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Analysis of Corrosion Behaviour of Welded Austenitic Stainless Steel Immersed in Aqueous Alkaline Medium

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Authors' contributions

This work was carried out in collaboration between all authors. Authors IMBO and FGO designed the study. Author IMBO performed the experiments, wrote the first draft of the manuscript and managed literature searches. Authors DSY and IMD supervised the work. Authors FGO and IMBO managed the statistical analyses. All authors read and approved the final manuscript.

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ABSTRACT

Aims: This research is aimed at investigating the corrosion behaviour of welded austenitic stainless steel (ASS) immersed in an alkaline sodium hydroxide medium. The tensile properties of the structure were also determined.
Study Design: Weight loss method, Factorial Design of Experiment and scanning electron microscope were used for the analysis.
Place and Duration of Study: Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria, between March and November, 2014.
Methodology: The corrosion behaviour of type 304 austenitic stainless steel (ASS) immersed in sodium hydroxide (NaOH) medium (0.5 M) at ambient temperatures was investigated using conventional weight loss method together with factorial design of experiment, scanning electron microscopy (SEM), Gas metal arc welding machine. The design expert was used to determine the surface responses and interactions between the parameters; SEM was used to examine the test

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specimen microstructural analysis after immersion in the basic medium while the Monsanto Tensometer was used to examine material optimum performance in hydrochloric acid medium in terms of strength.

Results: It was found that tensile strength increased with increasing welding parameters (from 189 MN/m^2 to 203 MN/m^2). It was also found that increase in welding current and speed at constant voltage gave the optimum performance of the ASS structure in NaOH medium obtained at speed 40 mm/sec and current 110 Amp. Surface corrosion deposit composition was analyzed with the SEM paired with energy dispersive spectrometer (EDS).

Conclusion: This research shows that corrosion susceptibility of ASS in sodium hydroxide medium during the exposure time period studied is due to the aggressiveness of the hydroxyl ion (^{-}OH). The materials' susceptibility to stress corrosion cracking was conspicuous after a successful corrosion analysis in the medium with a tensile test results. It was concluded that relatively high speed and current at a constant voltage gave a satisfactory weldment of the structure.

Keywords: Welding; current; speed; austenitic stainless steel; sodium hydroxide; SEM; EDS.

1. INTRODUCTION

The discovery of stainless steels, over 100 years ago, made possible large scale building of equipment and devices that are corrosion and oxidation resistant. Knowledge acquired in the development and improvements made in these steels have later been used in the development of nickel or cobalt-base superalloys. Despite these developments, austenitic stainless steels (ASSs) are still nowadays widely used, mainly due to their simple processing and their lower price. For instance, the ASSs are used at high temperatures in the following industries: aerospace, heat treating equipment, mineral and metallurgical processing, chemical processing, petroleum refining and petrochemical processing, ceramic, electronic, and glass manufacturing, automotive, pulp and paper, fossil fuel power generation, coal gasification and nuclear [1].

Austenitic stainless steels constitute the largest stainless steel family in terms of alloys and usage. They include these grades: Iron-chromium-nickel grades corresponding to both standard AISI 300-series alloys and modified versions of these alloys. Such alloys, which are based on type 304 stainless steel, generally contain 16 to 26% Cr, 8 to 22% Ni, and small amounts of other alloying elements such as molybdenum, titanium, niobium, and nitrogen [2]. The role of Cr is to passivate. Even though Cr is generally a less noble metal than iron, this passivation converts the steel from being a 'normal', active alloy that fits within the electrochemical series, to a passive alloy with a vastly improved corrosion resistance [3].

Many researchers have worked on stainless steels. Tanimu [4], investigated the effects of welding and heat treatment on mechanical properties of duplex stainless steel using GMAW and SMAW processes. He found out that welding and heat treatment really affected the mechanical properties of the alloy. Loto et al. [5] investigated the resistance and susceptibility of austenitic stainless steel, Type 304, exposed to strong tetraoxosulphate (VI) acids (2 and 5M concentrations) contaminated with sodium chloride at ambient temperatures. The results obtained showed the weak corrosion resistance/appreciable corrosion susceptibility of the stainless steel alloy to the test environments. Hence, it is therefore pertinent to investigate the influence of some welding parameters on the corrosion behavior of austenitic stainless steel type 304 in alkaline medium.

This research is aimed at investigating the corrosion behaviour of a welded ASS immersed in an alkaline sodium hydroxide medium.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

2.1 Materials/Equipment

ASS was locally sourced for at Kakuri Market in Kaduna State, Nigeria, and its chemical composition was analyzed in National Metallurgical Development Centre, Jos as shown in Table 4. Other materials that were used are: stainless steel electrode wire of 0.9 mm, acetone, distill water and paper grit of 340, 400, 600 and 800 and the selected medium; sodium hydroxide (NaOH). The equipment were; Gas Metal Arc Welding machine, Digital Weighing Balance, Grinding Machine and Phenom ProX Scanning Electron Microscope.

2.2 Experimental Procedure

A 120 mm x 15 mm x 3 mm dimension of ASS was used for this analysis. The sample was cut to produce a plain face sample for butt welding, with a root opening of 2 mm. The butt welding method was used as shown below in Fig. 1. The number of passes used was one on the specimen according to Omiogbemi et al. [6]. Specimens were cleaned of dirt and oil using paper grit (340, 400, 600 and 800) and acetone. Grinding machine was used to grind their surfaces prior to and after welding.

2.3 Factorial Design of Experiment for the Welding Parameters

Three factors were selected to investigate the corrosion behaviour of welded ASS in sodium hydroxide medium. Speed (S), Current (I) and constant Voltage (E) which are represented as A, B and C respectively are the parameters. The corrosion behaviour was investigated by varying these factors at two levels (22), high (+1) and low (-1) with a centre point (0) in the experimental runs (Tables 1 and 2). The interactions between these factors were studied and optimization was done using three dimensional plots and cube plots according to Okibe [7]. Design Expert software 6.0.6 was used to generate the experimental runs and for the statistical analysis of weight loss in milligram of the ASS in the NaOH in an interval of eight (8) for forty (40) days as shown in Fig. 3 and Fig. 4.

2.4 Weight Loss Measurement

The samples of ASS were immersed in 1 dm^3 of volumetric flask containing solution of 20.89 $cm^3$of NaOH as prepared in accordance with

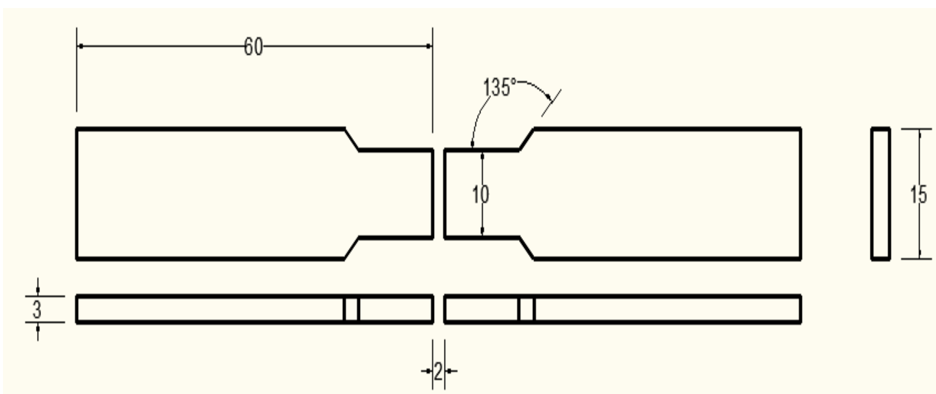

Fig. 1. Standard joint preparations for plain face sample for welding

Table 1. Factors and levels used in the factorial design for the welding parameters

Welding parameters	Symbol	Unit	Factor levels		
			Low (-)	Centre (0)	High (+)
Speed	S	cm/min	20	30	40
Voltage	E	Volts	230	230	230
Current	I	Amp	90	100	110

Table 2. Design matrix for the welding parameters of the welded ASS

Std	Run	A: Speed (cm/min)	B: Current (Amp)	C:Voltage (volts)
1	1	20	90	230
3	2	20	110	230
5	3	30	100	230
4	4	40	110	230
2	5	40	90	230
6	6	30	100	230

Yawas [8] for 40 days. The test specimens were taken out of the alkaline medium after every 8 days, wash with distilled water and acetone, air dried and re-weighed. The digital weight balance machine of sensitivity of 0.0001 g was used to assess the weight loss of the samples.

2.5 Sample Labeling

Table 3. Sample labeling

Sample C	Control sample not welded and not immersed (As received)
Sample C_1	Sample welded with 20cm/min speed and 90A current at constant voltage of 230V
Sample C_2	Sample welded with 20cm/min speed and 110A current at constant voltage of 230V
Sample C_3	Sample welded with 30cm/min speed and 100A current at constant voltage of 230V
Sample C_4	Sample welded with 40cm/min speed and 110A current at constant voltage of 230V
Sample C_5	Sample welded with 40cm/min speed and 90A current at constant voltage of 230V

3. RESULTS AND DISCUSSION

3.1 Chemical Composition of Research Material

The actual chemical composition of the research material was determined using X-ray florescence test.

The result in Table 4 shows that the material is an austenitic stainless steel type 304. This is due to the presence of high percentage of chromium (Cr) and nickel (Ni) as major alloying elements, low percentages of Carbon (C) and other elements in accordance with the AISI standard grade.

3.2 Results of Factorial Design

The analysis of variance (ANOVA) is presented in Table 5. From the results of the ANOVA, model F-value of 50.44 implies that the model is significant. There is only a 1.95% chance that a "Model F-Value" could occur due to noise. Values of "Prob > F" less than 0.0500 indicate model terms are significant. Since model terms A, B and AB are all less than 0.0500, it therefore means that they are all significant model terms.

Presented in Table 6 is the variation of the selected welding parameters (factors) affecting the behaviour of ASS in 0.5 M concentration of sodium hydroxide medium and the corresponding weight loss in milligrams obtained after each experimental run was performed on the welded ASS immersed for 40 days in an interval of 8 days. The results show that experimental run four (4) gave the least weight loss values for eight (8) days and forty (40) days as 0.0008 mg and 0.0020 mg respectively at a welding speed of 40 cm/min, welding current of 110 Amperes at a constant voltage of 230 volts. This implies that experimental run four (4) gave the minimal weight loss value. This shows a good corrosion resistance of the steel to the environment since the least weight loss was observed with it.

Figs. 2 – 3 are the response surface plots to show the interactions between the speed and current at constant voltage on the ASS immersed in 0.5 M concentration of NaOH for eight (8) days and forty (40) days. From the results obtained, the interactions of these two variables on the ASS were clearly shown. Increase in welding current and welding speed at constant voltage gave the optimum performance of the ASS in the environment (that is, at speed of 40cm/min and current of 110 Amp). The least weight loss values for eight (8) days and forty (40) days were 0.0008 mg and 0.0015 mg at a welding speed of 40 cm/min and welding current of 110 Amperes at a constant voltage of 230 volts as shown in Figs. 2 and 3 respectively. These substantiate the best welding parameters' values to obtaining an optimum performance of an ASS occurs when the current and the speed were moderately high.

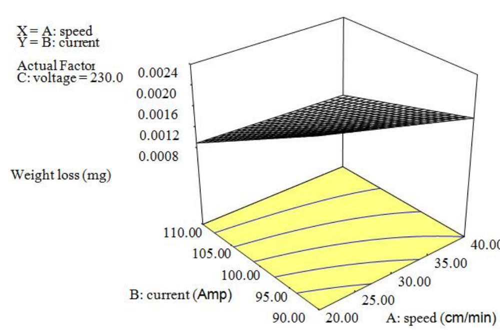

Fig. 2. Response surface plot for ASS immersed in NaOH for 8 days

Table 4. Chemical composition (wt %) of ASS sample

Element	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Fe
Wt %	0.122	0.540	1.360	0.030	0.019	20.120	8.340	0.188	0.257	Bal

Table 5. ANOVA for the factorial model for speed and current at a constant voltage for NaOH

Source	Sum of Squares	DF	Mean Square	F Value	Prob>F	Remark
Model	$2.163X10^{-5}$	3	$7.209X10^{-6}$	50.44	0.0195	Significant
A	$5.063X10^{-6}$	1	$5.063X10^{-6}$	35.42	0.0271	Significant
B	$1.056X10^{-5}$	1	$1.056X10^{-5}$	73.91	0.0133	Significant
AB	$6.002X10^{-6}$	1	$6.002X10^{-6}$	42.00	0.0230	Significant
Residual	$2.858X10^{-7}$	2	$1.083X10^{-7}$			
Lack of Fit	$4.083X10^{-8}$	1	$4.083X10^{-8}$	0.17	0.7532	Not Significant
Pure Error	$2.450X10^{-7}$	1	$2.450X10^{-7}$			
Cor Total	$2.191X10^{-5}$	5				

Table 6. Design matrix and responses of welding parameters of ASS in NaOH environment

Std	Run	A: Speed (cm/min)	B:Current (Amp)	C:Voltage (volts)	WL_8 (mg)	WL_{16} (mg)	WL_{24} (mg)	WL_{32} (mg)	WL_{40} (mg)
1	1	20	90	230	0.0024	0.0012	0.0024	0.0016	0.0035
3	2	20	110	230	0.0009	0.0004	0.0011	0.0012	0.0037
5	3	30	100	230	0.0020	0.0021	0.0018	0.0017	0.0028
4	4	40	110	230	0.0008	0.0002	0.0006	0.0004	0.0020
2	5	40	90	230	0.0016	0.0059	0.0053	0.0040	0.0094
6	6	30	100	230	0.0009	0.0014	0.0010	0.0024	0.0034

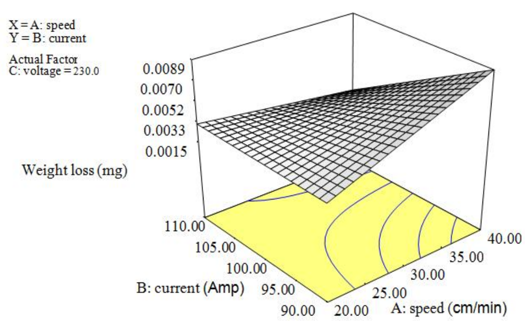

Fig. 3. Response surface plot for ASS immersed in NaOH for 40 days

Shown in Figs. 4 – 5 are the cube plots of the effect of the interactions of current, speed and constant voltage on corrosion behaviour of the ASS immersed in 0.5 M concentration of NaOH for eight (8) days and forty (40) days. In application, an ASS has a high corrosion resistance in an alkali medium because ASSs exhibit active-passive behaviour in sodium hydroxide solution. At room temperature and concentration up to 50%, sodium hydroxide exhibit low uniform corrosion rate [9]. The results show that at constant voltage of 230V, a varied speed from 20 cm/min to 40 cm/min and a varied current from 90 Amp to 110 Amp, weight losses for eight (8) days and forty (40) days were obtained as follows;

For eight (8) days are; 16% (C+, B-, A+), 0.08% (C+, B+, A+), 0.24% (C+, B-, A-) and 0.09% (C+, B+, A-) while for forty (40) days are; 0.89% (C+, B-, A+), 0.15% (C+, B+, A+), 0.30% (C+, B-, A-) and 0.32% (C+, B+, A-). It was observed at the end of this analysis that ASS has a strong corrosion resistance in an alkali environment since the percentages of deterioration for the days observed for the corrosion process was non-uniform and it was minimal. This clearly shows that NaOH solution causes stress corrosion cracking (SCC) on ASS since the rate of deterioration is gradual [10].

The equations that defines each of the responses obtained in the factorial design for speed and current at a constant voltage for NaOH medium for forty (40) days are given by Equation 1 to 5 below; [That is, the weight loss (WL) for eight (8) days, sixteen (16) days, twenty-four (24) days, thirty-two (32) days and forty (40) days];

$$WL_8 = +0.013108\ 1.97500 \times 10^{-4}A - 1.10000 \times 10^{-4}B + 1.75000 \times 10^{-6}AB \quad (1)$$

$$WL_{16} = -0.022008 + 1.33750 \times 10^{-3}A + 2.05000 \times 10^{-4}B - 1.22500 \times 10^{-5}AB \quad (2)$$

$$WL_{24} = -0.010267 + 9.10000 \times 10^{-4}A + 1.05000 \times 10^{-4}B - 8.50000 \times 10^{-6}AB \quad (3)$$

$$WL_{32} = -0.013317 + 8.40000 \times 10^{-4}A + 1.40000 \times 10^{-4}B - 8.00000 \times 10^{-6}AB \quad (4)$$

$$WL_{40} = -0.038017 + 2.00500 \times 10^{-3}A + 3.90000 \times 10^{-4}B - 1.90000 \times 10^{-5}AB \quad (5)$$

Where;

A Represents Speed (cm/min).
B Represents Current (Amperes).

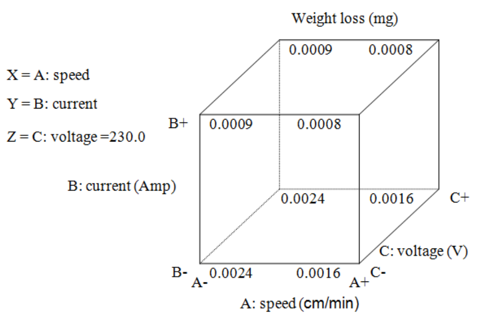

Fig. 4. Cube plot for ASS in NaOH for 8 days

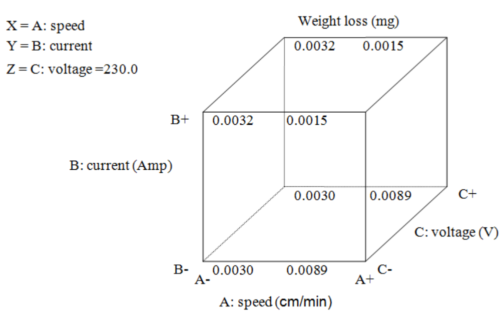

Fig. 5. Cube plot for ASS immersed in NaOH for 40 days

3.3 Scanning Electron Micrograph of the Samples

The micrographs of the samples, as taken by scanning electron microscope, are presented in Figs. 6 to 8.

SEM was used to study the microstructure of the welded and as received samples. Figs. 6 to 8 show the SEM micrographs of the samples with their respective EDS profiles indicating iron to have the highest percentage as the base metal followed by chromium as the highest alloy element. Fig. 6 shows the SEM micrograph of as received sample of ASS. It is observed that the microstructure clearly shows a fine grain boundary and is an indication of a better blending of parent material and the alloying elements. Also, Fig. 7 shows the SEM micrographs of unwelded ASS sample immersed in 0.5M of NaOH for 40 days indicating uniform corrosion of the metallic structure. While Fig. 8 shows a good weldment of ASS immersed in 0.5M of NaOH for 24 days indicating a high integrity weldment that has less corrosion attack on the structure.

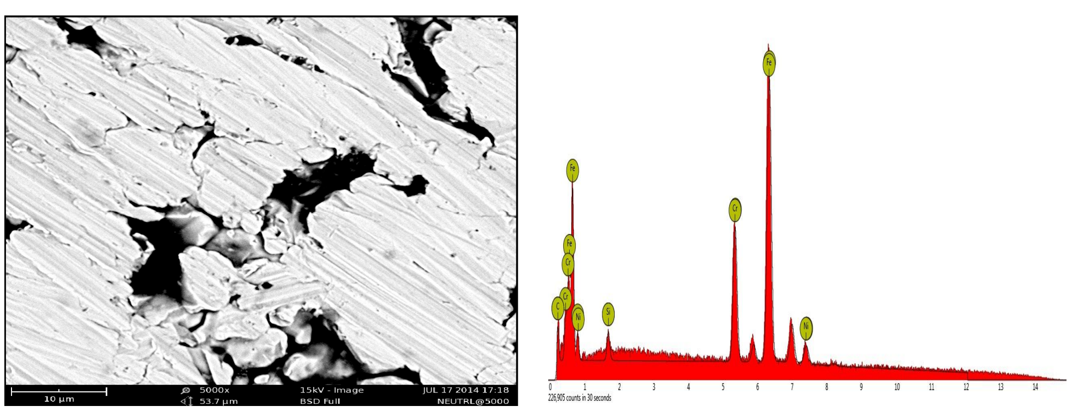

Fig. 6. Micrograph of the control sample (as received) with EDS profile

3.4 Tensile Properties of the Samples

From Fig. 9, it can be seen that for samples immersed in 0.5 M of NaOH the parameters has a significant role in the tensile strength of the welded ASS joint. The variation on the maximum load and extension is a function of the weld parameter and it is observed that the highest values are obtained at weld parameter C_3 which is current, I = 100A, speed = 30 mm/s followed closely by weld parameter C_1. It is seen that the immersion of the metal in 0.5 M of NaOH has a sizable deteriorative effect on the steel which in turn affects the tensile strength when compared to the control which also shows its susceptibility to stress corrosion cracking [10].

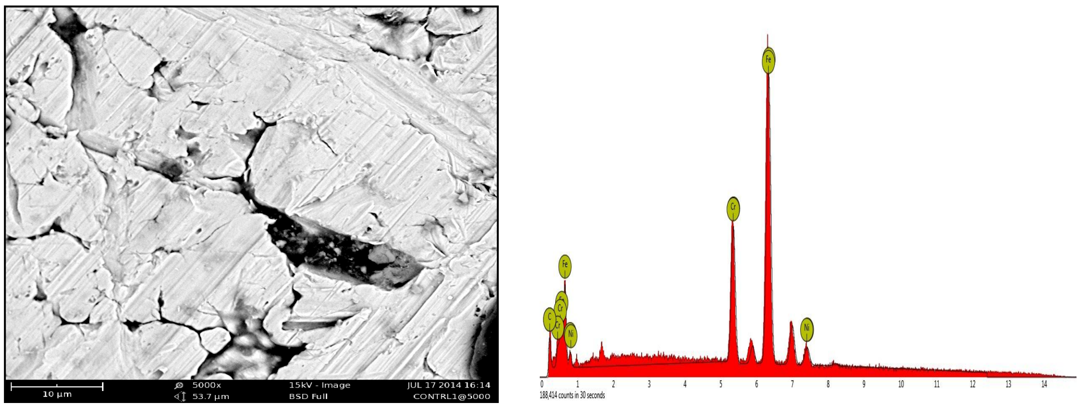

Fig. 7. Micrograph of the control sample immersed in NaOH for 40 days with EDS profile

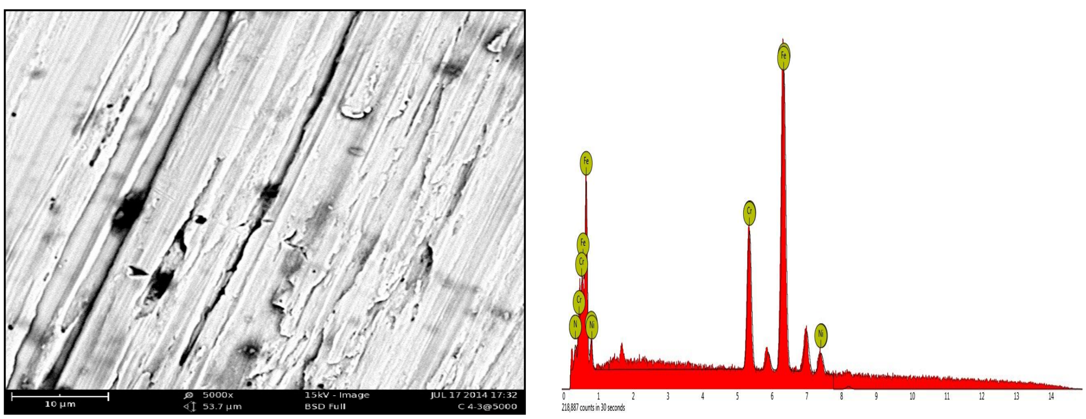

Fig. 8. Micrograph of FZ C_4 welded and immersed in NaOH for 24 days with EDS profile

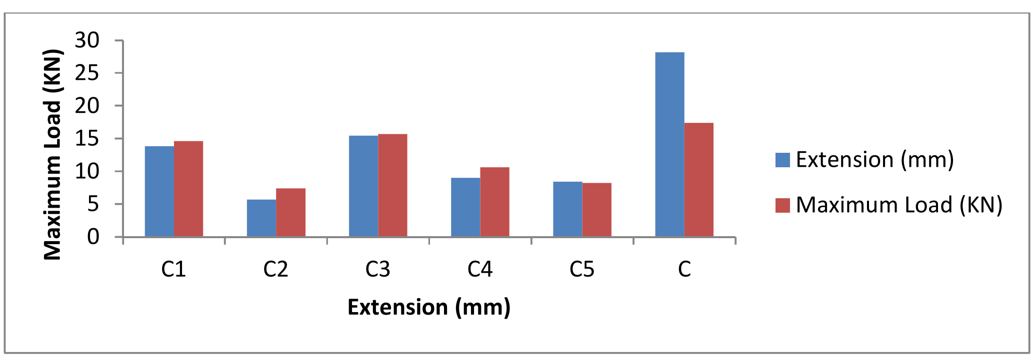

Fig. 9. Load-Extension of tensile test on ASS immersed in NaOH medium

4. CONCLUSIONS

In conclusion, corrosion susceptibility of ASS in sodium hydroxide medium during the exposure time period studied is due to the aggressiveness of the hydroxyl ion (^{-}OH). Also, surface passivation of ASS observed in sodium hydroxide is attributed to film stability in the compound. The interaction effect of speed and current at constant voltage on ASS immersed in sodium hydroxide medium evaluated using factorial design of experiments shows that at moderately high speed and current, a lower corrosion rate of the material is experienced in the alkaline environment. The materials' susceptibility to stress corrosion cracking was conspicuous after a successful corrosion analysis in the medium with a tensile test results.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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