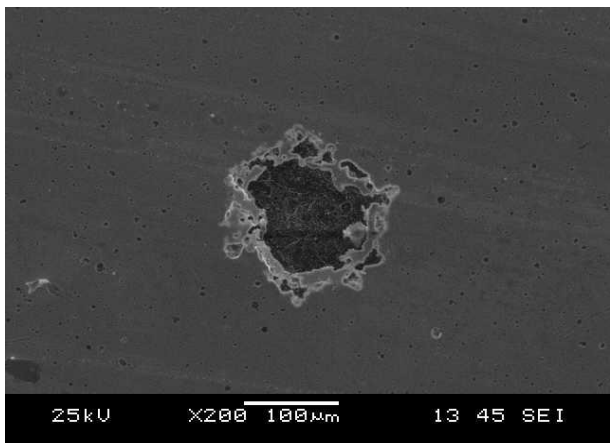


Fig 3.24 SEM Image of 430 after corrosion test

The SEM image of SS 430 is shown in Figure 3.24. We could see large pit formation and surrounding the large pit many small pits are also seen.

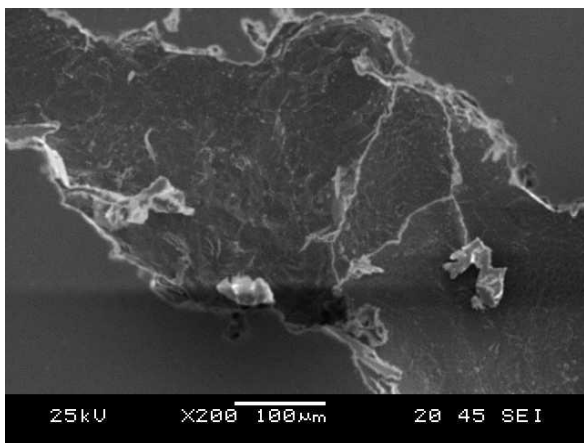


Fig 3.25 SEM Image of 304 after corrosion test

The SEM image of SS 304 corrosion test is shown in Figure 3.25, slight dissolutions on the surface can be seen.

5. CONCLUSION

The wear resistance of 409M has been studied using pin on disc machine and compared with Mild steel, SS 430 and SS 304. 409M has higher wear resistance than Mild steel and SS 430. It has lower wear resistance than SS 304. The wear mechanism could be oxidation wear. Since 409M find many structural applications, the corrosion behavior of 409M is studied using potentiostat. 409M has better corrosion resistance than mild steel and it has less corrosion resistance than SS 430 and SS 304. This is due to lower chromium content than SS 430 and SS304.

- The results show that increasing in sliding distance increase the wear volume for various loads 2kg, 3kg, and 4 kg. 409M in both annealed and normalized condition has lower wear volume loss than mild steel and SS 430 and this is in agreement with the earlier work.
- Increase in load increases the wear rate for various sliding distance 1570.80m, 2356.19m and 3141.59m. 409M has lower rate than mild steel and SS 430 in both annealed and normalized condition.
- Wear resistance of 409M both in annealed and normalized condition show higher wear resistance than that of SS 430 and mild steel.
- As expected SS 304 has superior wear resistance than SS 409M, SS 430 and mild steel.
- SS 409M has excellent passivation than mild steel, thus it has high corrosion resistance than mild steel.
- SS 304 and SS 430 show more passivation region than SS 409M and mild steel and this is in agreement with the earlier work.

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