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Effect of Heat Treatment on Mechanical Properties and Corrosion Behaviour on ASTM A36 Mild Steel

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ABSTRACT:

The present study discusses the effect of heat treatment on mechanical properties and corrosion behaviour of ASTM A36. Steel which contains 0.26% C is annealed at 830^{0}C and 870^{0}C followed by cooling in water and air. Effect on hardness ,microstructural changes and corrosion behaviour were investigated. The resulting microstructures had ferrite-plus-pearlite for annealed and normalized samples, whereas for quenched sample it is martensite-plus-ferrite. The value of ultimate tensile strength was observed to higher for the hardened specimen possibly as a result of the refinement of the primary phase after the subsequent cooling processes, followed by tempered, normalized and annealed specimens. The value of hardness is observed to be in the order of hardened > tempered > normalised > annealed. The corrosion of mild steel in 0.5 N hydrochloric acid has been investigated by weight loss and potentiodynamic polarization techniques. The heat treated specimens exhibited better corrosion resistance than as received specimen.

Keywords: Mild steel; heat treatment; microstructure; mechanical properties; corrosion

INTRODUCTION:

Mild steel (0.05–0.25 %C) is easily available and least expensive having all material properties that are acceptable for many engineering applications. ASTM A36 (C-0.26%, Mn-0.75%, S-0.05%, P-0.04% and balance Fe) is a versatile material which shows considerable properties with appreciable cost. It is the most commonly used mild and hot-rolled steel having density of 7.85g/cm^3. Mild steel is extensively used in forming tanks, bearing plates, automotive & agricultural applications, walkways, boat landing ramps and trenches because it has higher and better machinability and good weldability [1] . ASTM A36 is broadly used in structural applications because it exhibits proper combination of strength, toughness and ductility. It was however known that mechanical properties of steel were strongly connected to their microstructure obtained after hear treatment. Extensive research work was carried out on effect of heat treatment on mechanical properties by Oyeleke and Ade (2). It was found that heat treatment improves ultimate tensile strength and hardness of low carbon steel but the ductility decreases. Research works carried out by D.A. Fadare, T.G. Fadara and O.Y. Akanbi found that hardness value (NST 37-2 steel, 0.3442% C) is higher for quenched sample and it is very low for annealed sample, tensile strength is also varying in the same manner only [3]. Mild Steel is extensively used in industries as a result it corrodes when exposed to various environments and conditions. Hydrochloric acid is higher corrosive towards mild steel because of great solubility of chloride and higher mobility of chloride ions. Research works carried out by Ehteram A. Noor and Aisha H. Al-Moubaraki found that corrosion rate of mild steel (0.21%C) increases with the increase in hydrochloric acid concentration [4]. The present study discusses the effect of heat treatment on mechanical properties and corrosion response on Fe-0.24%C (ASTM A36) steels.

Experimental Procedure:

Mild steel samples of composition C-0.26%, Mn-0.75%, S-0.05%, P-0.04% and balance Fe were used. Specimens of 20 mm in diameter and 14 mm in thickness were obtained from the trader (Krish Met, Chennai, India). All specimens were austenised in two different set of temperatures such as 830^0 C & 870^0 C. Austenisation of samples were carried in Muffle furnace and Direct Heating Furnace (heating rate of 5^{0}C/min). The time taken to reach 830^0 C & 870^0 C was 166 minutes and 174 minutes respectively. Various heat treatment processes like Annealing, Normalizing, Quenching, and Tempering will be done for two set of samples at two different temperatures. After reaching required temperature, the sample is allowed to soak for 30 minutes, in order to homogenize the internal structure. Different types of cooling processes were

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adopted based on the purpose of heat treatment. Tempering of the samples proceeded in two ways, Low temperature tempering (< 250^{o}C) and Medium Temperature Tempering (250^{o}C-500^{o}C) for eight samples. The eight quenched samples were reheated to 230^{o}C and 350^{o}C for 46, 70 minutes followed cooling in both air and water. After the completion of heat treatment in order to get the microstructural details the specimens grinded and subjected to sequential steps of polishing gives scratch free, mirror surface. The specimens were then etched with 6% Nital to reveal the microstructural features. All etched samples were observed under optical microscope at 100 X magnification. Rockwell and brinell are the two different Hardness tests were conducted to the Heat treated samples. Rockwell test was performed at a minor load of 10 kg and major load of 100 kg for 20 seconds using Rockwell Hardness testing machine (Ratnakar Enterprises, RAS-model,) and Brinell test was carried at a load of 3000 kg for about 30 seconds using a steel ball indenter by using Brinell hardness testing machine (Ratnakar Enterprises, RB-3000 (J)) as per the ISO standards. Two measurements were taken at random positions to obtain more accurate results.

The definite relationship between Ultimate Tensile Strength of a metal and Brinell hardness number by some experimental work will help us to obtain UTS values.

Plain carbon steels in normalized and annealed condition:

$$\text{UTS (kg/mm}^2\text{)} = 0.36 * \text{BHN}$$

Plain carbon steels in hardened and tempered condition:

$$\text{UTS (kg/mm}^2\text{)} = 0.32 * \text{BHN}$$

The weight loss measurements of mild steel, ASTM A36 in 1 N HCl for different specimens have been performed. Samples were immersed in 100 ml solution for 90 minutes and after that they were taken out, cleaned and kept it in oven for some time (10 minutes) to dry. The initial and final weights of mild steel were taken by Electronic balance (Wenser, MAB 220 model, max. weight = 200 gm. and d=0.1 mg). Corrosion rate was found out using the formula (1) below.

$$\text{Corrosion Rate (mpy)} = \frac{534\ W}{D\,A\,T}$$

Where, W- Weight Loss (mg), D- Density of MS A36 (gm. /cm^3), A- Area of specimen (Sq. inch), T- Time of Exposure (hr.)

Electro chemical measurements were conducted on Potentiostat (IVIUM, Germany) connected to personal computer by using a conventional electrochemical cell of three electrodes. Mild steel is used as a working electrode, saturated calomel electrode as reference electrode and platinum foil as the counter electrode. The potentiodynamic polarization measurements were carried out using a scan rate of 1mV. The specimen was polished and washed with distilled water before the experiment. Before each experiment the open circuit potential (OCP) was recorded for at least 30 min. The observed current was plotted against applied potential. Faraday's law can be used to calculate the corrosion rate in terms of penetration rate (CR).

$$CR = K_1 \frac{i_{corr}}{\rho} EW$$

Where, CR is given in mm/yr, i_{corr} in μA/cm^2, $K_1 = 3.27 * 10^{-3}$ mm g/μA cm yr, ρ = density in g/cm3, EW = Equivalent weight of mild steel, is considered to be dimension less in this calculation. The mild steel equivalent weight is estimated to be 28.4693 (detail calculation is shown in appendix).

3. Results and discussions

The microstructures of all specimens are presented below in Figure: 1 (a-f) and Figure: 2 (g to n), The microstructure of annealed specimen exposed the presence of coarse ferrite and coarse pearlite (figure: 1 a, b); because after austenisation it was allowed to soak at that temperature for 1 hour so all the material was transformed into austenite, then it was cooled slowly inside the furnace so as to get coarse microstructure, but in case of normalizing it was cooled in normal atmosphere, so due to the fast cooling there is no time for grain growth which results in the structure of fine pearlite and fine ferrite (figure: 1 c, d). When it comes to quenching, after the completion of austenisation and soaking, the samples were allowed to cool in water, this rapid cooling won't give sufficient time for the grain growth so the microstructure shows martensite flakes (figure: 1 e, f) in ferrite matrix. Martensite is a metastable structure, and it decomposes to other phases when re heated to certain tempering temperatures. The specimen which is tempered

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at 250^0C revealed the transformation of retained austenite into ferrite and cementite (figure: 2 g, h, i, j) whereas 350^0C tempered specimen results in lath like Fe_3C precipitation (figure: 2 k, l, m, n) due to high tempering temperature.

The heat treated specimens hardness test were shown in Table: 1. It shows the result at a temperature of 830^0C, and 870^0C for different heat treated samples. The values of hardness for quenched specimens was observed to be much higher than annealed and normalized specimens which can be associated to the martensite structure in the former, that formed during rapid cooling (water quenching) induced lot of internal stresses in the sample. Normalized specimen also have a greater value than that of annealed sample, which can be linked with the formation of soft ferrite matrix in annealed specimen and pearlite matrix structure obtained in normalized specimen. Tempered specimens were also having higher hardness values because of the subsequent tempering process that results the formation ferrite upon the decomposition of martensite. The cooling medium will also affect in tempering processes, here the values are quite higher in water than that of air because of less time provided to cooling. The ultimate tensile strength values were observed to be in the rank of quenched > tempered > normalized > annealed, as a result of the grain re-arrangement.

Weight loss measurements for different heat treated samples are presented in table: 2. compared with as received, annealed samples are having less corrosion rate, because of the softness induced after annealing treatment and also the lack of internal stresses. The extra time in annealed 870^0C will allow removing all internal stresses, so, annealed 830^0C sample is having high corrosion rate than annealed 870^0C sample. Potentiodynamic polarization behavior of ASTM A36 in 0.5 N hydrochloric acid was shown in figure 3, 4& 5. Electrochemical measurements for different heat treated samples are presented in table: 3. Annealed samples are showing lower corrosion rates when compared with as received sample because of removing internal stresses and induced ductility in annealed samples. A good agreement was observed between weight loss measurements coupled with electrochemical measurements.

Conclusions:

From the results obtained, it can be deduced that mechanical properties reckons largely upon the various forms of heat treatment operations and cooling rate. Hence depending upon the properties and the applications that may be required for any design purpose, a suitable form of heat treatment should be adopted. For high ductile and toughness, annealing and normalizing the mild steel will give satisfactory results, along with that normalizing will also improves machinability with refined microstructure. For high hardness quenching process will be more beneficial. Tempering process will give moderate properties depending on parameters like time, temperature and cooling medium. The results obtained from weight loss and polarization measurements suggests that if there is highly corrosive atmosphere in application, heat treatment provides solution (as the corrosion rate is less for heat treated samples) but at the cost of hardness. The corrosion rates determined by weight loss and electrochemical measurements were in reasonable agreement.

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Table: 1 Mechanical properties for different heat treated samples for 830^{0}C & 870^{0}C

Sample	Rockwell Hardness [C Scale]		BHN		UTS [kg/mm^2]	
	830^{0}C	870^{0}C	830^{0}C	870^{0}C	830^{0}C	870^{0}C
As received	C 78.5	C 78.5	477.7	477.7	171.9	171.9
Annealed	C 43.6	C 69.0	241.3	241.3	86.8	86.8
Normalized	C 67.1	C 58.9	341.3	302.1	122.8	108.7
Quenched	C 101.2	C 83.0	856.9	444.8	274.2	142.3
Tempered (230, A.Q)	C 87.2	C 72.6	444.8	387.8	142.3	124.1
Tempered (230, W.Q)	C 98.2	C 79.1	477.7	414.8	152.8	132.7
Tempered (350, A.Q)	C 92.0	C 76.0	414.8	444.8	132.7	142.3
Tempered (350, W.Q)	C 108.0	C 80.0	856.9	444.8	274.2	142.3

Table: 2 Weight Loss Measurements for different heat treated samples

Specimen	Weight Loss	Area of Specimen[Sq. Inch]	Density of MS[gm./cm^3]	Time of exposure[hr.]	Corrosion rate[mpy]
Annealed 830^{0}C	17.5	0.4809	7.85	1.5	1650
Annealed870^{0}C	10.1	0.4778	7.85	1.5	958
As Received	33.4	0.5530	7.85	1.5	2739

Table: 3 Electro chemical Measurements for different heat treated samples

Specimen	I_{corr} (μA/cm2)	Equivalent Weight (g)	Density [gm./cm^3]	Corrosion rate[mm/yr]
Annealed 870^{0}C	0.215	28.4693	7.85	$2.54*10^{-3}$
Annealed830^{0}C	0.410	28.4693	7.85	$4.86*10^{-3}$
As Received	1.275	28.4693	7.85	$15.12*10^{-3}$

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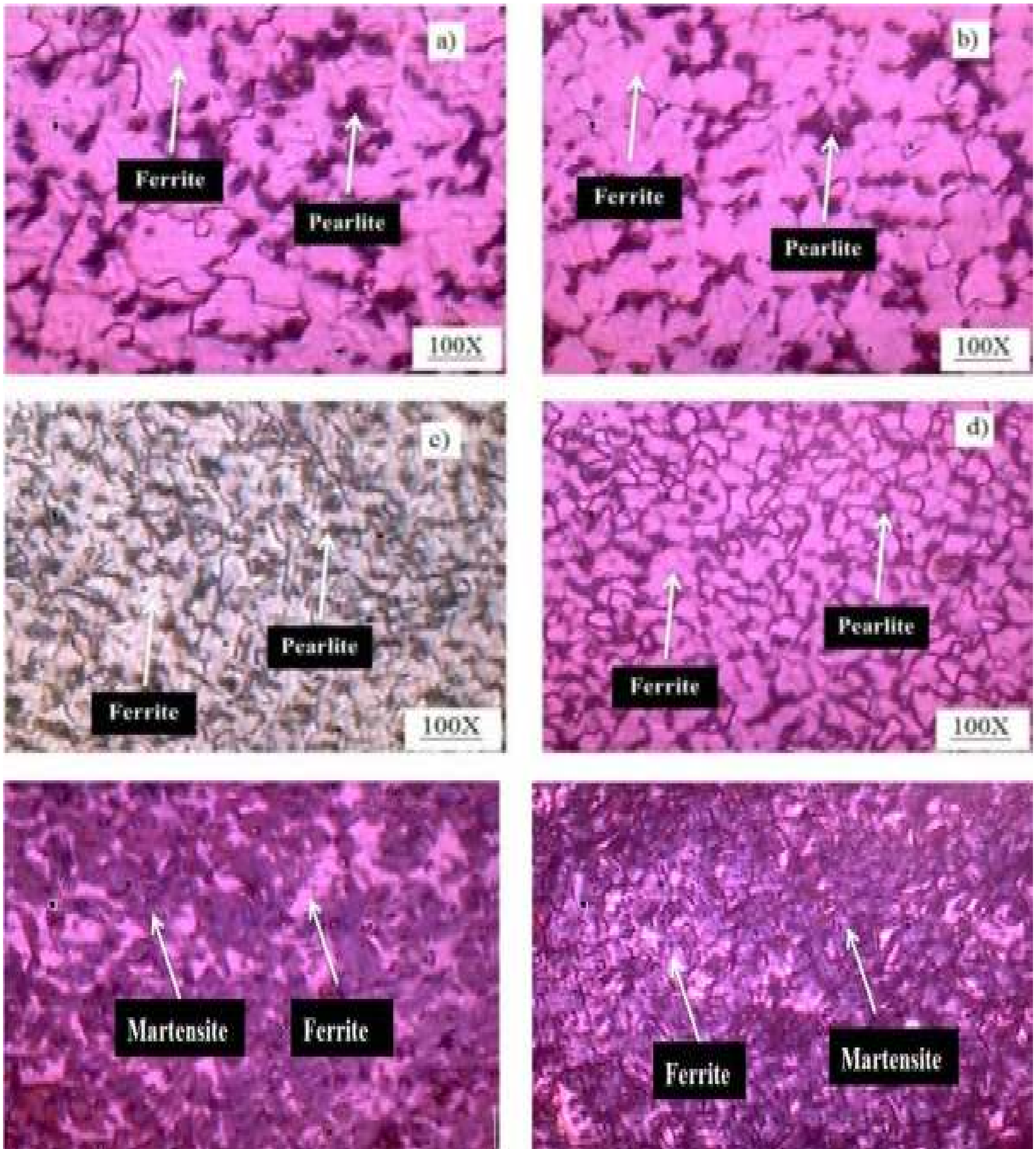

Figure 1: Microstructure of 0.26 %C steel for different heat treatments a) Annealed 830^{0}C, b) Annealed 870^{0}C, c) Normalized 830^{0}C, d) Normalized 870^{0}C, e) Quenched 830^{0}C, f) Quenched 870^{0}C.

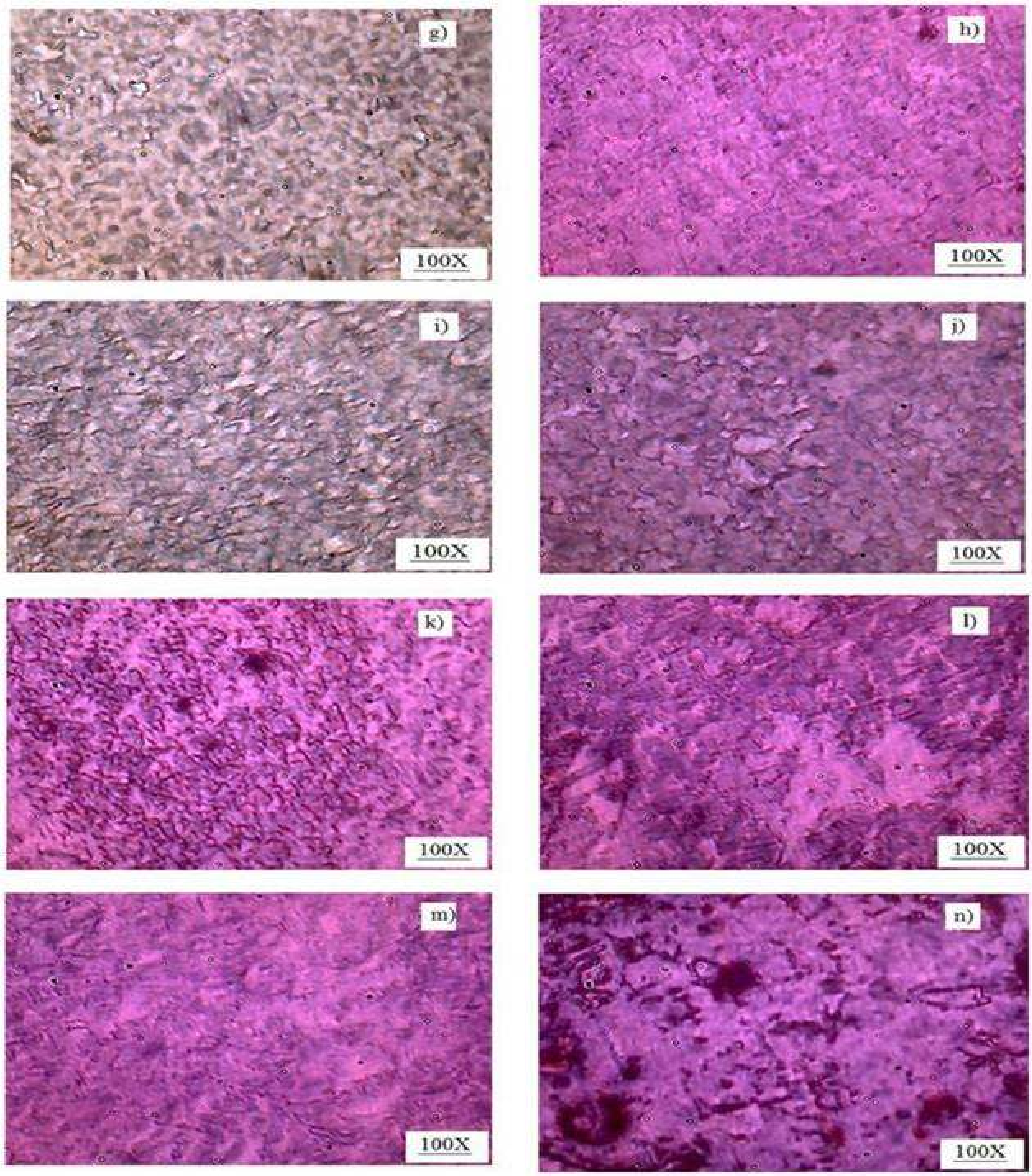

Figure 2: g) Tempered 230 air quench, h) Tempered 230 water quench, i) Tempered 350 air quench, j) Tempered 350 water quench for 830^{0}C respectively, k) Tempered 230 air quench , l) Tempered 230 water quench, m) Tempered 350 air quench, n) Tempered 350 water quench for 870^{0}C respectively are tempered microstructures for 0.26% C steel showing *tempered martensite*.

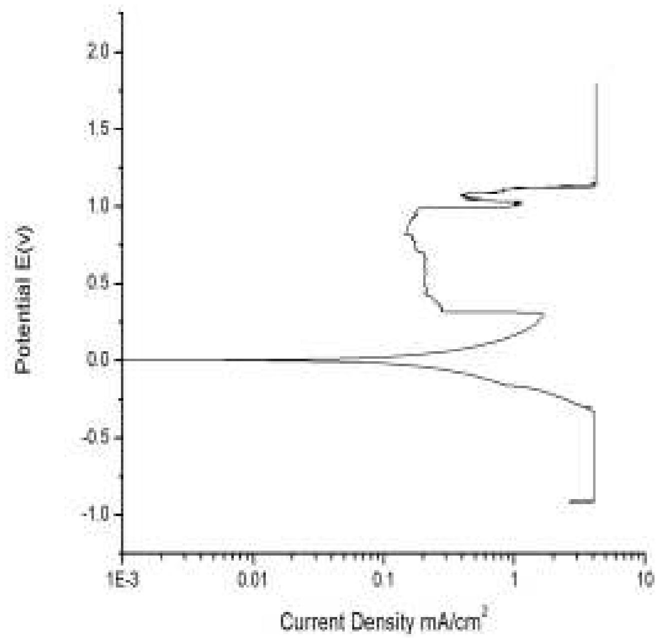

Figure 3: Potentiodynamic polarization behavior of Annealed 870^{0}C specimen in 0.5 N HCl.

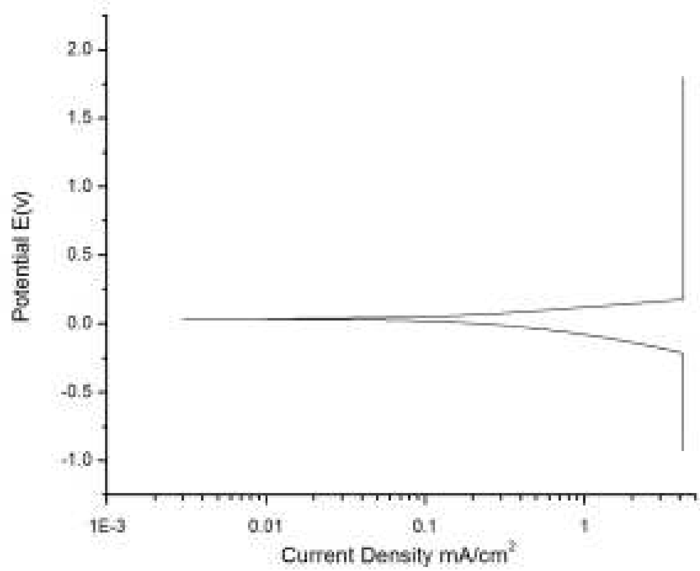

Figure 4: Potentiodynamic polarization behavior of Annealed 830^{0}C specimen in 0.5 N HCl.

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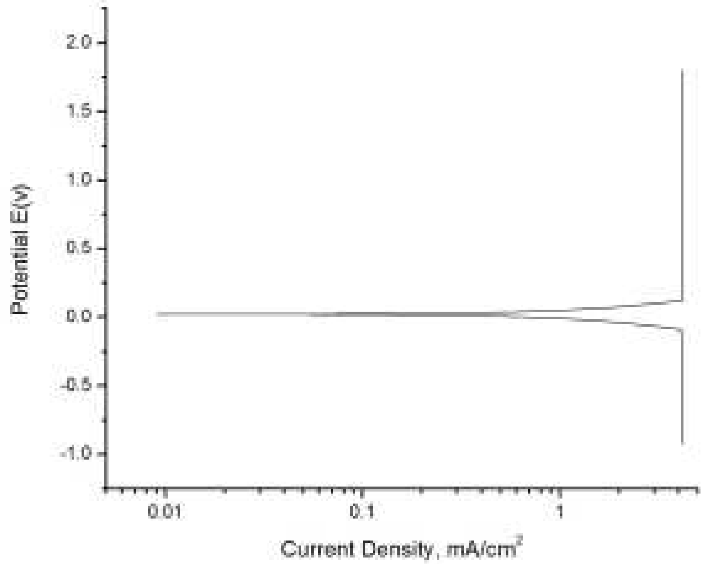

Figure 5: Potentiodynamic polarization behavior of as received specimen in 0.5 N HCl.