Corrosion resistance of the dissimilar alloy AL6XN-Inconel 718 in 0.5 M NaCl

Natalya V Likhanova, Miguel A Cruz Castañeda, Paulina Arellanes-Lozada, Octavio Olivares-Xometl, Irina Lijanova and J Arriola-Morales

1 Instituto Mexicano del Petróleo, Eje Central Lázaro Cárdenas No. 152, Col. San Bartolo Atepehuacán, 07730 Ciudad de México, México
2 Instituto Politécnico Nacional, CIITEC, Cerrada Cecati S/N, Colonia Santa Catarina de Azcapotzalco, 02250 Ciudad de México, México
3 Benemérita Universidad Autónoma de Puebla, Facultad de Ingeniería Química, Av. San Claudio y 18 sur, Ciudad Universitaria, Col. San Manuel, 72570 Puebla, Pue, México

* Author to whom any correspondence should be addressed.

E-mail: oxoctavio@yahoo.com and paulina.arellanes.lozada@gmail.com

** Keywords: corrosion resistance, dissimilar alloy, potentiodynamic polarization, electrochemical impedance spectroscopy

Abstract

In the present work, the corrosion resistance of the dissimilar alloy AL6XN-Inconel 718 bound by the Gas Tungsten Arc Welding (GTAW) method was studied. Different alloy zones were analyzed: base materials (BMs), heat affected zones (HAZs) and welds. The effect exerted by the GTAW method on the corrosion resistance displayed by such dissimilar alloy in 0.5 M NaCl was established by means of corrosion studies employing potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS) tests. The electrochemical results revealed that the alloy HAZs are more susceptible to corrosion due to microstructure changes caused mainly by elements such as Ni, Cr and Mo during the GTAW process.

1. Introduction

The use of superalloys is fundamental in different industry sectors and it has been diversified due to outstanding properties such as mechanical resistance and structural integrity under challenging work conditions. The chemical composition defines the characteristics of the different superalloys, which can be based on iron, cobalt, nickel, etc. Superalloys are unavoidably needed if the useful life of metal parts or equipment is to be extended, for conventional materials are not technologically viable [1, 2]. For this reason, the technological advance has allowed the development and understanding of superalloys such as Inconel 718 or AL6XN, which are relatively new and have shown to be a good alternative to conventional materials before more complex operation conditions [3–5].

Among the main characteristics of Inconel 718, its capacity to form intermetallic compounds of the type Ni3(Nb, Al, Ti), which extend the material useful life in terms of hardness and toughness [6], stands out. In addition, according to the thermal treatment conditions, the secondary hardening phases [γ′(Ni3(Al, Ti) and γ′′(Ni3Nb)] can precipitate and strengthen the alloy to reach its maximal resistance [7]; although, the intermetallic compounds can also affect the mechanical properties due to high heat gradients [8]. Despite the aforesaid, Inconel 718 offers high performance characteristics and properties because of its high Cr, Co, Al and Ni contents, being widely used in parts that are present in planes, turbine engines, cryogenic tanks, etc. [1]. On the other hand, the alloy AL6XN is a type of stainless steel with high Ni, Cr and Mo contents, where its ductility, strain resistance and creep as a function of temperature [9–12] are some of the remarkable properties displayed by this material. Its use is important in heat exchangers, reactor structural components, marine environment equipment, etc. Furthermore, this alloy is widely used due to its good corrosion resistance in corrosive environments with the presence of halide ions, for other types of stainless steel are not recommendable [13–17]. Since Inconel 718 is an austenitic alloy with high Ni and Cr contents (up to 50 and 18%, respectively), it can be used within a wide temperature interval (from –253 to 650 °C), preserving its physical and chemical properties nearly untouched, thus guaranteeing its useful life [7, 18–20]. In both alloys, the high Ni and Cr contents provide...
good protection against corrosion in aggressive media. The presence of Mo in Inconel 718 and AL6XN promotes their repassivation in corrosive media rich in chlorides and confers stability to the passive film in harsh media at high temperatures [21].

According to the aforementioned, these two superalloys present individually important structural advantages, but there is special interest in the synergy between both materials forming a dissimilar alloy by means of the Gas Tungsten Arc Welding (GTAW) process. The application of this method to bind different alloys has been the topic of several research works, where some of them have been focused on the homogeneity and properties of the weld; others have been centered on studying the changes presented by the microstructure of the base materials (BMs) as a result of the effect exerted by the temperature heterogeneity, which promotes the formation of different grain sizes and morphologies.

As a result of these research works, it has been confirmed that microstructural alterations and possible changes regarding the properties of materials occur as a consequence of using the GTAW process [22–25]. It has been observed that the heat affected zone (HAZ) adjacent to the weld can affect the performance of dissimilar alloys. For this reason, the selection of the filler material (FM) is carried out according to the chemical composition of the matrix of alloys in order to avoid altering significantly the original properties of the base material and reduce the negative GTAW effects [26]. The modification of the chemical composition of alloys near the weld and HAZ can have negative effects on the corrosion resistance. Then, the study of the corrosion rate of dissimilar alloys is of great interest. In the research work by Bright O Okonkwo et al on the galvanic corrosion between low alloy steel (LAS) A508 and 309/308L stainless steel (SS), it was concluded that the galvanic corrosion rate of coupled dissimilar metals for long times is reduced by the formed oxide film [27]. On the other hand, Chenghang Zhang et al studied the localized corrosion of the thermo–mechanically affected zone (TMAZ) in the dissimilar alloy AA2024/7075, confirming that the thermally affected zones were more susceptible to suffer more severe corrosion damage than the base materials [28]. Like the GTAW process, the use of metal oxide fluxes with dissimilar metals such as stainless steel 316L and Alloy 800 has been studied on the weld region as well as the corrosion damage performance [29].

In works on dissimilar welded X-42 and grade B pipelines using the shielded metal arc welding (SMAW) process, it was observed that the thermal energy gradient affects the corrosion rate, being higher at the weld line than at the HAZ, followed by the base metals. This phenomenon was explained by microstructural alterations of the alloys by the SMAW process [30]. Generally, in alloys where a protecting oxide layer is formed, the corrosion type tends to be localized, promoted by different factors such as the presence of aggressive anionic species in the medium, which corrode the alloy, breaking the external layer of the protecting film in specific zones like surface defects, inclusions (compositional heterogeneity), intermetallic particles, segregated or precipitated species, etc. Some authors have tried to explain the breaking of passive films in saline media in terms of the competitive absorption between chloride ions and oxygen and the equilibrium between chloride ions and the oxide film [31]. It should be kept in mind that the chemical composition of the alloy in the presence of saline aqueous media can prompt the formation of active sites and promote localized corrosion [32]. In general, the localized corrosion mechanism in alloys that form passive films is studied by employing NaCl electrolytic solutions due to the effect exerted by the chloride ions on passive films and alloy matrix, which stems from their small size, high diffusivity and strong acid anionic nature [33–35]. The effect of the thermal gradient on both the welding of dissimilar alloys and formation of protecting films capable of withstanding the attack in electrolytic media rich in aggressive ions is of the utmost importance to understand the localized corrosion mechanism. Since it has been reported that welding thermal processes affect the anticorrosion performance of dissimilar alloys because of
modified properties [25], the present work evaluates the corrosion resistance of a dissimilar alloy between Inconel 718 and AL6XN obtained by the GTAW process. In order to reach these goals, corrosion studies were carried out in different alloy zones (BMs, HAZ and weld), in a 0.5 M NaCl solution, employing electrochemical techniques such as Tafel potentiodynamic polarization and EIS, which were complemented with weight loss tests.

2. Experimental

2.1. Materials and test solutions

The chemical composition of the employed alloys is shown in table 1 and the conditions of the GTAW process were already reported [25]. In order to reduce the negative effects of the welding process on the BMs, ERNiFeCr-2 was used as FM due to the mechanical properties and chemical composition of the used BMs [25]. Figure 1 shows a representation of the different zones being part of the dissimilar alloy: non-thermally-affected zone of the AL6XN (Z1AL) and Inconel 718 (Z1IN) alloy; thermally-affected zones of the AL6XN (Z2AL) and Inconel 718 (Z2IN) alloy; and ERNiFeCr-2 weld zone or FM. Metal coupons were obtained from each zone, which were abraded with SiC emery paper with grit numbers from 320 to 2000 and finally mirror polished using 3-μm alumina. After the abrading process, the surface was degreased with acetone-ethanol and the particles adhered to the surface were removed by means of ultrasonic cleaning bath. On the other hand, the corrosive aqueous medium was a 0.5 M NaCl solution prepared with analytical grade NaCl and deionized water.

2.2. Metallographs

The microstructural changes provoked by the welding process were revealed by means of the gliceregia reagent (15 ml of HCl, 5 ml of HNO₃ and 10 drops of C₃H₈O₃). The micrographs were obtained by employing an inverted metallurgical optical microscope model Nikon Eclipse MA100.

2.3. Weight loss

For the weight loss tests, dissimilar alloy metal coupons were obtained from the zones indicated in figure 1 and had a work area of 13.3 cm². The tests were carried out in a muffle furnace Barnstead Thermolyne model 47900 at 600, 700 °C and 800 °C with time intervals of 1, 25 and 50 h. The preparation and treatment of the metal coupons were done according to the ASTM G1–03 standard practice [36].

2.4. Electrochemical methods

A potentiostat/galvanostat PGSTAT302N, Autolab model, was employed to run the electrochemical tests. The experiments were performed at stationary state. The electrochemical measurements were carried out in a three-electrode glass cell at 25 °C ± 1 °C. The working electrodes had a contact area of 0.3 cm² and were obtained from different zones according to figure 1: a saturated calomel electrode was the reference electrode, and a platinum electrode was used as counter electrode. Before each experiment, the working electrode was kept immersed in the test electrolyte for 20 min to attain a steady open circuit potential (E_OCP). The potentiodynamic polarization (PDP) tests were carried out within a potential scanning interval ranging from −250 to +250 mV against E_OCP with a scanning rate of 0.16 mV/s. The electrochemical parameters of the Tafel curves were obtained by linear extrapolation of the anodic and cathodic curves by using the software Nova version 2.1.3, which carries out the fitting process according to the non-linear least square fitting method by Levenberg/Marquardt. The electrochemical impedance spectroscopy (EIS) measurements were carried out at stationary state within a frequency interval ranging from 100 kHz to 10 mHz, using a sinusoidal wave with 5 mV of amplitude after establishing the E_OCP. The reproducibility of the electrochemical experiments was assured by running the tests in triplicate.

| Table 1. Chemical composition of the alloys and weld metal. |
|---|
|   | C  | Cr | Mn | Ni | Mo | Ti | Al | Nb | Si | N  | Fe |
| AL6XN   | 0.05 | 21.00 | 1.00 | 24.50 | 6.50 | 5.45 | 0.22 | Bal. |
| Inconel 718 | 0.05 | 18.20 | 0.07 | 52.97 | 2.89 | 0.65−1.15 | 0.57 | 4.98 | Bal. |
| ERNiFeCr-2 | 0.05 | 17.70 | 0.08 | 51.70 | 3.10 | 0.98 | 0.45 | 5.45 | Bal. |
3. Results and discussion

3.1. Metallographic analysis

Figures 2(a) and (b) show the metallographs of the stainless steel samples AL6XN and Inconel 718 BM, respectively. Figure 2(a) shows a completely austenitic structure with an average grain size of 95 μm. On the other hand, the micrograph in figure 2(b) displays an austenitic matrix with equiaxed grain and average grain size of 72 μm. In addition, the presence of MC- or M₆C-type carbides, which can consist mainly of Mo, Nb, Ti, Fe or W and are generated by the segregation of Nb and Mo during solidification, is shown. This observation can be supported by the analysis performed by Tresa M. Pollock and Sammy Tin who studied Nickel-Based Superalloys and stated that the MC carbide phases were selected depending on the composition of the primary MC carbide and the constituent elements present in the alloy; in addition, the subsequent solid-state transformation may decompose the MC carbide into different phases [37].

Figure 2(c) shows the interface between the BM AL6XN and the FM, where the formation of a zone located at the limit of both materials is observed, which is characterized by the presence of grains, referred to as the ‘no-mixing zone’. This morphological change is related to the difference between the chemical composition and fusion points of the materials (AL6XN from 1357 °C to 1430 °C and ERNiFeCr from 1260 °C to 1336 °C).
Furthermore, in the AL6XN matrix, the presence of carbides formed by the intergranular segregation of intermetallic compounds because of the welding process, generating a zone that is susceptible to suffer corrosion damage, is observed. The results of the interface between the FM and Inconel 718, shown in figure 2(d), reveal the growth of partially melted grains through the fusion line and Z2IN. In addition, intergranular carbides are observed, which make this zone highly prone to corrosion damage. Finally, the FM micrograph shown in figure 2(e) reveals a column-dendritic-type microstructure.

3.2. Weight loss

Figure 3 presents the results obtained from the corrosion rate (CR) of the studied dissimilar alloy zones at different temperatures and exposure times. The CR was calculated with the following equation [38]:

\[
CR = \frac{8.76 \times 10^4 \cdot W}{A \cdot T \cdot D}
\]

where, W is the mass loss in g, A is the area in cm\(^2\), T is the exposure time in h and D is the density in g cm\(^{-3}\).

An increase in the CR as a function of the temperature and exposure time is observed. The CR displayed by the alloy AL6XN was more stable than that of Inconel 718 due to the presence of Cr, Mo and Ni in the alloy; these elements react with oxygen forming Cr\(_2\)O\(_3\), NiO, MoO\(_2\), and MoO\(_3\), which are complexes that preserve the stability of the passive film formed on the metal substrate [39–41]. For this reason, understanding the passivation mechanism of alloys is a very complex process. In order to do so, several models have been proposed, but most of them are aimed at establishing the chemical composition of the film as a function of the beneficial effect by the elements that are part of the alloy [42].

As for Inconel 718, the intragranular segregation of intermetallic compounds of the type Ni\(_3\)(Nb, Al, Ti) and Cr\(_2\)Nb was promoted during the GTAW process; as a result, active sites were formed at grain limits, making the iron matrix susceptible to the corrosion processes [43]. In addition, since it has a lower Mo content, the formed passive layer is less effective against corrosion at high temperatures. Likewise, the heat input (HI) effect on AL6XN is capable of promoting the segregation of MO in both the nuclei and dendritic limits [44]. Furthermore, the segregation of intermetallic compounds based on Fe, Cr and Mo (σ phase) at the granular limits promotes the formation of intragranular active sites [45]. This reordering of the main alloy elements and migration of Mo toward the fusion zone during the welding process [46] promote the formation of galvanic pairs in each interface present in the dissimilar alloy (Z2AL/MA and MA/Z2IN). Also, the FM zone showed the highest CR, which could be due to the Nb influence, promoting the intragranular segregation of intermetallic compounds based on Ni, Nb, Ti and Al. Since heat can promote both the precipitation of intermetallic compounds in interdendritic sites based on Cr, Fe and Mo and the migration of Mo from thermally affected zones, this phenomenon resulted in corrosion localized in interdendritic zones.
3.3. Potentiodynamic polarization (PDP)

Figure 4 shows the Tafel curves of the dissimilar alloy AL6XN-Inconel 718 in 0.5 M NaCl solution at 25 °C. It is observed that the PDP curves present Tafelian behavior. In addition, it is evident that the FM curve has higher current density than the different dissimilar alloy zones. The low corrosion resistance is due to its chemical composition; during the GTAW process, the segregation of intermetallic compounds based on Ni₃(Al, Nb and Ti) and Cr₂Nb in dendritic nuclei and Cr and Mo precipitates at the dendritic limits are unavoidable as stated in a previous work by R. Cortés et al [25]. Then, the grain limits and dendritic nuclei were the vulnerable active sites to be attacked by the chloride ions present in the 0.5 M NaCl solution. In general, the curves of stainless-steel-based materials present lower corrosion current density due to the presence of elements such as Cr, Ni and Mo in the matrix of alloys, which improve their physicochemical properties and increase the corrosion resistance [33, 34, 47, 48].

PDP electrochemical parameters such as corrosion current density (Icorr), anodic (βa) and cathodic (βc) Tafel slopes and corrosion potential (Ecorr) were calculated and reported in Table 2. The Ecorr values indicate that the thermal effect of the welding process in the Z2 zones produced a displacement of Ecorr toward more positive values, i.e. the formation of corrosion products by the redox reactions was favored. Furthermore, it is observed that the Icorr of the Z1AL is lower than that displayed by Z1IN, indicating that the alloy Inconel 718 presented higher corrosion rate due to the segregation of Ni₃(Al, Ti, Nb) and Cr₂Nb in intradendritic sites originated during the welding process, which has been reported by other authors [49], and could promote the formation of active zones at grain limits, making them vulnerable to the attack of chloride ions in the medium. However, the thermal effect on the BMs promoted slightly the opposite behavior pattern, for the Icorr value of Z2IN is lower than that of Z2AL, indicating that the Z2IN zone has better corrosion resistance against chloride ions. This behavior was attributed to the Ni concentration in Inconel 718 (52.97 wt.%), which is higher than in AL6XN (24.5 wt.%); this fact confirmed that this element plays a major role in the surface

Table 2. Electrochemical parameters of the dissimilar alloy in 0.5 M NaCl obtained by the PDP technique.

| Zone  | βa  (mV dec⁻¹) | βc  (mV dec⁻¹) | Ecorr (mV/SCE) | Icorr (μA cm⁻²) |
|-------|----------------|----------------|----------------|----------------|
| Z1AL  | 255            | 126            | 269            | 0.331          |
| Z2AL  | 289            | 243            | 136            | 0.924          |
| FM    | 254            | 265            | 160            | 4.578          |
| Z1IN  | 244            | 158            | 267            | 0.537          |
| Z2IN  | 310            | 208            | 200            | 0.776          |
passivation and resistance to be attacked by chloride ions in the aqueous medium, for it favors the formation of a more stable and compact film in Inconel 718 [50]. This phenomenon can be explained by the production of nickel oxides in combination with chromium oxides; additionally, since it is a gamma-iron element, it stabilizes the austenitic microstructure of the alloy, thus improving its corrosion resistance [51].

The results of the thermal effect on the AL6XN stainless steel indicate that the \( I_{\text{corr}} \) value presented by Z2AL is higher than that of Z1AL, which evidences that the thermal gradient close to the weld affects the alloy microstructure during the GTAW process. The diffusion of chloride ions from the aqueous medium toward the steel surface through the passive film was higher in Z2AL, which increased the susceptibility to suffer corrosion damage in the aqueous medium. Furthermore, the difference between the \( I_{\text{corr}} \) values displayed by Z2AL and Z1AL can be associated with the segregation of intermetallic compounds based on Mo, Cr and Ni. Under normal conditions, Ni based alloys with presence of Mo exhibit high corrosion resistance in media with chloride ions due to the presence of exchange cations (\( \text{Mo}^{4+}, \text{Mo}^{5+} \) and \( \text{Mo}^{6+} \)), which provide stability to the protection film, reducing the damage by uniform corrosion or located on the steel surface [52]. Notwithstanding, it has been reported that the Mo concentration on a metal surface tends to be reduced by leaching processes toward the medium in contact with the passive layer [53]. During the welding process in this type of welds, molybdenum

\[ \text{Figure 5. (a) Nyquist and (b) Bode plots of the dissimilar alloy AL6XN-Inconel 718 in 0.5 M NaCl solution at 25 }^\circ\text{C.} \]

\[ \text{Mater. Res. Express 8 (2021) 086509 N V Likhanova et al} \]
normally migrates toward the liquid phase, which generated the deficiency of this element in Z2AL. Furthermore, it has been confirmed that the microsegregation of Cr and Mo toward interdendritic zones reduces the material capacity to repassivate the nuclei due to the segregation of sigma (σ)-type phases in the dendritic nuclei \[54, 55\]. Similarly, the curves of the AL6XN alloy, the current resistance of Z2IN in 0.5 M NaCl was also affected by the GTAW process, however, the HI affected less the passive film in Z2IN than in Z2AL, indicating that in the alloy-film interface, the diffusional processes of the chloride ions toward the alloy matrix in Inconel 718 are more limited.

3.4. EIS analysis

The Nyquist and Bode plots of the dissimilar alloy AL6XN-Inconel 718 in 0.5 M NaCl solution after the GTAW process are shown in figure 5, where different impedance responses can be observed for the diverse zones in the dissimilar alloys. The specific features in the general shape of the spectra indicate that there was a change in the corrosion mechanism. The Bode phase plot in figure 5(b) shows that Z1AL had three maximal phase displacements (approximately at 25° at 0.13 Hz, at 37° at 25 Hz and at 23° at 6310 Hz) whereas the thermal treatment produced by the welding process, i.e. Z2AL, reduced the response to two maximal phase displacements (approximately at 59° at 2 Hz and at 72° at 75 Hz), which can be related to three and two interfaces present on the metal surface with different electric properties, respectively. As for the Inconel 718 zones, it is observed that the spectra display two maximal phase displacements with two time constants. In the Z1IN zone, no phase drop is observed at low frequencies and additionally, in figure 5(a), the capacitive loop is not closed; instead, there is a proportional increase of $-Z'$ with $Z'$, which is related to a diffusive process \[56–58\] that suggests that the dissolution of the alloy Inconel 718 was controlled by the transport of either chlorides to the metal surface or electrode Fe$_x$Cl$_y$ complexes to the solution by means of a diffusive process. On the other hand, at low frequencies, figure 5(b), it is observed in the Bode impedance plot that both Z1AL and Z1IN had the highest values whereas the FM had lower impedance values, which indicates that the zones that were not affected thermally and FM displayed the lowest and highest corrosion damage in NaCl, respectively.

Figure 5(a) shows that the diameter of the semicircles in the Nyquist plots corresponding to the alloys diminished with the thermal treatment of AL6XN and Inconel 718, which confirms that the welding process
reduced the corrosion resistance of the dissimilar alloy. As for the FM, its lower corrosion resistance was also revealed due to smaller diameter of the capacitive loops.

The impedance parameters reported in table 3 were obtained by fitting the impedance spectra to equivalent electric circuits (EECs), which are shown in figure 6. Figure 6(a) exhibits the EEC with a model featuring three time constants that fitted the Z1AL spectrum. Figure 6(b) displays the EEC of the Z1IN zone with two time constants and a Warburg element. Finally, figure 6(c) fitted the spectra with a model considering two time constants, i.e. Z2AL, Z2IN and FM. In the EECs, $R_n$, $R_{pf}$, $R_{ct}$ and $R_{rf}$ are the solution, repassivated film, passive film and charge transfer resistances, respectively; $CPE_{pf}$, $CPE_{ct}$ and $CPE_{dl}$ are constant phase elements representing the capacitance of a repassivated film ($C_{pf}$), a passive film ($C_{ct}$) and of the electrical double layer ($C_{dl}$) whereas $W$ indicates the presence of a Warburg element related to a diffusive process. The capacitance can be related to two variables, $Y_0$ and $n$, where the first one is a magnitude or proportionality coefficient and the second one is an exponent that is associated with the phase displacement degree attributed to surface physical changes.

In Z1AL, an internal passive film was formed, which consisted of chromium and nickel oxides, Ni$_x$(Nb, Al, Ti) and Cr$_2$Nb, represented in figure 6(a) as $C_{pf}$, and a second layer composed by Mo oxides, identified as $C_{ct}$ was also produced. Possibly, the repassivation process was generated by the formation of insoluble complexes of Mo(IV) oxychloride or oxyhydroxide chloride according to the medium conditions as reported by Halada et al [59], exerting a positive effect on the Z1AL corrosion resistance. Notwithstanding, the heat produced by the welding process promotes the migration of Mo atoms toward the welding metal and for this reason, Z2AL did not present a repassivation process. Furthermore, since the alloy Inconel 718 has lower Mo amount, repassivation processes do not take place easily.

In addition, it is observed that the $C_{pf}$ value in Z2AL is higher than that of Z1AL, which indicates that the thickness of the passive film is modified by the thermal treatment because capacitance is inversely proportional to the film thickness; then, the zone without thermal treatment displayed a thicker passive film that retarded the corrosion rate. Likewise, by comparing Z1IN and Z2IN, it is concluded that the passive film is thicker in the non-thermally treated zones. The welding process for both stainless steel alloys promotes the microsegregation of Cr and Mo toward interdendritic sites, thus modifying the morphology of the passive film [60] and facilitating the redox processes at the intergranular limits. Furthermore, it has been reported that the thermal treatment promotes the selective dissolution of NiOOH, Ni(OH)$_2$, Fe(OH)$_2$ and FeOOH, making the protecting layer thinner in alloys with high Ni content [61]. In this way, the formation of active zones that are vulnerable to the adsorption of Cl$^-$ ions is promoted, facilitating its direct attack and originating pitting nuclei at grain limits, which generates the dissolution of the passive layer [62]. Also, the thermal process during the welding process can produce surface defects that allow the penetration of Cl$^-$ ions toward the metal substrate, increasing the corrosion rate.

As for the FM, the higher $C_{ct}$ and lower $R_p$ values reported in table 3 confirm that the alloy in NaCl solution presented a slightly-homogeneous-conducting-metal interface due to the segregation of Cr at grain limits and diffusion of Mo to the liquid phase [63]. The polarization resistance ($R_p$) values, calculated by adding the resistances reported in table 3, confirmed the results of the Tafel tests, displaying the following trend: Z1AL > Z1IN > Z2IN > Z2AL > FM.
The zones spared by the thermal treatment exhibited higher opposition to the flow of Cl\(^{-}\) ions from the solution to the active zones; on the other hand, the HAZs displayed higher passive layer conductivity due to the generated morphological changes whereas the FM showed less corrosion resistance. Furthermore, the alloy AL6XN had higher \(R_p\) than Inconel 718, for the latter has higher Ni content, which generates the formation of a thinner and more homogeneous passive layer.

3.5. Surface analysis
The surface damage of the studied alloys was analyzed by means of optical microscopy. To this end, immersion tests in 0.5 M NaCl solution for 168 h at 25 \(^\circ\)C were carried out. Figures 7(a) and (b) correspond to Z2AL and Z2IN after being exposed to the corrosive medium, respectively. The presence of active sites on the metal surface is evidenced, where the redox reactions were accelerated in the Z2AL and Z2IN materials, revealing clearly localized damage by 'pitting' corrosion and confirming that the matrix of the alloys was affected thermally by the weld action, making them more susceptible to present more serious localized damage.

3.6. Corrosion mechanism
According to the chemical comparison of the dissimilar alloy, Cr, Ni and Mo play a major role in the corrosion resistance of the metallic material, as confirmed by the employed tests. The corrosion mechanism started with
the formation of a passive layer consisting of NiO, Ni(OH)$_2$, Cr$_2$O$_3$ and MoO$_3$ on the surface of the alloys under normal operation conditions, however, the influence of grain boundaries on the protective properties of the film will be more pronounced in these alloys than for model ultrapure Fe-Cr-Ni alloys [64], figure 8. The numerous impurities contribute to intergranular corrosion. So, in Inconel 718, alloying elements such as Nb, Ti and Al also play an important part in the alloy mechanical properties, but additionally, complexes of the types Ni$_3$(Nb, Ti, Al) and Cr$_2$Nb can be formed at the grain limits rich in Fe leading to the disadvantage of being exposed to redox reactions, thus generating active sites that are prone to suffer pitting-type localized corrosion when the passive film is surpassed by the medium action.

Additionally, the 0.5 M NaCl aqueous medium can also affect the passive film naturally formed in both alloys [65]: at a first stage, the diffusion of the Cl$^-$ ions takes place through the imperfections of the passive layer toward the active sites located at the alloy surface defects and welding fusion line. This phenomenon generates the evolution of redox reactions in active sites and concomitant formation of corrosion products such as green rust, Fe$_x$Cl$_y$, FeOOH, and FeCr$_2$O$_4$ complexes. Due to the solubility of Fe$_x$Cl$_y$ and its weak adherence to the steel surface, it can generate the partial loose of the metal/passivating layer interface, and with this, the unavoidable penetration of Cl$^-$ toward the metal matrix occurs, which promotes the continuous advance of the pitting damage or localized corrosion. Furthermore, due to the medium conditions, damage by uniform corrosion cannot be ignored. The FM alloy contains a lower percentage of chromium in its composition, and a high percentage of nickel, which promotes the formation of iron oxyhydroxides in the presence of chlorine ions [66, 67].

It has been reported that a repassivation process is possible because of the formation of Mo(IV) oxychloride or oxyhydroxide chloride, since these species are insoluble, they can block the active sites from the attack of the Cl$^-$ ions, thus mitigating the alloy pitting damage [21, 59]. However, since Mo tends to migrate to the liquid zone during the welding process [63, 68], the thermally affected zones present Mo deficiency and as a result, repassivation is not possible; for this reason, the heat exposure of the alloys during the welding process modified the material structure, affecting its corrosion resistance as confirmed by the CR results.

4. Conclusions

- Based on the obtained results, the corrosion process of the dissimilar alloy started by the segregation of the different intermetallic compounds toward intradendritic and interdendritic sites. This phenomenon promotes the presence of active zones at dendritic limits and nuclei.
- The $I_{corr}$ results obtained from the PDP tests presented the following order: FM > Z2AL > Z2IN > Z1IN > Z1AL. The HAZs of the alloys AL6XN and Inconel 718 presented higher $I_{corr}$ than their corresponding BM up to 279 and 145%, respectively. Then, it is concluded that the welding process affected
the corrosion resistance of the HAZs because of certain elements such as Ni, Cr and Mo. Mo migrated toward
the fusion zone, affecting the capacity of Z2AL to be repassivated in aqueous medium. In the Inconel 718
zones, the higher amounts of Cr and Ni promoted the formation of a passive film resistant to pitting corrosion,
however, at high temperatures, lower Mo amount in the metal matrix weakens the passive film.

- The CR results confirmed the formation of a passive film on the surface of the dissimilar alloy by the reduction
  of the CR values as the exposure time to the corrosive medium passed by. The welding process not only
  sensitizes the adjacent region to the weld, but also affects the repassivation processes in the HAZs in both
  materials.

- The EIS analysis indicated that corrosion sensitization of the materials because of the welding process
  occurred, because the \( R_{eq} \) in Z2 is lower in the Z1 zones of the alloys, and since \( R_{eq} \) is inversely proportional to
  the CR, the PDP results are validated.

Acknowledgments

The authors gratefully acknowledge CONACYT-Mexico, IPN-CIITEC, and BUAP-VIEP for the granted
financial support. Thanks to Dr. David Jaramillo for providing the dissimilar alloy AL6XN-Inconel 718.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Natalya V Likhanova  
https://orcid.org/0000-0003-4152-0953

Paulina Arellanes-Lozada  
https://orcid.org/0000-0003-0918-5008

Octavio Olivares-Xometl  
https://orcid.org/0000-0003-0525-6155

Irina Lijanova  
https://orcid.org/0000-0003-1682-4509

J Arriola-Morales  
https://orcid.org/0000-0002-4745-5868

References

[1] Qi H 2012 Review of INCONEL 718 alloy: its history, properties, processing and developing substitutes J. Mater. Eng. 92–100 http://
 jme.biam.ac.cn/EN/Y2012/V0/18/92

[2] Akca E and Gürsel A 2015 A review on superalloys and IN718 nickel-based INCONEL superalloy Period. Eng. Nat. Sci. 315–27

[3] Briones R, Ruiz A, Rubio C and Carreon H 2014 Caracterización microestructural y mecánica de una soldadura disimil de aceros
inoxidables 316L./AL-6XN Rev. Latinoam. de Metal. y Mater. 34 306–15 http://www.rllm.org/ojs/index.php/rllm/article/
view/525

[4] Betteridge W and Shaw S W K 1987 Development of superalloys Mater. Sci. Technol. 3 682–94

[5] El-Bagoury N 2016 Ni based superalloy: casting technology, metallurgy, development, properties and applications Int. J. Eng. Sci. Res.
Technol. 5 108–52 http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.742.3232&rep=rep1&type=pdf

[6] Slama C, Servant C and Cizeron G 1997 Aging of the inconel 718 alloy between 500 and 750 °C J. Mater. Res. 12 2298–316

[7] Zhang Z et al 2021 Cold spray deposition of Inconel 718 in comparison with atmospheric plasma spray deposition Appl. Surf. Sci. 535
147704

[8] Yu Z S, Zhang J X, Yuan Y, Zhou R C, Zhang H J and Wang H Z 2015 Microstructural evolution and mechanical properties of inconel
718 after thermal exposure Mater. Sci. Eng. A 634 55–63

[9] Meng L, J, Sun J and Xing H 2012 Creep and precipitation behaviors of AL6XN austenitic steel at elevated temperatures J. Nucl. Mater.
427 116–20

[10] Abed F H and Voyiadjis G Z 2005 Plastic deformation modeling of AL-6XN stainless steel at low and high strain rates and temperatures
using a combination of bcc and fcc mechanisms of metals Int. J. Plast. 21 1618–39

[11] Nemat-Nasser S, Guo W-G and Kihl D P 2001 Theromomechanical response of AL-6XN stainless steel over a wide range of strain rates
and temperatures J. Mech. Phys. Solids 49 1823–46

[12] Meng L, J, Sun J, Xing H and Pang G W 2009 Serrated flow behavior in AL6XN austenitic stainless steel J. Nucl. Mater. 394 34–8

[13] Janikowski D S 2007 Selecting tubing materials for power generation heat exchangers Int.Power-Gen International Conference (New
Orleans) (Plymouth Tube Company) 1–17
[53] Sivakumar M, Mudali U K and Rajeswari S 1994 \textit{In vitro} electrochemical investigations of advanced stainless steels for applications as orthopaedic implants J. Mater. Eng. Perform. \textbf{3} 744–53

[54] Sugimoto K and Sawada Y 1977 The role of molybdenum additions to austenitic stainless steels in the inhibition of pitting in acid chloride solutions Corros. Sci. \textbf{17} 425–45

[55] Lee C, Lee Y, Lee C and Hong S 2018 Precipitation behavior of the sigma phase with Ni and Mn content variations in superaustenitic stainless steel weld metal Mater. Charact. \textbf{144} 148–54

[56] Feliu S 2020 Electrochemical Impedance Spectroscopy for the Measurement of the Corrosion Rate of Magnesium Alloys: Brief Review and Challenges Metals \textbf{10} 775

[57] Das S, Baranwal P K and Rajaraman P V 2018 Effect of soft cations on carbon steel corrosion in chloride media Corros. Rev. \textbf{36} 395–402

[58] Cesiulis H, Tsyntsaru N, Ramanavicius A and Ragoisha G 2019 \textit{Nanostructures and Thin Films for Multifunctional Applications: Technology, Properties and Devices} ed I Tiginyanu et al (Cham: Springer International Publishing) pp 3–42

[59] Halada G P, Clayton C R, Herman H, Sampath S and Tiwari R 1995 An x-ray photoelectron spectroscopic study of the passive film formed on pure Mo and MoSi	extsubscript{2}, in 4M HCl J. Electrochem. Soc. \textbf{142} 74–81

[60] Vilche J R and Arvia A J 1978 Kinetics and mechanism of the nickel electrode–II. Acid solutions containing a high concentration of sulphate and nickel ions Corros. Sci. \textbf{18} 441–63

[61] Vilche J R and Arvia A J 1975 Kinetics and mechanism of the nickel electrode–I. Acid solutions containing a high concentration of chloride and nickel ions Corros. Sci. \textbf{15} 419–31

[62] Kim S J, Hong S G and Oh M-S 2017 Effect of metallurgical factors on the pitting corrosion behavior of super austenitic stainless steel weld in an acidic chloride environment J. Mater. Res. \textbf{32} 1343–50

[63] Ren W, Lu F, Yang R, Liu X and Li Z 2015 Liquation cracking in fiber laser welded joints of inconel 617 J. Mater. Process. Technol. \textbf{226} 214–20

[64] Safonov I A, Andreev Y Y and Dub A V 2012 Results of thermodynamic calculation of the composition of passive films on Ni-Cr system alloys compared to Fe-Cr alloys Prot. Met. Phys. Chem. Surf. \textbf{48} 699–709

[65] Winston Revie R and Uhlig H H 2008 \textit{Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering} (New Jersey, NJ: Wiley-Interscience)

[66] Konishi H, Yamashita M, Mizuki J I and Uchida H 2006 \textit{Characterization of Corrosion Products on Steel Surfaces} ed Y Waseda and S Suzuki (Berlin, Heidelberg: Springer) pp 199–222

[67] Waseda Y and Suzuki S 2005 \textit{Advances in Materials Research} ed Y Kawazoe (New York, NY: Springer) pp 210–34

[68] Manikandan S G K, Sivakumar D, Prasad Rao K and Kamaraj M 2015 Laves phase in alloy 718 fusion zone microscopic and calorimetric studies Mater. Charact. \textbf{100} 192–206