Effects of immersion in the NaCl and H2SO4 solutions on the corrosion rate, microstructure, and hardness of stainless steel 316L

Anugrah Budi Wicaksono, Hadi Sutanto, Wegie Ruslan

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Effects of immersion in the NaCl and H₂SO₄ solutions on the corrosion rate, microstructure, and hardness of stainless steel 316L

Anugrah Budi Wicaksono*,a, Hadi Sutantob, Wegie Ruslanc

Department of Mechanical Engineering, Atma Jaya Catholic University of Indonesia, Jakarta 12930, Indonesia

Article Info	Abstract
	Stainless steel is one of the materials with excellent corrosion resistance, so it is widely applied in various fields such as the chemical industry, aerospace, power generation, and biomedicine. The environmental condition (neutral, acidic, salty, or basic) is the most important thing to be considered prior to choosing palpable stainless steel materials. In this study, the corrosion behaviors of stainless-steel type SS 316L under exposure immersions in salty and acidic environments using sodium chloride (NaCl) and sulfuric acid (H₂SO₄) solutions were investigated, by referring to a standard method of ASTM G31-72. Scanning electron microscopy (SEM) results revealed that the specimen in NaCl solution exhibited a darker color, and relatively similar shape of cracks are observed. In contrast, the specimen immersed in H₂SO₄ was observed to have a large diagonal crack. The corrosion rate of SS 316L immersed in NaCl was lower with a value of 0.4260 mpy, compared to that of H₂SO₄ which was 2.5141 mpy. The Vickers hardness test showed that the hardness value of NaCl immersion was higher than that of H₂SO₄, which was 6.34% and 1.94%, respectively. It can be concluded that the SS 316L is better used in a salty environment compared to acidic conditions, because the main function of SS 316L is to be able to withstand rust, one of which is caused by chloride compared to other types of stainless-steel.

1. Introduction

Austenitic stainless steel is a common material that has good corrosion resistance, excellent mechanical strength, low thermal expansion, lower process costs, and good reliability [1]. Most manufacturing industries use this material as the primary material for making their products. Stainless Steel AISI 316L (SS 316L) is one of the austenitic stainless steel materials with excellent corrosion resistance, so it is widely applied in various fields such as the chemical industry, aerospace, power generation, and biomedicine [2]. This material is also recommended as a biomaterial due to its low carbon content, which increases its corrosion resistance to chlorinated environments [3,4]. The passive protective layer on the surface of SS material provides high prevention against uniform corrosion in ordinary oxidizing environments but can induce localized forms of corrosion under special conditions [5–7]. The existence of corrosive substances can lead to local passivation degradation and dangerous pitting [8–10]. The exposure of austenitic stainless steel 316L to the high temperature followed by slow cooling in air, such as, during welding, is corresponding to their vulnerability to another type of localized intergranular corrosion. In addition, low-chromium regions are the preferred pathways for crack propagation under other localized corrosion attacks and tensile stresses [11,12].

This type of stainless steel is used in medical devices such as implants [13]. Moreover, the high corrosion resistance of SS 316L provides by a thin chromium oxide film that has high stability against corrosion [14,15]. However, this SS 316L material still has some shortcomings; for example, when SS 316L is used as one of the materials for shipbuilding. Marine vessels will come into contact with the marine environment, which contains sodium chloride (NaCl) salt. Therefore this material often experiences pitting-type corrosion due to exposure to seawater and through the deposition of salt in the air, which has high humidity and high chloride concentration [16]. SS 316L is also sensitive to chloride (Cl) compounds in the environment, affecting this material's corrosion resistance. The presence of chloride compounds in the environment can corrode SS 316L and affect its service life.

Recently, the relationship between extreme environments and the pitting corrosion tendency of stainless steel materials has been the field of numerous investigations. Based on the available literature, pH, temperature, and types of the environment play a critical role in the corrosion susceptibility of stainless steel materials [17–19]. A combination of pickling and passivation in aqueous solutions of hydrochloric and nitric acids has been found to be the best choice for rust removal [20]. Several studies have reported the role of MnS inclusions in initiating pitting corrosion in sensitized austenitic SS. Another study compared the effect of different mechanical surface treatments on the pitting resistance of sensitized SS 304 in a 3.5 wt% of NaCl solution [18]. Immersion method has been popular to investigate the corrosion and durability property of stainless-steels. Lieth et al investigated effects of heat treatment on different water condition i.e., sea water, fresh water, and crude oil by immersion method. They found that the severe corrosion occurred in the sea water at high temperature [21]. Another study by Ji et al found that the higher the concentration of the mixed solution and the higher the test temperature, the greater the corrosion rate of 316L stainless steel wire and the lower the breaking strength of 316L stainless steel wire [22]. Adnan et al observed that heat treatment affects the corrosion rate. The annealed sample showed the lowest corrosion rate, while the quenched sample seemed to corrode more compared to the other samples [23]. Moreover, Reda and coworkers have reported some important studies regarding the effect of several environmental aspects on the microstructure of stainless-steel materials have been investigated. They found that hydrogen caused the corrosion and alter the microstructure of electroplated steel alloy 4130 by diffusion mechanism [24]. Next, they also found that heating and solution treatment caused a hardening effect that improved the mechanical and microstructure properties of aluminum-zinc alloy 7075 [25]. Similarly, the heating and solution treatment has been employed on aluminum-copper 2024 alloy, which found that the heating and solution treatment increases the mechanical properties of the steel by short-distance diffusion coupled with precipitation mechanisms [26].

Several studies have been carried out to investigate the resistance of stainless steel materials in solution treatments, including the corrosion rate and hardness of SS 304L in a 0.01M NaCl medium [27]. Improvement of corrosion properties of nanostructured SS 304L in 0.6 M NaCl medium and the effect of incorporation of molybdenum Disulfide (MoS_2) in organic coatings on the corrosion resistance of stainless steel in 3.5% NaCl medium[28]. Furthermore, several other studies also discuss the resistance of 316L when immersed in an H_2SO_4 medium, including the corrosion rate of SS 316L in an H_2SO_4 medium containing the amino acid methionine [29] and the corrosion rate of SS 316L in an H_2SO_4 medium with various temperature treatments [30].

According to the literature, it is reported that the environmental condition (neutral, acidic, salty, or basic) is the most important thing to be considered prior to choose the right stainless steel materials [8,20,31,32]. Nevertheless, the comparison study regarding the corrosion properties of stainless steel, specifically SS 316L, under different conditions is

extremely limited; thus, a comprehensive study that provides a comparison of different environmental conditions on the corrosion behavior of stainless steel materials is urgently needed. Therefore, in this study, the corrosion behaviors of SS 316L under exposure immersions in salty and acidic environments using NaCl and H_2SO_4 solutions were investigated. The ultimate goal of this study is to investigate the effects of acidic and salty conditions on the corrosion behavior of SS 316L. The specimen of SS 316L was immersed in NaCl and H_2SO_4 under the same condition, by referring to a standard method of ASTM G31-72. The corrosion behavior was determined using the corrosion rate and mass loss method. Microstructures of SS 316L of before/after exposure immersion experiment were analyzed using scanning electron microscopy (SEM). Meanwhile, the chemical composition of the specimen was analyzed using energy dispersive spectroscopy (EDS). The mechanical properties of SS 316L before/after treatment were assessed using the Vickers hardness test. Finally, the results of this study was expected to provide recommendations for industry in selecting the right condition for a durable and corrosion-resistant use of SS 316L.

2. Materials and Method

2.1. Materials

A standard stainless steel 316L (SS 316L) plate was supplied from Bozhong Metal Groups, China, which fulfilled the standard specification of SS 316L by ASTM A240 and JIS G4304. The standard composition and mechanical properties of SS 316L that was used in this study are summarized in Table 1 and standard mechanical properties of SS 316L are listed in Table 2. Sodium chloride (NaCl, 99%), sodium hydroxide (NaOH, 99%), and sulfuric acid (H_2SO_4, 98%) that were used for the immersion experiment were provided by Merck, Germany. Deionized (DI) water was always used in chemical solution preparation and all experimentation.

Table 1. Standard additive composition in SS 316L [33,34].

Elementals	Composition (wt%)
C (Carbon)	≤ 0.03
Si (Silicon)	≤ 1.00
Mn (Manganese)	≤ 2.00
P (Phosphorous)	≤ 0.045
S (Sulfur)	≤ 0.045
Cr (Chromium)	16.0 – 18.0
Mo (Molybdenum)	2.0
Ni (Nickel)	10.0

Table 2. Standard mechanical properties of SS 316L [35,36].

Mechanical Properties	Unit	Value
Yield strength	MPa	≥ 200
Tensile strength	MPa	≥ 480
Elongation at break	%	≥ 50
Hardness	HV	≤ 180

2.2. Corrosive Medium Immersion Test

The corrosive medium immersion test was conducted by adapting a standardized method of ASTM G31-72 [37]. This method is commonly used in the determination of laboratory corrosion testing for metals. In this experiment, NaCl and H_2SO_4 were used as the immersion medium that simply represented the salty and acid environments, respectively.

Firstly, 100 mL of NaCl and H_2SO_4 solutions with the same molar concentration (0.017 M) were prepared in a different compartment. After that, a rectangular shape of SS 316L was prepared with a dimension of 20 mm x 10 mm x 2 mm and hanged with a inert rope [38,39]. Fig. 1 depicts the schematic representation of corrosive medium immersion test. The initial weight of the plate was weighed using a precision analytical balance (Precisa Series 390, USA) with an accuracy of 4 significant figure. Then, the SS 316L plates were immersed in both solutions and were left for three days. After three days, the SS 316L samples were taken from the solution and washed with DI water to clean the spent solution [37,39]. The cleansed samples were dried in an oven for four hours until they were completely dried. The samples were put into a desiccator before being weighed, which is noted as the final weight after the corrosion test. Finally, the corrosion rate can be simply determined using Eq. 1 [40,41].

$$C_R = \frac{\left(W_i - W_f\right) \times K}{\rho \times A \times t} \tag{1}$$

Where C_R represents the corrosion rate (mils per year/mpy), W_i and W_f are the initial and the final weight (mg) of the sample, respectively. K is a constant in the corrosion rate equation (534), and ρ shows the density of the immersion solution (g/cm^3). A is the total surface area of the sample (cm^2), and t is the time of exposure (h).
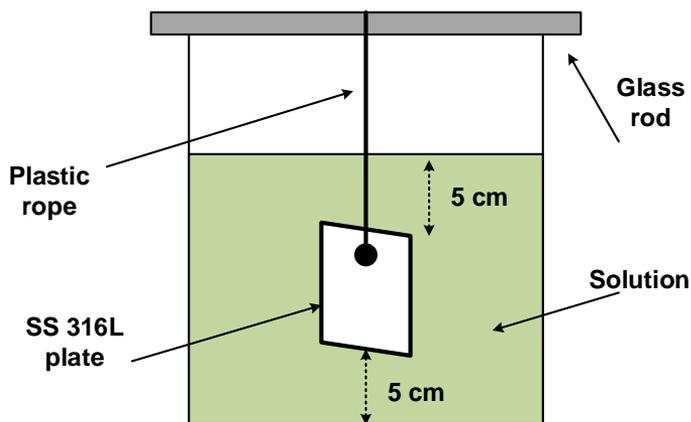

Fig. 1 Schematic illustration of corrosion immersion experiment

2.3. Characterization

Scanning electron microscopy (SEM, Thermo-Fischer Scientific, USA) was performed to capture the surface morphology of the pristine SS 316L and samples after going through the corrosion immersion test. This instrument can provide a surface picture of the samples with some magnifications. To further understand the effects of corrosive medium immersion on the chemical composition of the SS 316L, an energy dispersive spectroscopy (EDS, Thermo-Fischer Scientific, USA) was used. This analysis can show the chemical entities of the samples, which corresponds to the SEM images [42–44]. Therefore, some new insights regarding the effects of corrosive medium immersion using NaCl and H_2SO_4 on the microstructure of SS 316L can be achieved.

2.4. Mechanical Strength Evaluation Using Vickers Hardness Test

Vickers hardness test method was used to evaluate the mechanical strength of the SS 316L before and after corrosion immersion tests. The basic concept of this test is to test the

hardness of the material with a stacker. The shape of this pounder is like a pyramid and is made of square diamonds. The angle produced by Vickers's eye is 136°[45]. To describe the hardness of the sample, Vickers hardness number (VHN) is used, as can be expressed in Eq. 2 [46,47].

$$VHN = \frac{1.854 \times P}{d^2}$$
(2)

Where VHN stands for Vickers hardness number (kg/μm²). P is the applied load (kg), and d is the average diagonal length (μm).

3. Results and Discussion

3.1. Effects of Immersion in NaCl and H₂SO₄ on The Mass Reduction and Corrosion Rate of SS 316L

Effects of different types of corrosive medium, which are salty and acidic conditions, on the SS 316L sample were investigated. Table 3 summarizes the data regarding the mass reduction and corrosion rate of SS 316L after being immersed in NaCl and H₂SO₄ solution. According to Table 3, it can be seen that initially, the SS 316L samples had a mass of 2.9796 g and 2.9938 g before being immersed in NaCl and H₂SO₄ solutions. The samples were left for 72 h to assess the corrosion process of SS 316L in salty and acidic conditions. After 72 h, it can be observed that the final weights of both samples are 2.9795 g for immersion in NaCl and 2.9933 g for H₂SO₄. Hence, the weight difference can be simply computed by subtracting the initial and final weights of the samples. It was found that the SS 316L exhibited 0.0001 g of weight loss due to immersion in the NaCl solution. Moreover, the SS 316L possessed a more dramatic weight loss of 0.0005 g when the sample was immersed in the H₂SO₄ solution. The occurrence of weight loss can be due to the reaction between the dominant metal in the SS 316L, which is iron (Fe), and the corrosive solutions. The greater mass reduction represents the greater loss of Fe that can be extracted from the body of SS 316L [48]. The sample that was immersed in H₂SO₄ exhibited greater mass loss. It is explainable that the corrosion reaction in this condition occurs in two ways, namely, the redox corrosion reaction between iron and oxygen and the direct acid leaching due to a large number of H⁺ ions [49]. The reactions can be written as follows [48,50].

Redox reaction mechanisms;

Oxidation reaction:

$$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^-$$
$E^o = +0.44\ V$
(3)

Reduction reaction:

$$O_{2(aq)} + 2H_2O_{(aq)} + 4e^- \rightarrow 4OH^-_{aq}$$
$E^o = +0.40\ V$
(4)

Overall reaction:

$$2Fe_{(s)} + O_{2(aq)} + 2H_2O_{(aq)} \rightarrow 2Fe^{2+}_{(aq)} + 4OH^-_{(aq)}$$
$E^o = +0.84\ V$
(5)

Acid leaching reaction:

$$Fe_{(s)} + H_2SO_{4(aq)} \rightarrow 2H^+_{(aq)} + FeSO_{4(aq)}$$
(6)
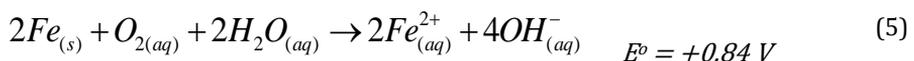
On the other hand, the sample that was immersed in NaCl solution seems to have a lower mass loss compared to that of H_2SO_4. It is clearly due to the corrosion reaction that occurred in the NaCl system being just the redox mechanisms (see Eq. 3-5); thus, the mass loss due to corrosion is found lower. Corroboratively, the measured corrosion rate of the SS 316L in H_2SO_4 is way much faster than that of NaCl, with the exact values of 2.5141 mpy and 0.4260 mpy, respectively. The corrosion rate in H_2SO_4 is 5.9 times higher than that in NaCl. Fortunately, the corrosion rate for SS 316L is still acceptable when it falls in the range of 1 – 5 mpy, and when the corrosion rate is < 1 mpy, it is called exceptional [51,52]. Therefore, these results indicate that SS 316L is better used for equipment in a salty environment compared to the acidic one.

Table 3. The mass reduction and corrosion rate of SS 316L after being immersed in NaCl and H_2SO_4 solutions.

Type of solution	Starting date	Finishing date	Duration (h)	Initial weight W_i (g)	Final weight W_f (g)	Weight difference ΔW (g)	Corrosion rate (mpy)
NaCl	2 September 2022	5 September 2022	72	2.9796	2.9795	0.0001	0.4266
H_2SO_4	2 September 2022	5 September 2022	72	2.9938	2.9933	0.0005	2.5176

3.2. Effects of Immersion in Corrosive Medium on The Surface Micromorphology and Chemical Composition of SS 316L

Fig. 2 shows the SEM images and EDS spectra of pristine SS 316L without immersion treatment. It can be seen that the surface micromorphology of the sample is quite uniform without any sign of corrosion. Meanwhile, The SEM test on the sample of SS 316L that was immersed in NaCl solution obtained a hollow structure in stainless steel as a result of immersion for three days, as can be seen in Fig. 3. After experiencing treatment, the material has defects in the microstructure of the material, which can further affect the service life of the material's properties. This also causes a reduction in the mass of the material because cracks and degradation occurred on the surface. This was also reported in a study, they explained that there were long depressions in the diagonal direction after being immersed in the corrosive solution [53]. Moreover, another finding can be observed in Fig. 2 that when stainless steel material is immersed in NaCl solution, some crystal constituents were formed on the surface of the material. The circle image shown is the form of crystallization that occurs when immersing SS 316L in NaCl solution. The type of corrosion occurred in immersion into NaCl solution is uniform corrosion [54].

Moreover, SEM results also show that the corrosion that occurs on SS 316L when immersed in H_2SO_4 solution possesses worse corrosion, with uniform defects observed on the surface of SS 316L as can be seen in Fig. 4. Corrosion occurs almost all over the surface of the specimen, and there are the same depressions and cracks, indicating that the type of corrosion that occurs is a type of uniform corrosion [55–57]. Almost the entire top surface of stainless steel formed new crystals and black spots. However, what distinguishes between the immersion of the two solutions is the erosion of the material when immersed in H_2SO_4 so that in general the hardness value of the specimen immersed in H_2SO_4 is much lower than the specimen immersed in NaCl solution. Then, based on the results of EDS on the test specimens showed that the percentage value of the Fe element was higher in SS 316L specimens immersed in H_2SO_4 solution than in SS 316L specimens immersed in NaCl. specimen immersed in H_2SO_4 is much lower than the specimen immersed in NaCl solution [37]
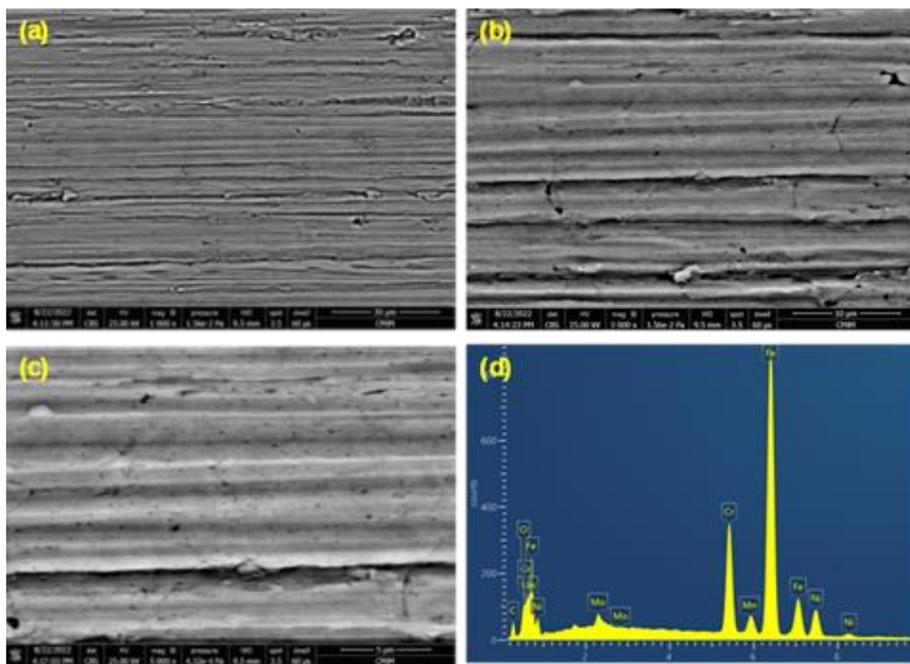
Fig. 2 SEM images of the pristine SS 316L under magnifications of (a) 1000x, (b) 3000x, and (c) 5000x. (d) EDS spectra of pristine SS 316L

The chemical composition of pristine SS 316L and the immersed SS 316L samples in NaCl and H_2SO_4 was analyzed using EDS. Table 4 summarizes the elemental composition of the samples. It is found that the pristine SS 316L consists of 68.1, 16.5, 10.3, 2.9, 1.2, and 1.0% of Fe, Cr, Ni, O, S, and Mn, respectively, which is in similar manner with previous studies [33,34]. While for the sample that immersed in NaCl exhibited compositions of 66.9, 16.4, 10.3, 4.1, 1.2, and 1.1 wt% for Fe, Cr, Ni, O, S, and Mn, respectively. While the sample immersed in H_2SO_4 solution exhibited compositions of 65.7, 15.6, 9.2, 6.5, 1.7, and 1.3 wt%, for Fe, Cr, Ni, O, S, and Mn, respectively. Based on the results, it is found that the immersion process reduced the Fe content and increased the oxygen content. This process followed the corrosion reaction mechanisms as discussed perviously. It is also clearly observed that H_2SO_4 caused worse corrosion on the main metals that constructed the SS 316L, such as Fe, Cr, and Ni, compared to that of in NaCl solution. It can be due to a strong electrochemical reaction between H_2SO_4 and the metals [58,59], as previously discussed in section 3.1. It is also evident by the SEM images that a sample of SS 316L in H_2SO_4 exhibited more defects in its microstructure compared to that of NaCl. The reduction content of constituent metals can alter the mechanical strength of the SS 316L sample [60]. Therefore, it can be concluded that H_2SO_4 caused more serious corrosion activity on SS 316L compared to NaCl.
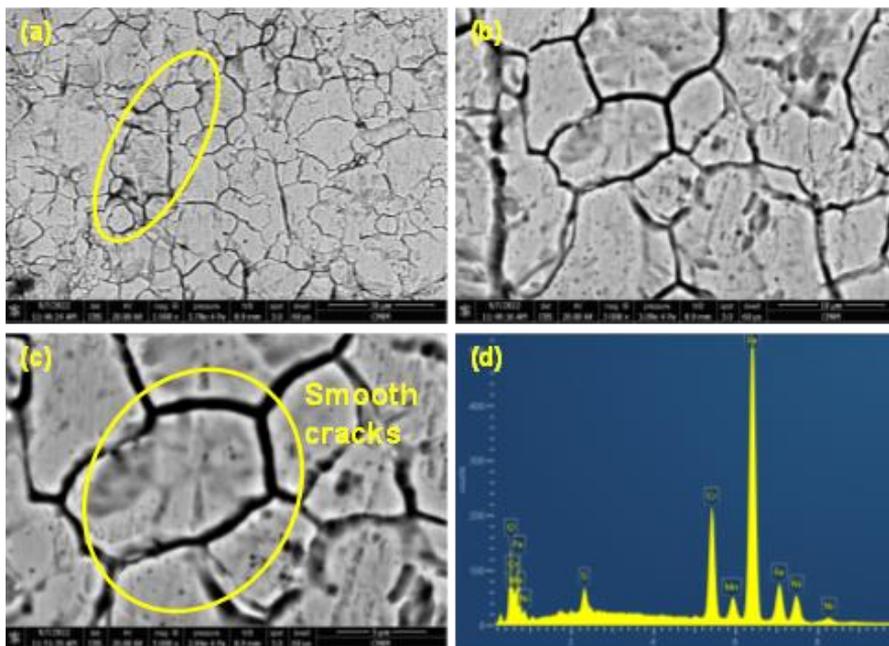
Fig. 3 SEM images of SS 316L sample after immersed in NaCl solution under magnifications of (a) 1000x, (b) 3000x, and (c) 5000x. EDS spectra of SS 316L sample after immersed in NaCl solution
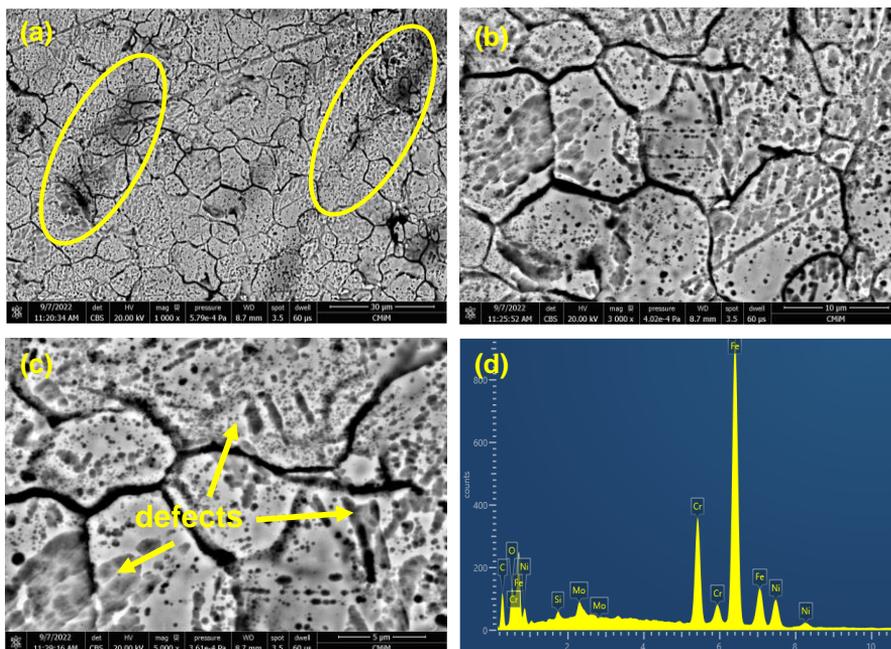

Fig. 4 SEM images of SS 316L sample after immersed in H_2SO_4 solution under magnifications of (a) 1000x, (b) 3000x, and (c) 5000x. EDS spectra of SS 316L sample after immersed in H_2SO_4 solution.

Table 4. Chemical compositions of the SS 316L samples after being immersed in NaCl and H_2SO_4 solutions.

Elementals	Composition (wt%)		
	Pristine SS 316L	SS 316L (NaCl)	SS 316L (H_2SO_4)
Iron (Fe)	68.1	66.9	65.7
Chromium (Cr)	16.5	16.4	15.6
Nickel (Ni)	10.3	10.3	9.2
Oxygen (O)	2.9	4.1	6.5
Sulfur (S)	1.2	1.2	1.7
Manganese (Mn)	1.0	1.1	1.3

3.3. Effects of Immersion in Corrosive Medium on The Hardness Level of SS 316L

Effects of immersion in NaCl and H_2SO_4 solutions on the mechanical strength of SS 316L were assessed through the Vickers hardness test. Fig. 5 shows the results of Vickers hardness numbers (VHN) for three samples, namely pristine SS 316L, SS 316L (H2SO4), and SS 316L (NaCl). It can be seen that the pristine SS 316L exhibited a VHN of 159.3 ± 1.32 kg/μm^2. The immersed products showed VHN numbers of 169.4 ± 0.52 kg/μm^2 for SS 316L (NaCl) and 162.4 ± 0.47 kg/μm^2 for SS 316L (H_2SO_4). It is found that the immersed samples have higher VHN values compared to the pristine SS 316L. It is explainable by the formation of a brittle surface of SS 316L due to the corrosion reactions on the surface. This corroded surface attributes more brittle property due to the oxidation, thus, the immersed samples attributed higher VHN values [61,62]. The HV value increased by 6.34% for materials soaked in NaCl solution, and the value obtained from materials soaked in H_2SO_4 solution increased by 1.94%. Moreover, the SS 316L sample from the NaCl solution has a slightly higher VHN than that of H_2SO_4.
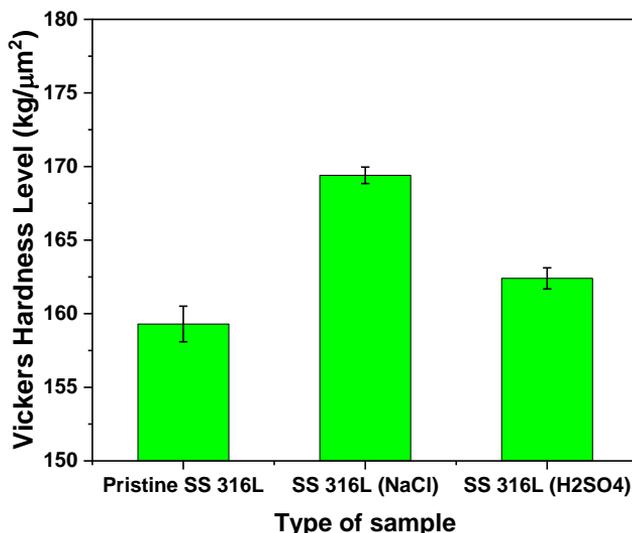

Fig. 5 Results of the hardness of the tested SS 316L samples.

The defect-free corrosion surface can be attributed to enhancing the mechanical strength of the SS 316L sample in NaCl. The generated crystals on the surface of SS 316L can also provide higher mechanical strength [59,63]. The hardness value of SS 316L increased by 6.34% for those immersed in NaCl solution. Therefore, SS 316L itself is widely used for the manufacture of equipment that is in direct contact with salt solutions because the main function of SS 316L is to be able to withstand rust, one of which is caused by chloride [64].

3.4. Effect of pH Variations

Effect of pH variations on the corrosion rate and hardness of the immersed SS 316L was investigated and the results are depicted on Fig. 6. Based on Fig. 6 it can be seen that the corrosion rate of SS 316L decreased significantly with a rise of pH. pH of solution was controlled using NaOH and H_2SO_4. Sample of SS 316L at lowest pH of 1 experienced the highest corrosion rate of 2.5563 mpy, while at pH of 7 and above the corrosion rate remained constant at 0.5317 mpy. pH is a measure of the acidity or basicity of a solution and plays a crucial role in the corrosion of stainless steel. The corrosion of stainless steel is an electrochemical process that involves the transfer of electrons between the metal and its environment. At low pH levels, the concentration of hydrogen ions (H^+) in the solution increases, leading to an increase in the corrosion rate of stainless steel [65]. Conversely, at higher pH levels, the concentration of H+ ions decrease, resulting in a decrease in the corrosion rate [66]. Therefore, pH variations can have a significant impact on the corrosion rate of stainless steel [1]. Similar results have been found that corrosion rate of stainless steels is affected by pH variations. For instance, a study by Samosir in 2017 demonstrated that the corrosion rate of stainless steel increased with a decrease in pH below 4 [67]. On the other hand, maintaining a neutral or higher pH can help reduce the corrosion rate of stainless steel [68]. Therefore, it is crucial to maintain optimal pH levels to minimize the corrosion rate of stainless steel and prolong its lifespan.

Fig. 6 also depicts the effect of pH variations on the hardness of SS 316L samples. It can be seen that the hardness of SS 316L decreased in a pH lower than 7 and higher than 7. The highest hardness value was found at neutral condition (pH=7) and the lowest hardness value was at acidic condition (pH=1). Hardness is an important characteristic of stainless steel, as it determines the material's resistance to wear and deformation. In a study conducted by Saefuloh et al. in 2020, the hardness of stainless steel 304 was measured in corrosive media, including sea water and 3.5% NaCl [65]. The results showed that the hardness of stainless steel decreased as the corrosion rate increased, indicating a negative correlation between hardness and corrosion rate. Additionally, maintaining a high level of hardness in stainless steel is crucial to ensure its durability and longevity in various applications. The pH level of the environment in which stainless steel is used can have a significant impact on its hardness. Research by Garcia-Cabezon et al. in 2022 found that precipitation hardening stainless steel (PH SS) manufactured by selective laser melting had varying levels of hardness depending on the pH level of the environment [69]. Similarly, Saefuloh's research in 2020 showed that the corrosion rate of stainless-steel duplex was affected by the pH level of the environment, but had no significant effect on the level of hardness [65]. However, research by Zai et al. in 2020 found that the high strength and hardness induced by precipitation hardening in PH stainless steels limits their workability [70]. Hence, it is important to balance pH control and hardness in stainless steel applications to ensure optimal performance. The hardness of stainless steel is a critical factor in its performance, and can be influenced by variations in pH levels. While maintaining a high level of hardness is important, it is also crucial to consider the effects of pH control on the material's corrosion resistance and workability. Further research is needed to fully understand the relationship between pH variations and the hardness of stainless steel, and to develop effective strategies for balancing these factors in various applications.
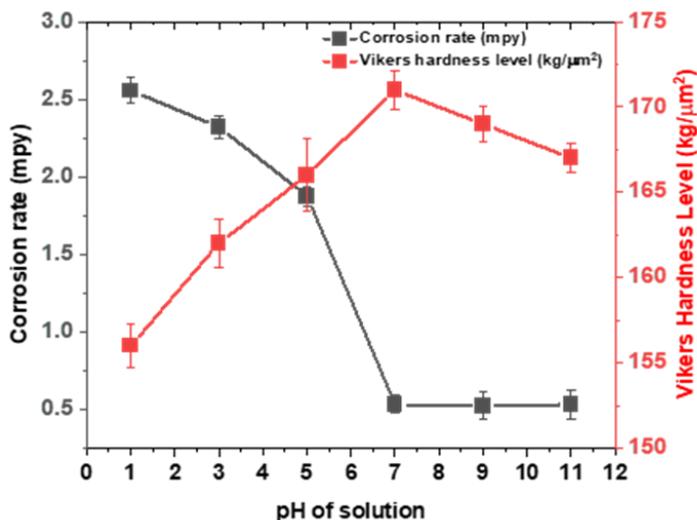
Fig. 6 Effect of pH of solutions on the corrosion rate and hardness of SS 316L

4. Conclusion

In this study, the corrosion behaviors of stainless-steel type SS 316L under exposure immersions in salty and acidic environments using sodium chloride (NaCl) and sulfuric acid (H_2SO_4) solutions were investigated, by referring to a standard method of ASTM G31-72. Scanning electron microscopy (SEM) results revealed that the specimen in NaCl solution exhibited a darker color, and relatively similar shape of cracks are observed. In contrast, the specimen immersed in H_2SO_4 was observed to have a large diagonal crack. It was found that the corrosion resistance of SS 316L immersed in NaCl solution is better because the corrosion rate value is < 1 mpy, which was 0.4260 mpy. This value is in the "excellent" category compared to the corrosion rate value of SS 316L immersed in H_2SO_4 solution, which was 2.5141 mpy in the "excellent" category. This indicates that SS 316L is better placed in a salty environment than in acidic conditions. In the Vickers test, it was found that the value of each material increased not too significantly. The HV value increased by 6.34% for materials soaked in NaCl solution, and the value obtained from materials soaked in H_2SO_4 solution increased by 1.94%. Moreover, the SS 316L sample from the NaCl solution has a slightly higher VHN than that of H_2SO_4. The defect-free corrosion surface can be attributed to enhancing the mechanical strength of the SS 316L sample in NaCl. The generated crystals on the surface of SS 316L can also provide higher mechanical strength. These results indicate that NaCl adds strength to the surface structure of the material compared to the H_2SO_4 solution. Therefore, SS 316L itself is widely used for the manufacture of equipment that is in direct contact with salt solutions because the main function of SS 316L is to be able to withstand rust, one of which is caused by chloride. Finally, it can be concluded that SS 316L used in the marine industry will perform better in terms of resistance and hardness compared to the other industries that often intersect with acidic solutions. It is crucial to maintain optimal pH levels to minimize the corrosion rate of stainless steel and prolong its lifespan. Further research is needed to fully understand the relationship between pH variations and the hardness of stainless steel, and to develop effective strategies for balancing these factors in various applications.

Acknowledgment

References

[1] Yasir M, Danish M, Mia M, Gupta MK, Sarikaya M. Investigation into the surface quality and stress corrosion cracking resistance of AISI 316L stainless steel via precision end-milling operation. The International Journal of Advanced Manufacturing Technology. 2021 Jan 9;112(3-4):1065-76. https://doi.org/10.1007/s00170-020-06413-4

[2] Bordji G, Jouzeau JY, Mainard D, Payan E, Delagoutte+ JP, Netter P. Evaluation of the effect of three surface treatments on the biocompatibility of 316L stainless steel using human differentiated cells. Vol. 17, Biomaterials. 1996. https://doi.org/10.1016/0142-9612(96)82723-2

[3] Yeganeh M, Rezvani MH, Laribaghal SM. Electrochemical behavior of additively manufactured 316L stainless steel in H2SO4 solution containing methionine as an amino acid. Colloids Surf A Physicochem Eng Asp. 2021 Oct 20;627. https://doi.org/10.1016/j.colsurfa.2021.127120

[4] Kusworo TD, Kumoro AC, Aryanti N, Kurniawan TA, Dalanta F, Alias NH. Photocatalytic polysulfone membrane incorporated by ZnO-MnO2@SiO2 composite under UV light irradiation for the reliable treatment of natural rubber-laden wastewater. Chemical Engineering Journal. 2023 Jan;451:138593. https://doi.org/10.1016/j.cej.2022.138593

[5] Lacerda JC de, Freitas LL de, Brito RF, Moura Filho F, Teixeira RLP. Comparative Study Between Sensitization Degree of the 0.4% Mo Austenitic Stainless Steel and UNS S31803 Duplex Stainless Steel. Materials Research. 2021;24(1). https://doi.org/10.1590/1980-5373-mr-2020-0408

[6] Baser E, Incesu A, Sismanoglu S, Gungor A. Wear performance investigation of AlSi8Cu3Fe aluminum alloy related to aging parameters. Research on Engineering Structures and Materials. 2018; https://doi.org/10.17515/resm2018.64is0829

[7] Balcıoğlu HE. An investigation on the mechanical strength, impact resistance and hardness of SiC filled natural jute fiber reinforced composites. Research on Engineering Structures and Materials. 2019; https://doi.org/10.17515/resm2019.131me0529

[8] Liu G, Liu Y, Cheng Y, Li J, Jiang Y. The Intergranular Corrosion Susceptibility of Metastable Austenitic Cr-Mn-Ni-N-Cu High-Strength Stainless Steel under Various Heat Treatments. Materials. 2019 Apr 29;12(9):1385. https://doi.org/10.3390/ma12091385

[9] Koç E, Makhlof FMS. Corrosion behavior of heat treated Mg-xZn (x=0.5 - 3) alloys. Research on Engineering Structures and Materials. 2018; https://doi.org/10.17515/resm2018.69is1007

[10] Dalanta F, Kusworo TD, Aryanti N, Othman NH. Optimization of AC/TiO2/CeO2 composite formulation for petroleum refinery wastewater treatment via simultaneous adsorption-photocatalytic process using D-optimal mixture experimental design. J Environ Chem Eng [Internet]. 2021 Dec 1 [cited 2021 Oct 24];9(6):106517. https://doi.org/10.1016/j.jece.2021.106517

[11] Zhou W, Ma W, Li Y, Sun Y. Effect of Sensitizing Treatment on the Microstructure and Susceptibility to Intergranular Corrosion of High-Nitrogen Austenitic Stainless Steel. Metallography, Microstructure, and Analysis. 2021 Feb 6;10(1):25-35. https://doi.org/10.1007/s13632-020-00708-4

[12] Bansod A v., Patil AP, Moon AP, Khobragade NN. Intergranular Corrosion Behavior of Low-Nickel and 304 Austenitic Stainless Steels. J Mater Eng Perform. 2016 Sep 25;25(9):3615-26. https://doi.org/10.1007/s11665-016-2221-2

[13] Stewart S, Bryant SJ, Ahn J, Hankenson KD. Bone Regeneration. In: Translational Regenerative Medicine. Elsevier; 2015. p. 313-33. https://doi.org/10.1016/B978-0-12-410396-2.00024-4

[14] Ayu Arwati IG, Majlan EH, Wan Daud WR, Shyuan LK, Binti Arifin K, Husaini T, et al. Temperature Effects on Stainless Steel 316L Corrosion in the Environment of Sulphuric Acid (H2SO4). In: IOP Conference Series: Materials Science and Engineering. Institute of Physics Publishing; 2018. https://doi.org/10.1088/1757-899X/343/1/012016

[15] Rusnak CR, Menzemer CC. Fatigue behavior of flush reinforced welded hand-holes in aluminum light poles. Research on Engineering Structures and Materials. 2021; https://doi.org/10.17515/resm2021.248st0122tn

[16] Wang H, Wu Y, Sun X, Ling J, Zou D. Corrosion Resistance to Chloride of a Novel Stainless Steel: The Threshold Chloride Value and Effect of Surface State. Materials. 2019 Jul 11;12(14):2235. https://doi.org/10.3390/ma12142235

[17] Cheng CQ, Klinkenberg LI, Ise Y, Zhao J, Tada E, Nishikata A. Pitting corrosion of sensitised type 304 stainless steel under wet-dry cycling condition. Corros Sci. 2017 Apr;118:217-26. https://doi.org/10.1016/j.corsci.2017.02.010

[18] Ezuber H, Alshater A, Nisar SO, Gonsalvez A, Aslam S. Effect of Surface Finish on the Pitting Corrosion Behavior of Sensitized AISI 304 Austenitic Stainless Steel Alloys in 3.5% NaCl Solutions. Surface Engineering and Applied Electrochemistry. 2018 Jan 3;54(1):73-80. https://doi.org/10.3103/S1068375518010039

[19] Tokuda S, Muto I, Sugawara Y, Hara N. Effect of Sensitization on Pitting Corrosion at MnS and CrS in Type 304 Stainless Steel. J Electrochem Soc. 2021 Sep 1;168(9):091504. https://doi.org/10.1149/1945-7111/ac28c6

[20] Liptáková T, Bolzoni F, Trško L. Specification of surface parameters effects on corrosion behavior of the AISI 316Ti in dependence on experimental methods. J Adhes Sci Technol. 2016 Nov 1;30(21):2329-44. https://doi.org/10.1080/01694243.2016.1182824

[21] Lieth HM, Al-Sabur R, Jassim RJ, Alsahlani A. Enhancement of corrosion resistance and mechanical properties of API 5L X60 steel by heat treatments in different environments. Journal of Engineering Research. 2021 Nov 4; https://doi.org/10.36909/jer.14591

[22] Ji JB, Tong J. Corrosion Rate and Mechanical Properties of 316L Stainless Steel Wires in Different Corrosive Conditions. Applied Mechanics and Materials. 2013 Dec;441:48-52. https://doi.org/10.4028/www.scientific.net/AMM.441.48

[23] Adham Adnan M, Kee KE, Raja PB, Ismail MC, Kakooei S. Influence of Heat Treatment on the Corrosion of Carbon Steel in Environment Containing Carbon Dioxide and Acetic Acid. IOP Conf Ser Mater Sci Eng. 2018 May;370:012039. https://doi.org/10.1088/1757-899X/370/1/012039

[24] Reda Y, El-Shamy AM, Eessaa AK. Effect of hydrogen embrittlement on the microstructures of electroplated steel alloy 4130. Ain Shams Engineering Journal. 2018 Dec;9(4):2973-82. https://doi.org/10.1016/j.asej.2018.08.004

[25] Reda Y, Yehia HM, El-Shamy AM. Microstructural and mechanical properties of Al-Zn alloy 7075 during RRA and triple aging. Egyptian Journal of Petroleum. 2022 Mar;31(1):9-13. https://doi.org/10.1016/j.ejpe.2021.12.001

[26] Reda Y, Yehia HM, El-Shamy AM. Triple aging of the RRA Al -Cu 2024 alloy and its impact on the mechanical and microstructure properties. Egyptian Journal of Petroleum. 2022 Sep;31(3):89-94. https://doi.org/10.1016/j.ejpe.2022.08.003

[27] Mastouri W, Pichon L, Martemianov S, Paillat T, Thomas A. Effect of immersion time at the stainless steel 304L/NaCl (0.01 M) interface. Journal of Electrochemical Science and Engineering. 2019 Feb 28;9(2):99-111. https://doi.org/10.5599/jese.639

[28] Olugbade T, Lu J. Enhanced corrosion properties of nanostructured 316 stainless steel in 0.6 M NaCl solution. J Bio Tribocorros. 2019 Jun 1;5(2). https://doi.org/10.1007/s40735-019-0235-7

[29] Sung Hong M, Park Y, Gu Kim J, Kim K. Effect of Incorporating MoS2 in Organic Coatings on the Corrosion Resistance of 316L Stainless Steel in a 3.5% NaCl Solution. https://doi.org/10.3390/coatings9010045

[30] Fossati A, Borgioli F, Galvanetto E, Bacci T. Corrosion resistance properties of glow-discharge nitrided AISI 316L austenitic stainless steel in NaCl solutions. Corrosion Science - CORROS SCI. 2006 Jun 1;48:1513-27. https://doi.org/10.1016/j.corsci.2005.06.006

[31] Lv J, Luo H. The Effect of Low Temperature Sensitization on Corrosion Resistance of Ultrafine-Grained Type 321 Stainless Steels. J Mater Eng Perform. 2014 Jan 14;23(1):262-7. https://doi.org/10.1007/s11665-013-0818-2

[32] Zhang C, Wei Y, Yang J, Emori W, Li J. Effects of nitric acid passivation on the corrosion behavior of ZG06Cr13Ni4Mo stainless steel in simulated marine atmosphere. Materials and Corrosion. 2020 Sep 29;71(9):1576-90. https://doi.org/10.1002/maco.202011597

[33] Attarzadeh N, Molaei M, Babaei K, Fattah-alhosseini A. New Promising Ceramic Coatings for Corrosion and Wear Protection of Steels: A Review. Surfaces and Interfaces. 2021 Apr;23:100997. https://doi.org/10.1016/j.surfin.2021.100997

[34] Kong D, Dong C, Wei S, Ni X, Zhang L, Li R, et al. About metastable cellular structure in additively manufactured austenitic stainless steels. Addit Manuf. 2021 Feb;38:101804. https://doi.org/10.1016/j.addma.2020.101804

[35] Zaffora A, di Franco F, Santamaria M. Corrosion of stainless steel in food and pharmaceutical industry. Curr Opin Electrochem. 2021 Oct;29:100760. https://doi.org/10.1016/j.coelec.2021.100760

[36] Eshkabilov S, Ara I, Sevostianov I, Azarmi F, Tangpong X. Mechanical and thermal properties of stainless steel parts, manufactured by various technologies, in relation to their microstructure. Int J Eng Sci. 2021 Feb;159:103398. https://doi.org/10.1016/j.ijengsci.2020.103398

[37] Beeharry P, Surnam BYR. Atmospheric Corrosion of Welded Mild Steel. Mater Today Proc. 2018;5(2):7476-85. https://doi.org/10.1016/j.matpr.2017.11.419

[38] Lieth HM, Al-Sabur R, Jassim RJ, Alsahlani A. Enhancement of corrosion resistance and mechanical properties of API 5L X60 steel by heat treatments in different environments. Journal of Engineering Research. 2021 Nov 4; https://doi.org/10.36909/jer.14591

[39] Alaskari, Liptakova T, Fajnor P, Halamova M. Mechanical surface treatments effects on corrosion of AISI 316 Ti stainless steel in chloride environments. Journal of Engineering Research. 2014 Sep 7;2(3):20. https://doi.org/10.7603/s40632-014-0020-1

[40] Orlikowski J, Szociński M, Żakowski K, Igliński P, Domańska K, Darowicki K. Actual field corrosion rate of offshore structures in the Baltic Sea along depth profile from water surface to sea bed. Ocean Engineering. 2022 Dec;265:112545. https://doi.org/10.1016/j.oceaneng.2022.112545

[41] Wang Z, Zhao Y, Liu M, Shen H, Fang Q, Yao J. Investigation of the effects of small flow rate and particle impact on high temperature CO2 corrosion of N80 steel. Corros Sci. 2022 Dec;209:110735. https://doi.org/10.1016/j.corsci.2022.110735

[42] Putignano A, Tosco V, Monterubbianesi R, Vitiello F, Gatto ML, Furlani M, et al. Comparison of three different bulk-filling techniques for restoring class II cavities: μCT, SEM-EDS combined analyses for margins and internal fit assessments. J Mech Behav Biomed Mater. 2021 Dec;124:104812. https://doi.org/10.1016/j.jmbbm.2021.104812

[43] Sargam Y, Wang K. Quantifying dispersion of nanosilica in hardened cement matrix using a novel SEM-EDS and image analysis-based methodology. Cem Concr Res. 2021 Sep;147:106524. https://doi.org/10.1016/j.cemconres.2021.106524

[44] Greer MC, MacDonald BL, Stalla D. Cobalt, lead, and borax: Preliminary LA-ICP-MS and SEM-EDS analysis of Late-18th- to Mid-19th-century British refined earthenware glazes. J Archaeol Sci Rep. 2021 Jun;37:103013. https://doi.org/10.1016/j.jasrep.2021.103013

[45] Donmez MB, Olcay EO, Demirel M. Influence of coloring liquid immersion on flexural strength, Vickers hardness, and color of zirconia. J Prosthet Dent. 2021 Oct;126(4):589.e1-589.e6. https://doi.org/10.1016/j.prosdent.2020.11.020

[46] Hu X, Li J, Wang Z, Wang J. A microstructure-informatic strategy for Vickers hardness forecast of austenitic steels from experimental data. Mater Des. 2021 Mar;201:109497. https://doi.org/10.1016/j.matdes.2021.109497

[47] Chu H, Wang T, Han L, Cao L, Guo MZ, Liang Y, et al. Vickers hardness distribution and prediction model of cement pastes corroded by sulfate under the coexistence of electric field and chloride. Constr Build Mater. 2021 Nov;309:125119. https://doi.org/10.1016/j.conbuildmat.2021.125119

[48] Tang C, Wang X, Zhang Y, Liu N, Hu X. Corrosion behaviors and kinetics of nanoscale zero-valent iron in water: A review. Journal of Environmental Sciences. 2022 Dec;

[49] Fan X, Guan X, Ma J, Ai H. Kinetics and corrosion products of aqueous nitrate reduction by iron powder without reaction conditions control. Journal of Environmental Sciences. 2009 Jan;21(8):1028-35. https://doi.org/10.1016/S1001-0742(08)62378-5

[50] CHEN J, ZHANG Q. Effect of electrochemical state on corrosion-wear behaviors of TC4 alloy in artificial seawater. Transactions of Nonferrous Metals Society of China. 2016 Apr;26(4):1011-8. https://doi.org/10.1016/S1003-6326(16)64164-X

[51] Chmelko, Šulko M, Garan M, Zvirko O, de Jesus AMP. Influence of additional factors on the integrity of pipelines with small corrosion defects. Procedia Structural Integrity. 2022;42:315-20. https://doi.org/10.1016/j.prostr.2022.12.223

[52] Costa EM, Dedavid BA, Santos CA, Lopes NF, Fraccaro C, Pagartanidis T, et al. Crevice corrosion on stainless steels in oil and gas industry: A review of techniques for evaluation, critical environmental factors and dissolved oxygen. Eng Fail Anal. 2023 Feb;144:106955. https://doi.org/10.1016/j.engfailanal.2022.106955

[53] Wu X, Liu Y, Sun Y, Dai N, Li J, Jiang Y. A discussion on evaluation criteria for crevice corrosion of various stainless steels. J Mater Sci Technol. 2021 Feb;64:29-37. https://doi.org/10.1016/j.jmst.2020.04.017

[54] Li X, Gong J. Effects of steel liner corrosion on the leak-tightness of prestressed concrete containment structure under severe accident loads. Ann Nucl Energy. 2023 Jan;180:109487. https://doi.org/10.1016/j.anucene.2022.109487

[55] Xiao Z, Liu J, Jiang Z, Luo L, Huang Q. Corrosion behavior and mechanism of CLAM and 316L steels in flowing Pb-17Li alloy under magnetic field. Nuclear Engineering and Technology. 2022 Jun;54(6):1962-71. https://doi.org/10.1016/j.net.2021.12.020

[56] Wongpanya P, Wongpinij T, Photongkam P, Siritapetawee J. Improvement in corrosion resistance of 316L stainless steel in simulated body fluid mixed with antiplatelet drugs by coating with Ti-doped DLC films for application in biomaterials. Corros Sci. 2022 Nov;208:110611. https://doi.org/10.1016/j.corsci.2022.110611

[57] Li H, Liu W, Chen L, Fan P, Dong B, Ma Z, et al. Corrosion crack failure analysis of 316L hydraulic control pipeline in high temperature aerobic steam environment of heavy oil thermal recovery well. Eng Fail Anal. 2022 Aug;138:106297. https://doi.org/10.1016/j.engfailanal.2022.106297

[58] Dong Y, Li J, Xu D, Song G, Liu D, Wang H, et al. Investigation of microbial corrosion inhibition of Cu-bearing 316L stainless steel in the presence of acid producing bacterium Acidithiobacillus caldus SM-1. J Mater Sci Technol. 2021 Feb;64:176-86. https://doi.org/10.1016/j.jmst.2020.05.070

[59] Zhao R, Xu W, Yu Q, Niu L. Synergistic effect of SAMs of S-containing amino acids and surfactant on corrosion inhibition of 316L stainless steel in 0.5 M NaCl solution. J Mol Liq. 2020 Nov;318:114322. https://doi.org/10.1016/j.molliq.2020.114322

[60] Lodhi MJK, Deen KM, Haider W. Corrosion behavior of additively manufactured 316L stainless steel in acidic media. Materialia (Oxf). 2018 Oct;2:111-21. https://doi.org/10.1016/j.mtla.2018.06.015

[61] Li Z, Chai L, Tang Y, Zhang C, Qi L, Zhang K, et al. 316L stainless steel repaired layers by weld surfacing and laser cladding on a 27SiMn steel: A comparative study of microstructures, corrosion, hardness and wear performances. Journal of Materials Research and Technology. 2023 Jan; https://doi.org/10.1016/j.jmrt.2023.01.162

[62] Guo H, Wei H, Li G, Sun F. Experimental research on fatigue performance of butt welds of corroded Q690 high strength steel. J Constr Steel Res. 2021 Sep;184:106801. https://doi.org/10.1016/j.jcsr.2021.106801

[63] Ruiz-Menéndez G, Andrade C, Carro-Sevillano G, Peña C, Adeva P, Medina J, et al. Identification of the failure mode of corroding steel rebars in a viaduct in service through hardness measurements. Results in Engineering. 2022 Mar;13:100331. https://doi.org/10.1016/j.rineng.2022.100331

[64] Pathote D, Jaiswal D, Singh V, Behera CK. Electrochemical corrosion behavior of tantalum coated 316L stainless steel by D.C. Magnetron sputtering for orthopedic applications. Applied Surface Science Advances. 2023 Feb;13:100365. https://doi.org/10.1016/j.apsadv.2022.100365