Post-weld heat treatment effect on the corrosion behavior of the weld joint AISI 316L with Inconel® 182 filler metal

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Abstract

The welding thermal cycle and the post-weld heat treatment (PWHT) can alter the microstructure of AISI 316L heat affected zone (HAZ), due to the critical temperature range, which is responsible for the formation of intermetallic phases and undesirable precipitates. The material studied in this work is a dissimilar metal weld joint with two AISI 316L plates with Inconel® 182 filler metal. The material was submitted to heat treatments at 600, 700 and 800 °C for 3 h. The aim of this work was to evaluate the effect of the PWHT in the corrosion behavior of the AISI 316L HAZ. Microhardness measurements and optical and scanning electron microscopy / microanalyses were performed to determine the effect of the PWHT in the microstructure. The corrosion behavior was evaluated by means of electrochemical techniques in sulfuric acid solutions (0.5 mol/L) at room temperature. The reduction in microhardness near the fusion line may indicate a reduction in residual stresses with PWHT. But the impedance results showed a decrease in the corrosion resistance of the HAZ with PWHT. The sample submitted to the PWHT at 600 ºC showed corrosion resistance close to the as welded material.

Keywords: corrosion, weld, HAZ, Inconel, PWHT.

Introduction

Nickel alloys have been widely used in nuclear power plants and others plants of energy generation, chemical and petrochemical as weld filler metal in dissimilar metal welds (DMW), which can involve carbon and stainless steel, nickel alloy and weld overlay.

Austenitic stainless steels and nickel alloy filler metals may require PWHT to relieve stresses from the welding processes. The heat treatment can reduce stress corrosion cracking by redistributing the localized load and by reducing the magnitude of the residual tensile stresses available to induce corrosion cracking. These PWHTs can however lead to a degradation of the weld and base metal microstructures, that is related to temperature and time of the heat treatment (1, 2, 3). Consequently, the corrosion resistance of autogenous welds and welds made with matching filler metal may be inferior to that of properly annealed base metal because of microsegregation, precipitation of secondary phases, formation of unmixed zones, recrystallization and grain growth in the weld heat-affected zone (HAZ) and contamination of the solidifying weld pool.

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For austenitic stainless steels, the PWHT in the range (425 to 595) °C is usually adequate to minimize stresses. The PWHT in the range (815 to 870) °C is occasionally necessary for relief of approximately 90 % stresses, but these heat treatments should be only used for low carbon grades "L" and the 321 and 347 stabilized steels (4). Sigma phase is an intermetallic phase composed mainly of Fe and Cr which forms in ferritic and austenitic stainless steels during exposure at (560 to 980) ºC. Austenitic stainless steel 316L type with high Cr and Mo may undergo precipitation of brittle sigma phase, if they are exposed to high temperatures for a certain period of time. The transformation from ferrite or directly from austenite to sigma proceeds most rapidly within the temperature range (750 to 850) °C (5). Having studied the corrosion behavior of the base metal, weld and weld joint (6) the aim of the work is now to study the corrosion behavior of the AISI 316L HAZ after different heat treatments. The corrosion behavior was evaluated by means of electrochemical techniques in sulfuric acid solutions (0.5 mol/L) at room temperature.

Methodology

The materials used in this work were austenitic stainless steel AISI 316L plates with (300x150x12.5) mm and Inconel® 182 - AWS A5.11 (ENiCrFe-3) as filler metal with diameters 2.5 mm and 3.2 mm. Their nominal chemical composition and typical mechanical properties are listed in Tables 1 and 2. The plates were welded together using a 60 ° V groove and narrow gap of 2.5 mm, using pre-heat at 150 °C and interpass at (100 to 150) °C. The weld joint was performed with (90 to 100) A for the root weld (filler metal of 2.5 mm), and (110 to 120) A for other beads (filler metal of 3.2 mm). After welding, three welded joints were subjected to PWHT in a vacuum oven at (600, 700 and 800) °C for 3 h, in order to reduce the weld residual stresses.

Vickers microhardness profiles were carried out for the weld joint at the base metal, the heat affected and weld metal zones. The applied load was 100 g at 30 s, in samples as welded and after PWHT conditions.

The cross-sections were polished and electrolytically etched with 10 % aqueous oxalic acid solution at 2.2 VDC for 60 s to examine the microstructure and to identify grain and dendrite boundaries and precipitates. Delta ferrite and sigma phases were identified with 60 % HNO_3 in water at 2 VDC for 20 s. The microstructures were examined by optical and scanning electron microscopy and analyzed by energy dispersive spectroscopy (EDS).

In this work only the AISI 316L HAZ submitted to different heat treatments was studied. The samples containing the weld joint were mounted in epoxy resin and the surface was ground and polished with 1 µm diamond solution. They were then degreased with acetone, washed with distilled water and dried. To avoid the influence of the base metal and the weld metal in the electrochemical tests those materials were covered by epoxy resin, shown in Figure 1. The most critical part of the HAZ was selected which had about 3 mm length.

The electrochemical tests were performed according to ASTM G 5-94 standard (7) in a 0.5 mol/L H_2SO_4 solution at room temperature (RT). The solution was bubbled with nitrogen gas for 1 h to reduce the oxygen levels. After this time the sample was immersed in the solution. The electrochemical cell used was a traditional three-electrode system comprising the working electrode, the reference electrode (Ag/AgCl/ 3 mol/L KCl) and a Pt plate as auxiliary electrode. The electrochemical tests were performed using an Autolab potentiostat system, PGSTAT20 with GPES (General Purpose Electrochemical System 4.9) and FRA (Frequency Response Analysis 4.9) softwares. The open circuit potential (OCP) was measured for 30 min. The polarization resistance was measured afterwards to test the stability of the system. The potential was scanned a range of ± 20 mV around the OCP at 0.17 $mV.s^{-1}$ scan rate. The impedance measurements were performed at the OCP using a frequency range from 12 kHz to 5 mHz (8 points per decade) with perturbation amplitude of 10 mV (RMS). The potentiodynamic polarization scan was then performed from (0.2 to 1.5) V at 0.17 $mV.s^{-1}$ scan rate.

Results and Discussion

Vickers microhardness profiles

Figure 2 presents the cross-weld Vickers microhardness profiles of specimens as welded and with PWHT for the three temperatures used, (600, 700 and 800) ºC. Without PWHT, near the fusion line (LF) the microhardness was higher probably due to residual stresses. With PWHT, the microhardness decreased probably due to relief of the residual stresses, but at 700 ºC the microhardness increased compared with PWHT at 600 ºC. In the weld metal, with PWHT at 800 ºC, the microhardness decreased more than at other PWHTs. The HAZ length is estimated in the range (3 – 6) mm from Figure 2.

Metallographic analysis

The microstructure of the AISI 316L consists of austenite grains and delta ferrite in the form of stringers. The PWHT caused dissolution of delta ferrite which is shown in Figure 3a. Figure 3b presents the evolution of delta ferrite in 316L HAZ with PWHT. Delta ferrite, which was partially dissolved in the HAZ, had its dissolution increased with increasing temperature of the PWHT. With the dissolution of delta ferrite, carbides and sigma phase precipitation occurred. With the PWHT at 800 °C, delta ferrite became finer and sigma phase was partially dissolved.

Table 3 shows the composition of delta ferrite in AISI 316L by EDS spectra. The results show that C, Cr and Mo contents increased and Fe and Ni decreased with temperature increase. Table 4 shows the composition of ferrite and sigma phase, in the HAZ, analyzed by EDS. The C content increased slightly at 600 °C, reached very high levels at 700 °C and at 800 °C it was lower than without PWHT. Cr, Fe and Ni contents were stable at 600 °C and 800 °C and decreased at 700 °C. Mo content increased continuously with increasing PWHT temperature.

Electrochemical tests

Figure 4 presents the open circuit potentials for AISI 316L HAZ samples submitted to different PWHTs in 0.5 mol/L H_2SO_4. One can see that the potential decreases in the beginning and reaches stables values in about 20 min. The OCP was found within the range: (– 238 to – 156) mV. The samples without PWHT presented a higher open circuit potential.

Figure 5 presents the potentiodynamic polarization curves of AISI 316L HAZ specimens in H_2SO_4 solution at room temperature. According to these results the passive behavior of AISI 316L HAZ was affected by the PWHTs. Table 5 presents the electrochemical parameters obtained from those curves. The closeness of the primary passive potentials to the corrosion potentials for the specimens submitted to PWHTs when comparing to the sample not heat treated suggests that the heat treatments increased the material tendency to passivate. However, the sample heat treated at 800 ºC presented a delayed passivation process as can be observed by the critical anodic current values. The samples showed passive currents of the same order of magnitude indicating that the samples showed similar degree of passivation. The transpassive potentials are also close for the different samples, which means that the passive film had similar stability.

Figure 6 (Nyquist plot) and Figure 7 (Bode plot) show the impedance results obtained for the AISI 316L HAZ samples submitted to different PWHTs. Two semicircles can be seen in the plots, each one assigned to a different electrochemical process occurring at the interface metal-solution. Two maxima can be seen in the phase angle plot, one at about 75 Hz and the other at lower frequencies, at about (20 – 40) mHz. From the impedance measurements it can be seen that the PWHTs affected the corrosion resistance of the AISI 316L HAZ. The impedance decreased when the samples were submitted to PWHTs. The higher the temperature of the heat treatment, the lower the impedance values. The possible explanation for this behavior is the precipitation of carbides and sigma phase which occurred with the heat treatments.

Conclusions

In this work the weld joint with two AISI 316L plates with Inconel® 182 filler metal submitted to different PWHT for the three temperatures used, (600, 700 and 800) ºC was examined by microhardness testing, metallography analysis and by microanalyses to determine the effect of the PWHT in the microstructure. The most critical part of the HAZ, which had about 3 mm length, as welded and with PWHT, was tested against corrosion by means of open circuit potential, anodic polarization curves and impedance measurements. From the test results we can conclude that:

- The reduction in microhardness near the fusion line with the PWHT may indicate a reduction in residual stress. With PWHT, the microhardness decreased probably due to relief of the residual stresses, but at 700 ºC the microhardness increased compared with PWHT at 600 ºC and 800 °C, probably due the carbides and sigma phase precipitation.
- Within the weld the delta ferrite was partially dissolved in the HAZ. Its dissolution increased with increasing temperature of the PWHT. With the dissolution of delta ferrite, carbides and sigma phase precipitation occurred until to 700 °C. With the PWHT at 800 °C, delta ferrite became finer and sigma phase was partially dissolved.
- The HAZ samples without PWHT showed a higher open circuit potential. With the PWHTs the open circuit potential decreased, indicating a reduction of the corrosion resistance.
- The potentiodynamic polarization curves showed that the PWHTs affected the passive behavior of the AISI 316L HAZ samples. Comparing the samples submitted to heat treatments to the one not heat treated it suggests that the heat treatments increased the material tendency to passivate.
- The transpassive potentials are close for the different samples, which means that the passive film had similar stability. However, the sample heat treated at 800 ºC presented a delayed passivation process.

- The impedance measurements showed that the PWHTs of the AISI 316L HAZ decrease the corrosion resistance. The possible explanation for this behavior is the precipitation of carbides and sigma phase which occurred with the heat treatments.
- The AISI 316L HAZ specimen heat treated at 600ºC showed however a corrosion resistance close to the non-heat treated material.
- The dissimilar metal welding may require PWHT to relieve stress from the welding process, thus the PWHT to 600 °C proved to be closer to the condition without PWHT in relation to corrosion resistance.

Acknowledgments

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Table 1 - Nominal chemical composition - AISI 316L and Inconel® 182 (% in weight)

Material	Cu	Co	Cr	Mo	Fe	Si	Mn	C	Ti	S	P	Nb	Ni
AISI 316L	-	-	16.000	2.000	Bal.	0.750	2.000	0.030	-	0.030	0.045	-	10.000
Inconel® 182	0.040	0.050	16.533	-	3.580	0.506	5.703	0.026	0.116	0.008	0.010	1.910	Bal.

Table 2 - Typical mechanical properties - AISI 316L and Inconel® 182

Material	Temperature (°C)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Hardness Rockwell B (HRB)
AISI 316L	25	260	530	45	88
Inconel® 182	25	-	658	42	-

Table 3 – Quantitative analyses of delta ferrite in AISI 316L by EDS (wt %)

PWHT (ºC)	C	Cr	Fe	Ni	Mo
Without	2.24	21.88	66.75	4.83	2.91
600	3.05	22.17	65.86	4.10	3.25
700	4.79	24.23	60.74	3.90	3.98
800	5.14	25.24	57.89	3.03	6.88

Table 4 – Quantitative analyses of second phase, in the HAZ by EDS (wt %)

PWHT	C	Cr	Fe	Ni	Mo
Without	4.17	21.59	65.13	4.67	3.10
600°C	4.34	21.36	63.72	4.49	4.70
700°C	26.22	15.84	48.39	3.36	5.01
800°C	3.34	21.23	61.30	4.51	7.76

Table 5 – Electrochemical parameters from potentiodynamic polarization curves of AISI 316L HAZ in 0.5 mol/L H_2SO_4 solution for different PWHTs

PWHT	E_o (mV)	Critical anodic current ($\mu A.cm^{-2}$)	Primary passive potential (mV)	Passive current ($\mu A.cm^{-2}$)	E_{transp} (mV)
No PWHT	- 224	3.0	- 26.1	1.5	904
600ºC	- 258	6.3	- 230	2.5	900
700ºC	- 218	2.8	- 74.9	1.3	912
800ºC	- 242	1.3	- 101	1.9	930

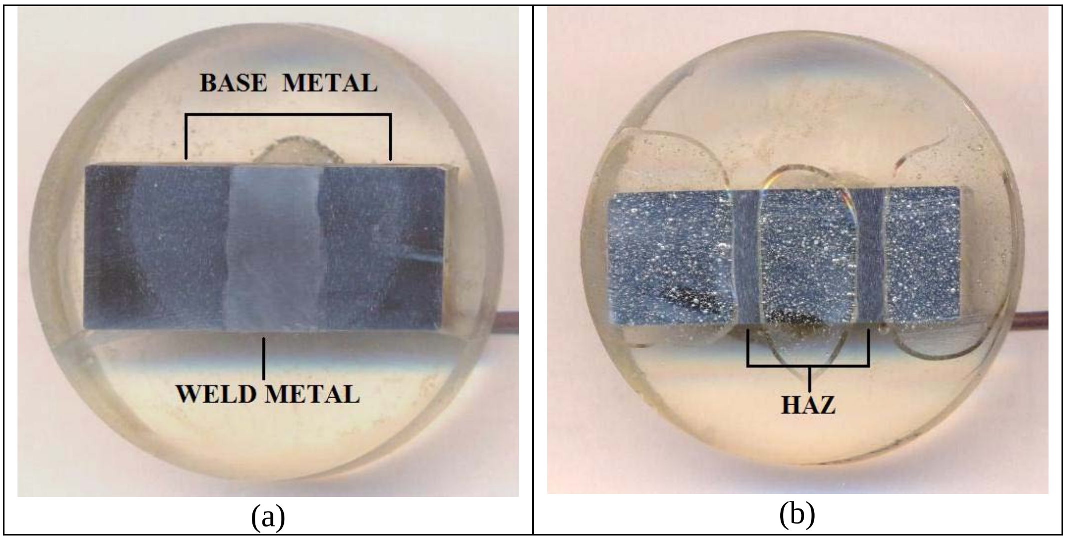

Figure 1 – The sample containing the weld joint mounted in epoxy resin (a) and the base metal and the weld metal covered by epoxy resin with the HAZ exposed (b).

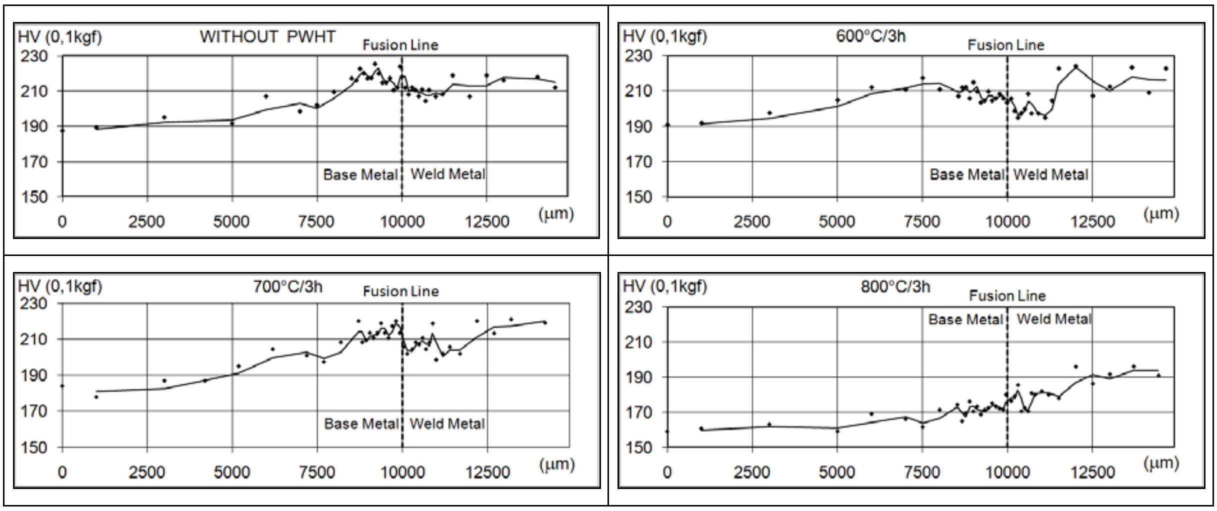

Figure 2 – Vickers microhardness profiles in weld joint (base metal, fusion line and weld metal), without and with PWHT, for the three temperatures used, 600 ºC, 700 ºC and 800 ºC. The HAZ length is between (3 to 6) mm

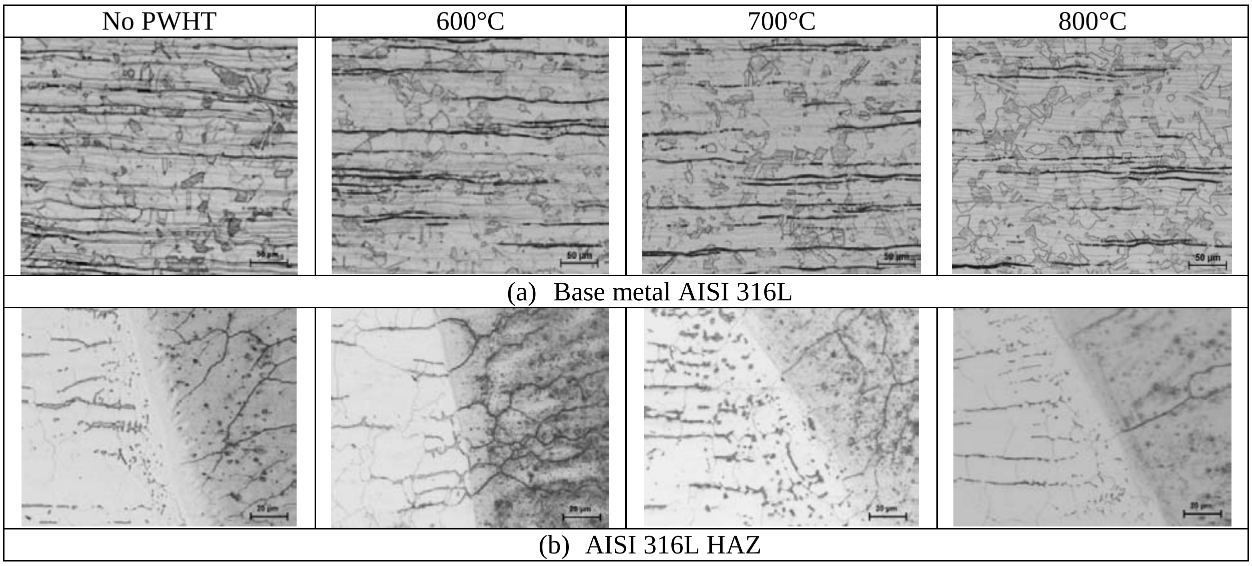

Figure 3 – (a) AISI 316L metallography showing delta ferrite in stringers form and its dissolution with PWHT; (b) evolution of delta ferrites in AISI 316L HAZ with PWHT

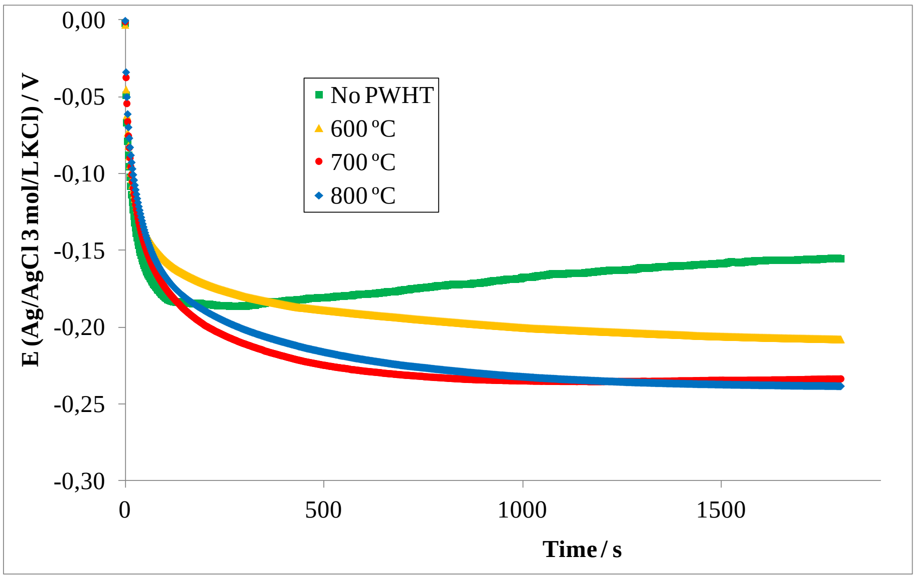

Figure 4 – Open circuit potential data for AISI 316L HAZ samples submitted to different PWHTs in 0.5 mol/L H_2SO_4 solution at room temperature

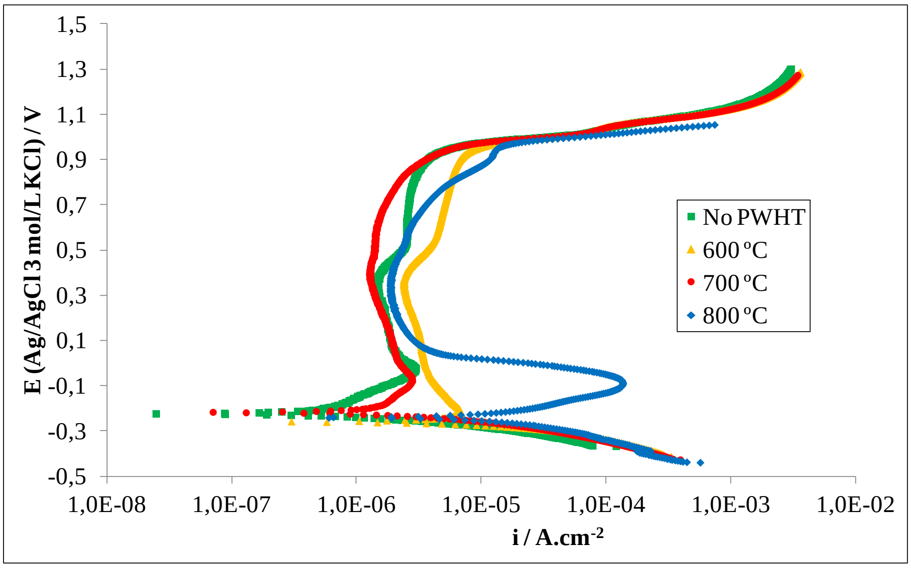

Figure 5 – Potentiodynamic polarization curves for AISI 316L HAZ samples submitted to different PWHTs in 0.5 mol/L H_2SO_4 solution at room temperature

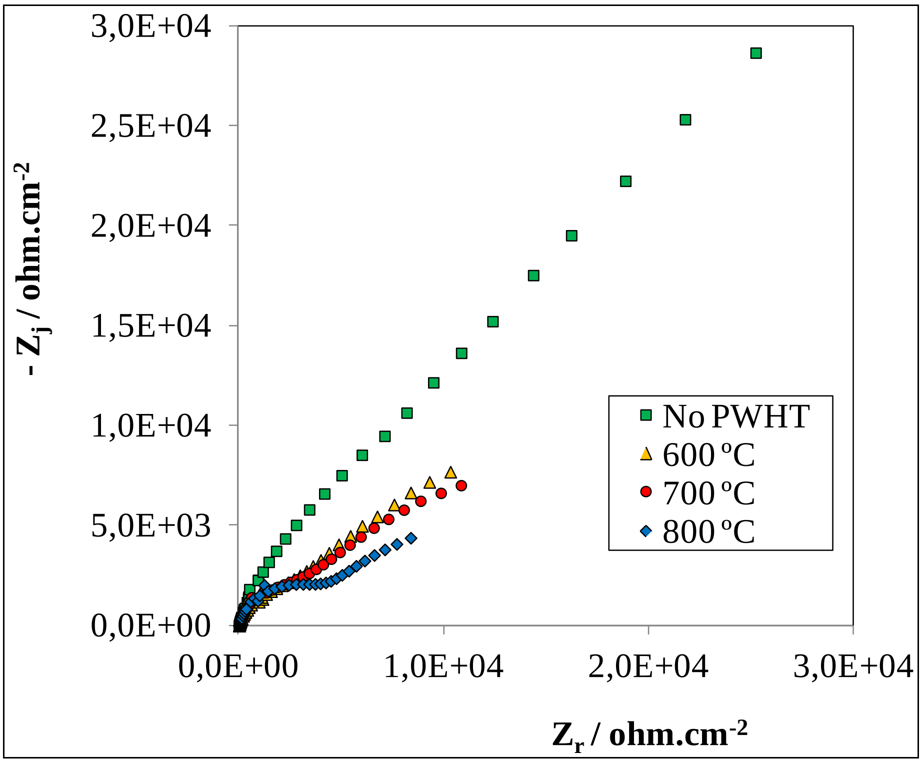

Figure 6 – Nyquist representation of impedance data of AISI 316L HAZ samples submitted to different PWHTs in 0.5 mol/L H_2SO_4 solution at room temperature

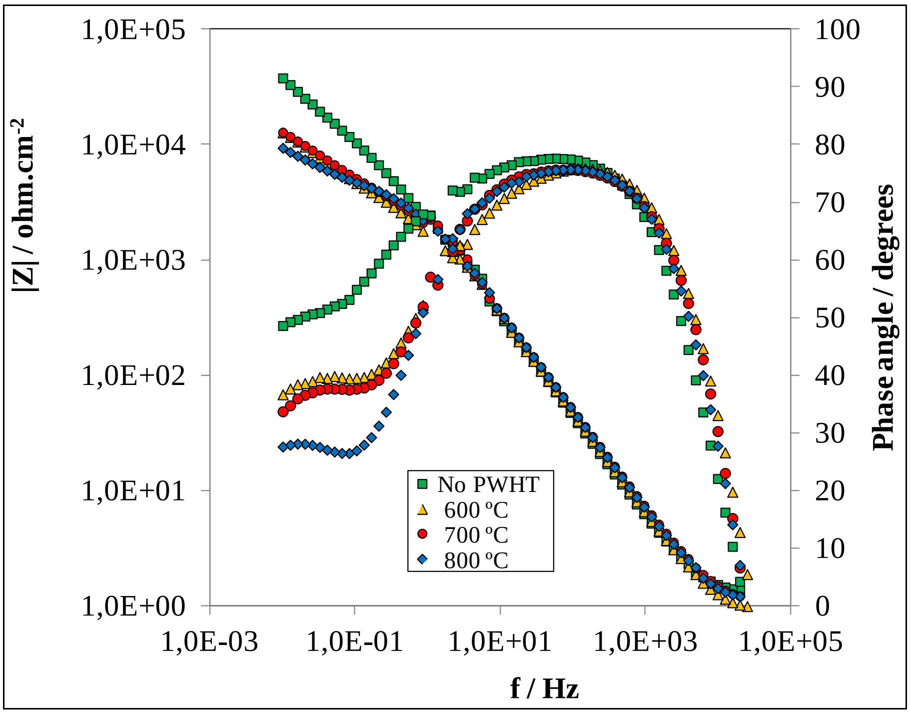

Figure 7 – Bode representation of impedance data of AISI 316L HAZ samples submitted to different PWHTs in 0.5 mol/L H_2SO_4 solution at room temperature