Effect of Electric Arc Welding Parameters on Corrosion Behaviour of Austenitic Stainless Steel in Chloride Medium

Ayo Samuel Afolabi

School of Chemical and Metallurgical Engineering, University of the Witwatersrand Johannesburg, South Africa, and
Metallurgical and Materials Engineering Department, Federal University of Technology Akure, Nigeria
<afolabisammy@yahoo.com>

Abstract

The effect of welding parameters (power input, weld geometry, welding speed, and post-weld heat treatment) on the corrosion behaviour of austenitic stainless steel in chloride medium was investigated in this work. Electrode potential measurement coupled with zinc rod reference electrode was used to evaluate the corrosion behaviour of the samples. It was found that the 3.6kW power input produces the highest resistance weld corrosion while chamfered face edge preparation is the best corrosion resistant sample in the chloride medium. The post-weld heat treatment proved that the best heat treatment temperature occurred at a range between 700^o and 800^{o}C while the medium-speed welded ASS sample proved to be best compared with the fast-speed and the low-speed weld. The results also show that the best electrode for welding stainless steel is a stainless steel-core electrode.

Keywords: *Electrode, power input, weld geometry, welding speed, post-weld heat treatment.*

Introduction

The importance of austenitic stainless steel (ASS) in industrial applications and development cannot be over-emphasised. Its excellent properties which range from high tensile strength, good impact resistance, corrosion and wear resistances have found various applications in many engineering industries. This material is used in almost all environments that require an optimization of these properties, some of which are low and high pressure boilers and vessels, fossil-fired power plant, flue gas desulphurization equipment, evaporator tubing, super heater reheating tubing and steam headers and pipes to mention but a few (Galal *et al.* 2005; Munoz *et al*. 2004; Streicher 1977).

It is therefore obvious that using ASS for these applications will in no doubt involves different shapes and sizes ranging from simple to intricate, the engineer must employ his ingenuity in fabrication to suit the environmental conditions. Welding is one of the most employed methods of fabricating ASS components. It is basically a fusion of two or more pieces of metals by the application of heat and sometimes pressure (Agarwal 1992). Thus welding involves a wide range of scientific variables such as time, temperature, electrode, power input and welding speed (Jariyabon *et al.* 2007; Lothongkum *et al*. 2001; Lothongkum *et al*. 1999; Karadeniz *et al.* 2007).

Many research findings have proved that improper techniques employed in welding ASS may lead to serious consequences of the structures (Avery 1963; Parijslaan 2002). Failures as a result of poor mechanical properties and corrosion resistance have also found their places in the annals of times, from household equipment to industrial structures such as railways, road bridges, storage tanks and ocean liners. One of such failures is the corrosion cracking of a grade 304 stainless steel pipe improperly seam welded and meant for the conveying of glucose solution in Illinois USA (James 2000). The Point Pleasant bridge disaster in Ohio was also traced to stress corrosion cracking initiated during welding (Chamberlain and Trethewey 1988). Many other failures have proved to be welding prone or propagated. It is therefore pertinent to investigate the influence of the various welding parameters on corrosion behaviour of ASS in various environments.

The following pertinent questions could be asked before welding ASS structures: ‘‘How do we weld these articles in order to forestall future occurrence of disasters?”, “How do we manipulate the welding variables to ensure homogenous and satisfactory weld that will meet various service conditions?” The answers to these questions prompted the investigation into ways of improving the quality and service conditions of welded ASS in chloride applications.

Therefore, the main objective of this study is to test the influence of power input, weld geometry, welding speed, and post-weld heat treatment on the performance of ASS immersed in one molar sodium chloride solution. The results obtained from this investigation are expected to provide more knowledge on the influence of welding variables on the corrosion behaviour of ASS articles and the thermal cycle undergone by these welded structures during and after fabrication. This among other factors would assist to forestall future disasters which may have occurred from failed parts due to corrosion of welded ASS structures.

Material and Methods

A 12mm diameter hot rolled ASS was used in this study. Its nominal chemical composition as revealed by spectrometer is shown in Table 1. The welding samples were prepared with different shapes as shown in Fig. 1. These welding geometries were chosen based on the suggestion of Agarwal (1992) that adequate welding penetration could easily be achieved using square butt, double V, single V U face, chamfered or single V ASS sample preparation. The edges of these samples were firmly clamped together with a little root gap between them. Stainless steel core electrode fluxed with manganese and molybdenum was used for almost all the welding operation, except under the electrode type parameter where one of the welding operations was carried out using a mild steel core electrode.

Power Input

Eight single V edge samples were welded in pairs at a constant voltage of 80V while the current was varied to give different power input, and the speed held constant as much as possible. The current settings used were 65A, 102A, 170A, and 250A giving power inputs of 0.94KW, 1.47KW, 2.45KW and 3.60KW respectively. During welding, the electrode was to run through the V-groove until the penetration and development of the weld pool were achieved to the thickness level of the rod. Thereafter an iron brush was used to remove the covering slag and welded samples were allowed to cool in air.

Weld Geometry

Welding was carried out at a constant current of 160A using two single V samples and two double V samples as well as two plain-faced samples and two chamfered face samples which were all welded in pairs to make four samples ready for corrosion test. Other parameters, such as welding power, speed, and electrode were kept constant.

Welding Speed

The welding speed was varied, while other parameters were kept constant to determine the effect of slow, medium and fast welding on the corrosion behaviour of ASS. Three samples were used: Single V (Six samples) groove welded to make three, one slow welded another medium speed welded and the third fast welded, this format was adopted because of lack of equipment to properly control the speed of the welding operation which can only be done by an automated welding machine.

Welding Electrode

The types of electrode used were varied with all other parameters kept constant. Two sets of samples were used with single V grove and one set welded with stainless steel electrode gauge 2.5mm (internal core) and flux covering making it up to 4.2mm. The other set was welded with a mild steel core electrode with dimension 2.5mm core and 4.0mm flux core covering**.**

Post-Weld Heat Treatment

Eight samples (four sets) were welded at a constant power input and as much as possible constant speed, with all the samples made into single V edges to keep the weld geometry constant also. The samples were heated to temperatures 500^o, 600^o, 700^o and 800^{o}C, respectively, and allowed to soak at these temperatures for 30 min and then normalised. This was done in order to see the level of stress relief and also the effect on the heat affected zones of the welded samples.

Electrode Potential Measurement

The welded and heat-treated samples were completely immersed in one molar solution of sodium chloride and their electrode potentials were measured at every five-day interval for 70 days, using a digital multimeter coupled with zinc rod reference electrode. The values obtained were converted to Saturated Calomel Electrode (SCE) using the formula: Electrode Potential mV (SCE) = [E_{Zn} – 1030] mV (Hilbert and James 1984; Afolabi and Fasuba 2006). Where E_{Zn} is the electrode potential obtained using zinc reference electrode.

Results and Discussion

Electrode Potential Measurement

Electrode potential is used to measure the corrosion potential of a metallic material with respect to a given reference electrode in a specified medium. This method measures the tendency of a metal to corrode in a medium of interest. Many experimental findings have confirmed that high values of electrode potential of a metal in a specified medium indicates high passivity of the metal in that medium while low (usually at negative) values of this quantity show the high tendency of the metal to dissolve in the corrosive environment (Afolabi 2005; ASTM 1991). Passivity of a metal in a medium refers to the ability of a metal to form a protective layer of film in a medium. The corrosion resistance of a passivated metal is often determined by its susceptibility to local breakdown and initiation of pits (Ilevbare and Burstein 2003). ASS is known for its corrosion resistance due to the presence of chromium and molybdenum which are soluble in the austenitic matrix. Chromium adds to the overall resistance through a passivation process by forming a complex spinel-type $\{(Fe,Ni)O(Fe,Cr)_2O_3\}$ passive film (Nakayama and Oshida 1968; Okamoto and Shibata 1978). This complex produces a coherent, adherent insulating and regenerating chromium oxide protective film on the metal surface; while molybdenum increases the ability of stainless steel to resist the localized corrosion in aggressive ion environments (Uhlig 1966). Figs. 2-6 show the electrode potential results obtained for different parameters in this study. It can be seen that all the curves in these figures show fluctuations in electrode potential throughout the exposure periods. This characteristic behaviour of ASS in chloride medium indicates constant breakdown of the protective film due to the aggressive chloride ion and film repair by the chromium ion in the steel and it is termed electrochemical noise (Cottis *et al.* 1997; Millard 1991).

Effect of Power Input on Corrosion Behaviour of ASS

The effect of various power inputs on the corrosion behaviour of ASS in sodium chloride medium is shown in Fig. 2 in terms of electrode potential values. It can be seen from this figure that the electrode potential values increase with increase in power inputs. Thus the corrosion tendency of ASS in this medium reduces with increase in electrode potential values. The as-received sample shows the greatest resistance to corrosion in this medium, this is closely followed by sample welded with 3.6 kW power input, 2.45 kW power input up till sample welded with 0.94 kW power input which has the least corrosion resistance in the medium during the exposure period studied. This behaviour can be attributed to the fact that low power input resulted to prolong heating of the samples during welding which might have resulted into precipitation of carbon from the solid solution leading to formation of chromium carbide, hence chromium depletion from the austenitic matrix (Khanaa 1990). Chromium depleted matrix will result to loss of metal passivity and aid corrosion attack more quickly by the aggressive chloride ion. Another possible explanation for the above result is that the low heat input welded samples underwent a long period of heating, the thermal conductivity of ASS being about 50% lower than that of plain carbon steel and the thermal expansion of ASS is 50% higher than that of plain carbon steels (Khanaa 1990), there is a tendency for greater expansion at prolonged heating circles due to low power input and this could lead to a greater tendency of warpage and distortion which may produce a higher weld cracking in the aggressive corrosion medium (Llewellyn 1992). The weld current is the current in the welding circuit during the making of a weld. The higher the current, the higher the power input and the deeper the penetration. However, the use of too high weld current may cause problems such as excessive spatter, electrode overheating and cracking while too high weld voltage could cause the beads to be wider and flatter. The low arc voltage produces a stiffer arc that improves penetration. If the voltage is too low, a very narrow bead will result (Lothongkum *et al.* 2001).

Effect of weld geometry on corrosion behaviour of ASS

Fig. 3 shows the effect of various weld geometry on the corrosion potential of ASS in chloride medium. It is observed that the double-V face sample has the highest corrosion tendency in this medium, this is closely followed by single-V face, chamfered face, plain face and the as-received samples in that order. This behaviour could be due to distortion which might have resulted from mechanical working due to realignment of grains near the points of machining during geometry preparation (Khanaa 1990). According to Ulick (1976), the stress corrosion cracking could have also occurred as a result of frettage introduced by machining welding surface during geometry preparation. Therefore, the double V groove sample might have experienced much damage to the microstructures close to the weld zone which could have led to severe deterioration during immersion in the chloride environment.

Effect of Post-weld Heat Treatment on Corrosion Behaviour of ASS

Fig. 4 shows the electrode potential values obtained for varying the post-weld heat treatment temperatures of ASS samples immersed in chloride. Although the electrode potential values of all the samples increase with exposure period, sample heat-treated at 500^{o}C show highest corrosion tendency throughout the exposure period. This is followed by samples heat-treated at 600^{o}, 700^{o} and 800^{o}C. In other words, the corrosion seems to be increasing with increase in heat-treated temperatures in this medium throughout the exposure period which correlates with findings of Pandey *et al.* (1997). According to Llewellyn (1992) at temperatures below 800-850^{o}C, the solubility of carbon in ASS falls below 0.03% and this can result in precipitation of $M_{23}C_6$ carbide. The proportion of carbide precipitated is dependent on the rate of cooling and fast cooling or water quenching from between 800-1000^{o}C suppresses carbide formation (Chamberlain and Trethewey 1988; Okamoto 1973), hence, the high resistance of the 800^{o}C treated sample compared to the others.

According to Honeycomb and Baddeshia (1995) the solubility limit of carbon is about

0.05% at 800^{o}C, rising to 0.5% at about 1100^{o}C, therefore, it can be inferred that, the higher the temperature of annealing, the greater the tendency of the material to display higher corrosion resistance except in the range 500 to 600^{o}C. Therefore solution treatment between 800^o and 1,150^{o}C will take almost all the carbon into solution and rapid cooling from this range will give a supersaturated austenitic solid solution at room temperature. Therefore, sensitisation, which will adversely result to weld decay, can be avoided. The non-passivity of the 600^{o}C sample can be attributed to the influence of sensitisation as carbon diffusion to grain boundaries is well promoted in this range of temperature (Fontana 1986).

Effect of Welding Speed on Corrosion Behaviour of ASS

Fig. 5 shows the effect of welding speed on corrosion behaviour of ASS immersed in one molar solution of sodium chloride. It is seen that the low speed welded sample displayed the lowest electrode potential while the high speed welded sample show the highest values of electrode potential throughout the exposure period. The speed the electrode travels along the joint has a direct influence on bead shape, depth of fusion, cosmetic appearance and heat input into the base metal. Faster travel speeds produce narrower beads that have less penetration. Travel speed also affects heat input, which in turn influences the metallurgical structure of the weld metal. If speeds are too fast there is tendency for undercut, slag inclusion and porosity, since the weld freezes quicker (Lothongkum *et al.* 2001).

Effect of Welding Electrode on Corrosion Behaviour of ASS

The effect of welding electrodes on corrosion behaviour of ASS in chloride medium is shown in Fig. 6. The result in this figure shows that the stainless steel electrode welded sample displayed a highest values of electrode potential for the entire period of immersion starting from -362 mV (SCE) to -201mV (SCE) while the sample welded with plain carbon electrode shows a relatively lower values of electrode potential throughout the exposure period. The effect of inhomogeniety in weld fusion as a result of the use of a carbon steel electrode could have been responsible for the high corrosion tendency. The steel-core electrode-welded sample displays low electrode potential compared to the stainless steel-core electrode-welded sample. The above clearly agrees with the suggestions of Agarwal (1992), that ASS weld should be carried out by a stainless steel-core electrode.

Conclusions

The results of this study have shown that welding variables have enormous effects on the corrosion behaviour of ASS in chloride medium. The following appreciable results were also obtained for the variations in the welding parameters in this medium.

i. The power input produces a better weld that can withstand adverse service conditions at values of 3.60kW, which corresponds to a welding voltage of 80V and 250A welding current.
ii. The weld geometry variation verified that the chamfered face edge preparation is the best for welding samples; this was clearly followed by the single V groove weld.
iii. The post-weld heat treatment parameter proved that the best heat treatment temperature occurred at ranges between 700^o and 800^{o}C.
iv. The medium-speed welded ASS sample proved to be best compared with the fast-speed and the low-speed weld.
v. The results also show that the best electrode for welding stainless steel is a stainless steel-core electrode.

It can therefore be deduced that an ASS welded structure will perform well in service chloride medium when the welded power input of 3.60 kW is used in combination with a Chamfered face or single V groove shaped edge and welding effected with a stainless steel-core electrode made to traverse ASS sample with a medium welding speed, after which the weld should be subjected to heat treatment in the range of 700° and 800°C and water-quenched.

References

Afolabi, A.S. and Fasuba, O.A. 2006. Corrosion of steel reinforcements in concrete immersed in different environments. Nigerian Soc. Engin. Tech. Trans. 41(4): 51-60.

Afolabi, A.S. 2005. Effects of corrosion inhibiting chemical admixtures on mild steel reinforced concrete in a chloride medium. International Research J. Eng. Sci. Technol. 2(1): 156-60.

Agarwal, R.L. 1992. Welding Engineering - A Textbook for Engineering Students, 4th ed., Khanaa Publ., Nai Sarai, Delhi, India.

ASTM C876. 1991. Standard Test Method for Half Cell Potential of Uncoated Reinforcing Steel in Concrete. 3(2) Amer. Soc. Testing and Mater, Philadelphia, PA, USA.

Avery, C.H. 1963. Heat Treatment of Stainless Steel. Metal Handbook, 8th ed. Amer. Soc. Metals, Ohio, 2: 243.

Chamberlain, J. and Trethewey, A.R. 1988. Corrosion for Student of Science and Engineering. Longman Scientific and Technology Books, London, England.

Cottis, R.A; Al-Ansari, M.A.; and Pettiti, A. 1997. Electrochemical noise measurements for corrosion studies. Mater. Sci. Forum. 8: 741.

Fontana, M.G. 1986. Corrosion Engineering, 3rd ed., McGraw Hill, New York, NY, USA.

Galal, A.; Atta, N.F.; and Al-Hassan, M.H.S. 2005. Effect of some thiophene derivatives on the electrochemical behaviour of AISI 316 austenitic stainless steel in acidic solutions containing chloride ions. Mater. Chem. Phys. 89: 38-48.

Hilbert, B.D.; and James, A.M. 1984. Dictionary of Electrochemistry. Macmillan Press, London, England.

Honeycomb, R.W.K.; and Bhadeshia, H.K.D.H. 1995. Steels; Microstructure and Properties, Metals and Materials Series, 2nd ed. Edward Arnold, Hodder-Headling, London, England.

Ilevbare, G.O. and Burstein, G.T. 2003. The inhibition of pitting corrosion of stainless steels by chromate and molybdate ions. Corrosion Sci. 45: 1545-69.

James, G.K. 2000. Chronology of Corrosion Disasters. Amer. Metal Soc. Handbook 5, New York, NY, USA.

Jariyabon, M.; Davenport, A.J.; Ambert, R.; Connolly, B.J.; Willians, S.W.; and Price, D.A. 2007. The effect of welding parameters on the corrosion behaviour of friction stir welded AA2024 – T351. Corrosion Sci. 49: 877-909.

Karadeniz, E.; Ozsarac, U.; and Yildiz, C. 2007. The effect of process parameters on penetration in gas metal arc welding processes. Mater. Design 28: 649-56.

Khanaa, O.P. 1990. A Textbook on Welding Technology for Engineering Students. Dhampa Rai & Sons, Delhi, India.

Llewellyn, D.T. 1992. Steels Metallurgy and Application. Heinemenn-Butterworths, Oxford, England.

Lothongkum, G.; Viyanit, E.; and Bhandhubanyong, P. 2001. Study on the effects of pulsed TIG welding parameters on delta-ferrite content, shape factor and bead quality in orbital welding of AISI 316L stainless steel plate. J. Mater. Proc. Technol. 110: 233-38.

Lothongkum, G.; Chaoumbai, P.; and Bhandhubanyong, P. 1999. TIG pulse welding of the 304L stainless steel in flat, vertical and overhead positions. J. Mater. Process Technol. 89-90: 410-4.

Millard, S.G. 1991. Reinforced Concrete Resistivity Measurement Techniques. Proc. Inst. Civil Engin., Part 2: 71-88.

Munoz, A.I.; Anton, J.G.; Nuevalos, S.L.; Guinon, J.L.; and Herranz, V.P. 2004. Corrosion studies of austenitic and duplex stainless steels in aqueous lithium bromide solution at different temperatures. Corrosion Sci. 46: 2955-74.

Nakayama, T.; and Oshida, Y. 1968. Identification of the initial oxide films on 18-8 stainless steel in high temperature water. Corrosion. 21: 336-7.

Okamoto, G.; and Shibata, T. 1978. Passivity and breakdown of passivity of stainless steel. R.P. Frankenthel and J. Kruger, Eds.

Passivity of Metals. Electrochem. Soc., New York, NY, USA.
Okamoto, G. 1973. Passive film of 18–8 stainless steel structure and its functions. Corrosion Sci. 13: 471-489.
Parijslaan, R. 2002. Welding Stainless Steels: Techniques and Principles - An Electronic Manual (www.cimeth.org\\stainless.htm)
Pandey, J.L.; Singh, I.; and Singh, M.N. 1997. Electrochemical corrosion behaviour of heat-treated AISI 304 austenitic stainless steel in inorganic acid mixture. Anti-corrosion Methods Mater 44(1): 6-9.
Streicher, M.A. 1977. Stainless Steels: Past, Present and Future. Proc. Symp. Stainless Steel. Climax Molybdenum Co, Ann Arbor, MI, USA.
Uhlig, H.H. 1966. The Corrosion Handbook. 9th ed. pp. 150-174. John Wiley, New York, USA.
Ulick, E.R. 1976. The Corrosion and Oxidation of Metals. Supplementary Vol. Evans Publ., London, England.

Table 1. Chemical composition (Wt. %) of the austenitic stainless steel sample.

C	Fe	Si	P	Mn	Ni	Cr	Mo	V	Others
0.032	68.439	0.486	0.026	1.055	10.594	16.213	2.081	0.092	Balance

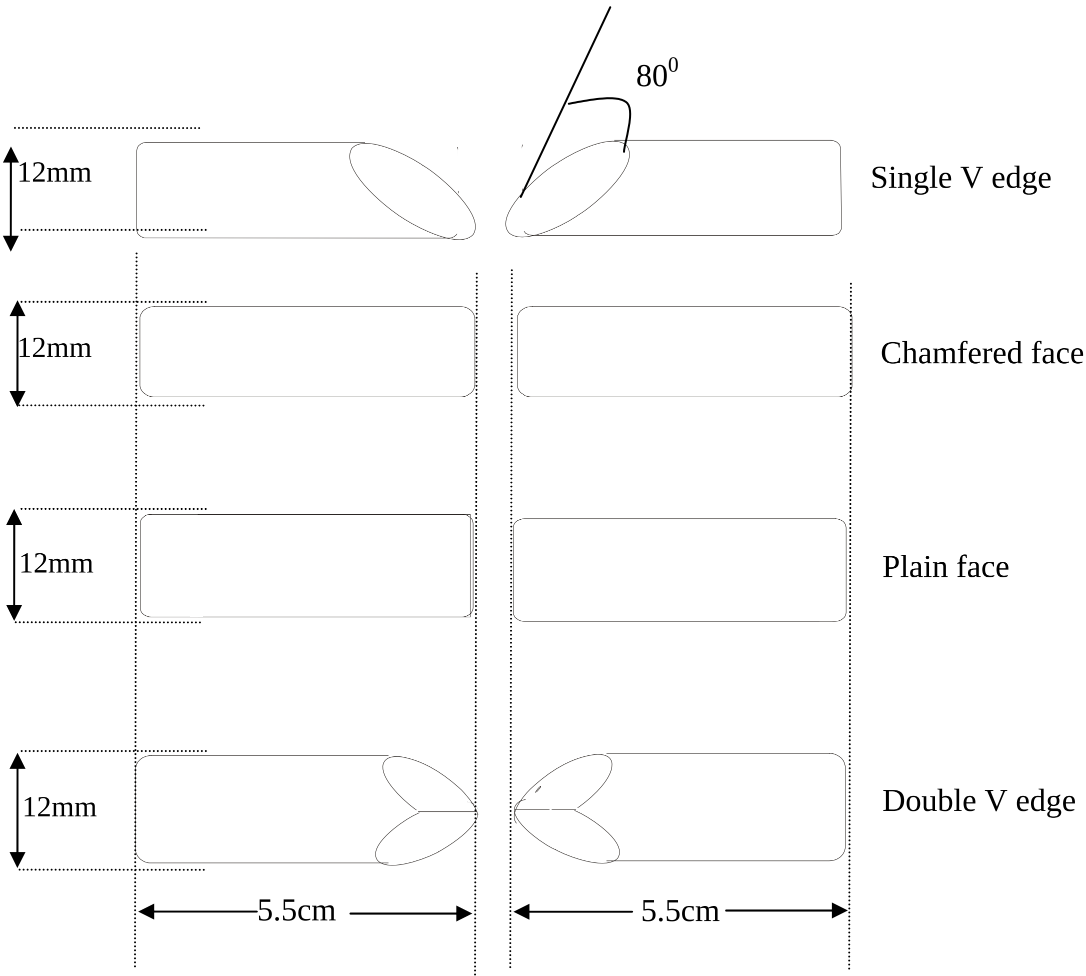

Fig. 1. Shapes of the ASS welding samples.

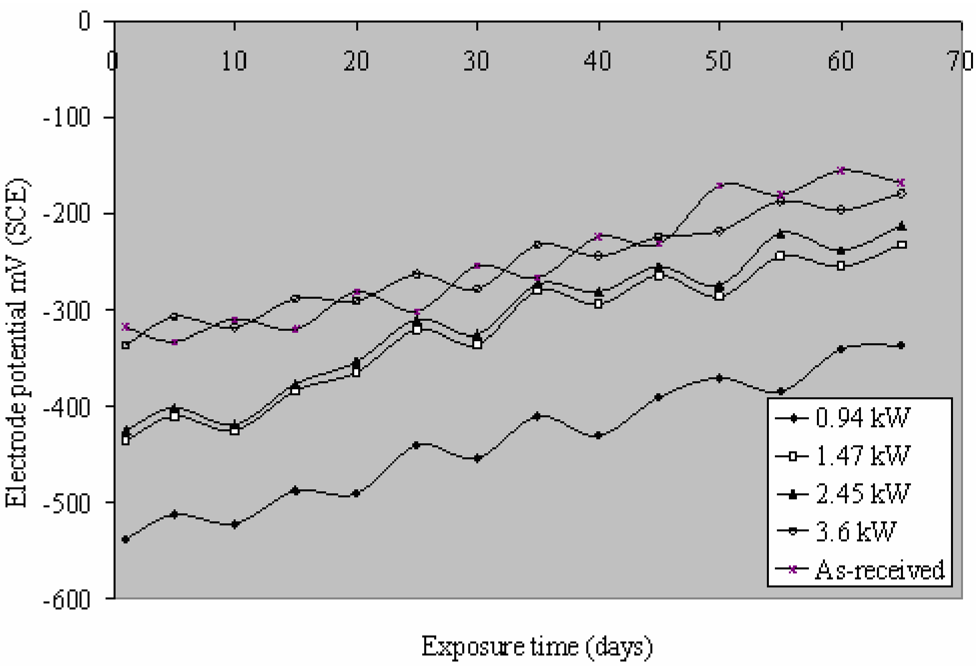

Fig. 2. Electrode potential vs. exposure time for ASS welded with varied power inputs and immersed in 1.0M NaCl.

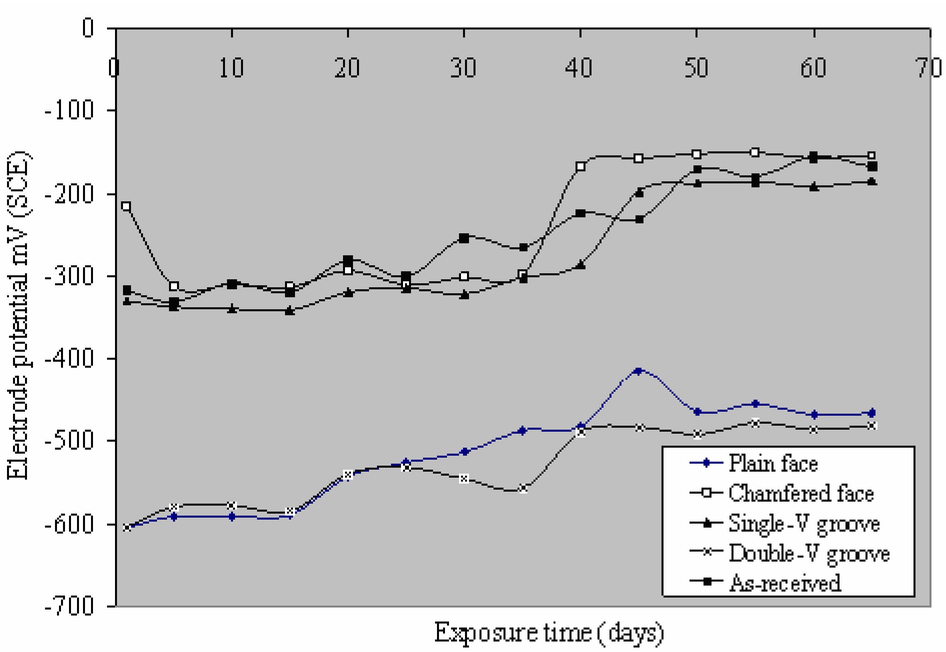

Fig. 3. Electrode potential vs. exposure time for ASS welded with different geometries and immersed in 1.0M NaCl.

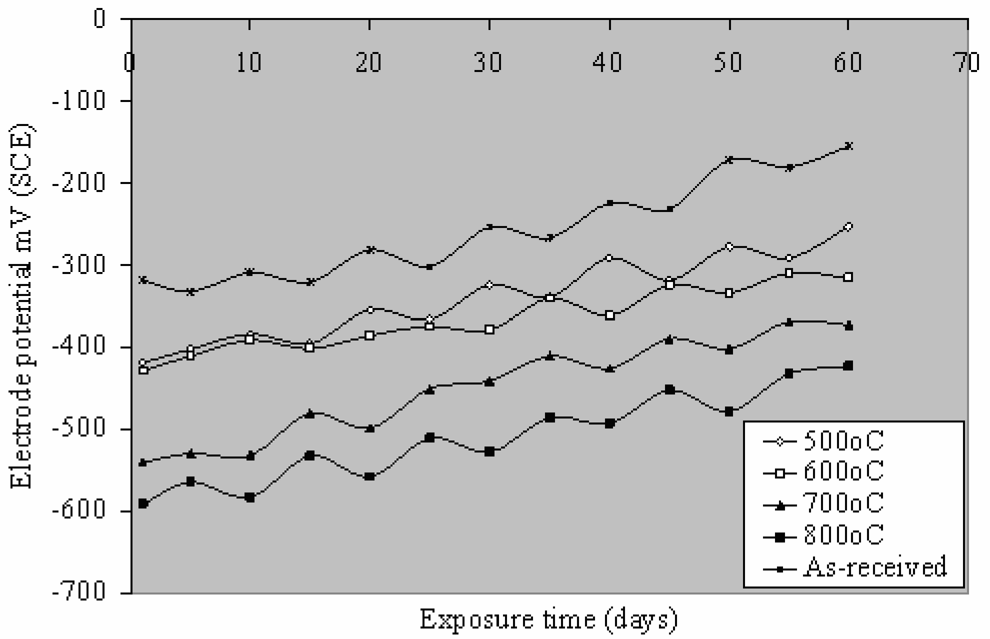

Fig. 4. Electrode potential vs. exposure time for welded ASS heat-treated at various temperatures and immersed in 1.0M NaCl.

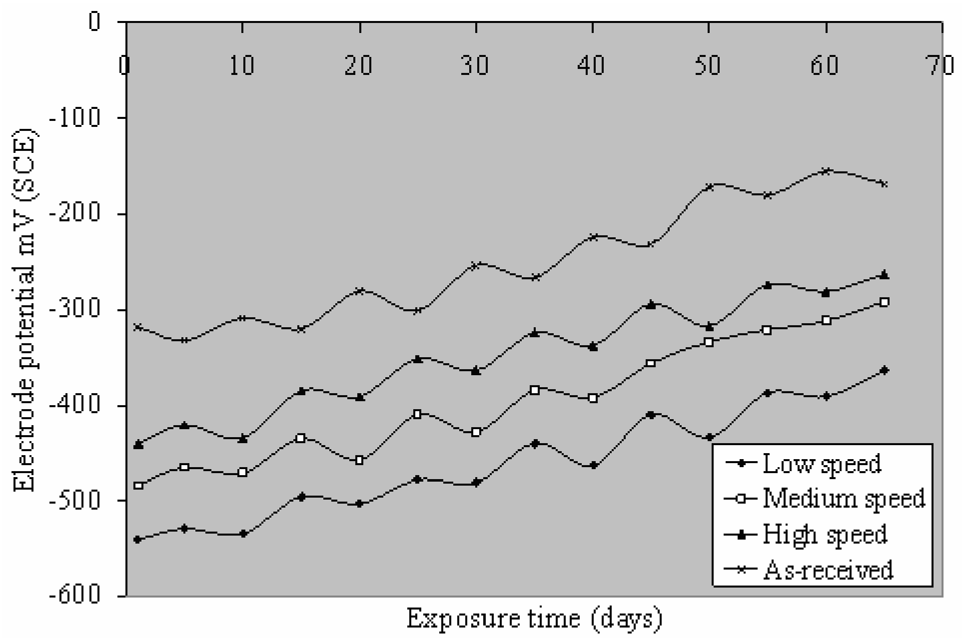

Fig. 5. Electrode potential vs. exposure time for ASS with different welding speed and immersed in 1.0M NaCl.

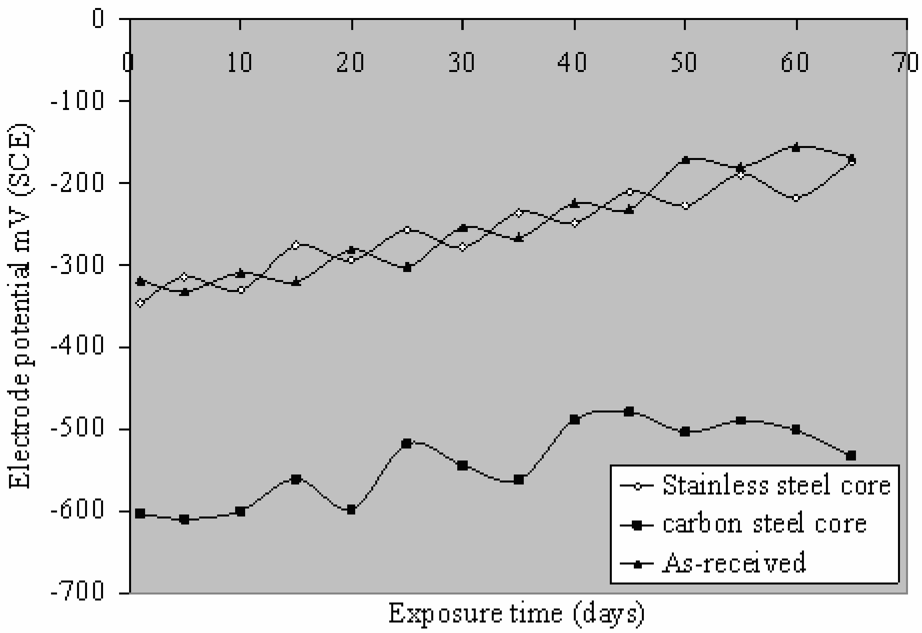

Fig. 6. Electrode potential vs. exposure time for ASS welded with different electrodes and immersed in 1.0M NaCl.