

Corrosion-induced mechanical properties deterioration in 304L and 316L stainless steels under simulated physiological conditions: A comparative study

Muslim Ali^{1*} , Nibras Kamil Falyyih Al-Asadi², Jabbar H. Mohammed³

¹ Prosthetics and Orthotics Engineering Department, College of Engineering, University of Kerbala, Iraq

² College of Eng., University of Kerbala, Iraq

³ Materials Engineering Department, University of Technology-Iraq, Baghdad, Iraq

* Corresponding author's e-mail: muslim.m@uokerbala.edu.iq

ABSTRACT

This study conducts a detailed investigation into the impact of chemical corrosion on the mechanical properties of austenitic stainless steels 304L and 316L, widely utilized in medical devices. The materials were immersed in phosphate-buffered saline (PBS) for a duration of five months to replicate physiological conditions. Corrosion progression was assessed through mass loss measurements, while mechanical deterioration was analyzed via tensile testing carried out before and after exposure. Statistical methods were employed to ensure the validity of the findings. The results revealed that 316L stainless steel exhibited greater corrosion resistance and better preservation of mechanical integrity compared to 304L. The reduction in mechanical properties after corrosion exposure was lower for 316L stainless steel compared to 304L stainless steel, amounting to 7.1% in yield strength and 4.8% in tensile strength, whereas for 304L stainless steel the corresponding reductions were 10.8% and 8.8%, respectively. Drawing upon the obtained results, this study offers evidence-based recommendations for the selection of implant materials that exhibit superior long-term performance and structural stability under simulated physiological conditions.

Keywords: 316L, 304L, stainless steel, phosphate-buffered saline solution, corrosion behavior, mechanical properties.

INTRODUCTION

The long-term functionality and clinical reliability of biomedical implants are critically dependent on the selection of materials that can resist corrosion and retain mechanical integrity within physiological environments. Among metallic biomaterials, austenitic stainless steels – particularly grades 304L and 316L – are widely employed in orthopedic, dental, and surgical applications due to their favorable combination of biocompatibility, mechanical robustness, and cost-effectiveness [1, 2]. Although these alloys share similar metallurgical characteristics, their in-vitro performance in simulated body fluids varies markedly, primarily as a result of their compositional distinctions. Notably, the higher concentrations of nickel and

molybdenum in 316L significantly improve its resistance to localized corrosion mechanisms, including pitting and crevice corrosion [3]. Zhang et al. [4] showed that 316L possesses superior electrochemical stability in static liquid lithium and PBS, while Gudić et al. [5] reported enhanced repassivation and lower corrosion susceptibility in 316L compared to 304L using potentiodynamic and impedance techniques at physiological temperature.

The deterioration of metallic implants under physiological conditions is governed by a combination of electrochemical interactions and mechanical degradation. Corrosion-related processes – such as surface roughness development, breakdown of passive films, and subsurface microstructural damage – can significantly compromise the mechanical behavior of biomedical

devices. The importance of corrosion-resistant materials in clinical use has been emphasized by Geetha et al. [1] and Williams [2], while Pourbaix [6] and Lodhi et al. [7] provided fundamental insights into electrochemical corrosion mechanisms affecting metals in biological environments.

Although the literature reflects an increasing interest in this area, there remains a lack of comprehensive studies that correlate extended corrosion exposure with changes in mechanical performance. For example, Mohd Talha et al. [8] reported tensile strength reduction in 304 stainless steel following PBS exposure, yet their immersion period was relatively short and lacked microstructural validation. Pathote et al. [9] evaluated the electrochemical characteristics of 316L in simulated fluids without addressing subsequent mechanical degradation. This highlights the need for integrated studies that assess both corrosion behavior and structural integrity over time.

Recent advancements have focused on improving corrosion resistance through surface engineering techniques. Borgioli [10] reviewed the effectiveness of low-temperature nitriding in enhancing pitting resistance of austenitic stainless steels in chloride-rich environments. Similarly, Alontseva et al. [11] demonstrated that in-situ coatings of Ti and Ti6Al4V on 316L improved tribocorrosion resistance and electrochemical stability in body fluid simulants. Ali et al. [12] reported that ethyl silicate coatings not only enhanced the corrosion resistance of low-carbon steel but also effectively maintained its tensile strength, demonstrating the dual benefit of surface protection and mechanical preservation. Walczak et al. [13, 14] demonstrated the effect of shot peening surface treatment on improving surface condition and modifying corrosion response of 316L steel and X5CrNi18-10 Steel, underscoring the importance of surface condition when evaluating the performance of biomedical alloys. Mohammed et al. [15] also pointed out that structural flaws, such as cracks, can severely compromise the mechanical stability of metallic parts – an influence that has a close parallel with the degradation experienced by biomedical alloys when exposed to corrosive media. Furthermore, Zainulabdeen et al. [16] showed that repeated exposure to fluctuating environmental conditions adversely affects the fatigue life of dual-phase low-carbon steels, pointing to the wider implications of surface degradation under cyclic service conditions.

Taken together, these observations highlight the paramount importance of investigating corrosion-induced degradation mechanisms and their influence on the structural reliability of stainless steels in biomedical applications. Addressing this requirement, the current study presents a detailed examination of the long-term corrosion influence on the mechanical behavior of 304L and 316L austenitic stainless steels. The materials were exposed to extended immersion in phosphate-buffered saline (PBS) to closely mimic physiological conditions. Through a combination of uniaxial tensile testing and surface characterization techniques, this work provides fundamental understanding to aid in the selection of implant materials that necessitate both mechanical integrity and corrosion resistance in biologically relevant environments. In this study, PBS was chosen as the test medium because of its ability to accurately mimic the ionic balance of human body fluids while maintaining the reproducibility of experimental results. Despite the absence of proteins and carbonates, this aspect is acceptable, and more complex physiological mimics may be addressed in future research.

The novelty of the current work lies in the extensive evaluation of the long-term corrosion effects of two stainless steels (304L and 316L), commonly used in the biomedical field, under simulated physiological conditions using PBS. In contrast to many earlier studies, the current investigation includes both quantitatively measuring mechanical degradation and detailed post-immersion surface characterization with a quantitative mechanical degradation analysis. It also provides practical implications for material choices in implants that require continuous performance in the chloride-rich environment.

MATERIALS AND METHODS

This work examines degradation of the mechanical behavior in two widely used austenitic stainless steels, 304L and 316L, due to corrosion, with specific interest in biomedical application. The materials were subjected to long-term exposure in a simulated physiological solution intended to replicate in vivo conditions. Uniaxial tensile tests were conducted after immersion to assess the extent of corrosion-related mechanical degradation. The reason for choosing these alloys is their prevalent use in temporary biomedical implants – e.g.,

for orthopedic, dental, and surgical applications – where long-term mechanical integrity and corrosion resistance to body fluids are critical to maintaining both structural integrity and biocompatibility.

Materials and chemical composition

The experimental alloys, 304L and 316L stainless steels, were obtained as cold-rolled sheets with a nominal thickness of 3 mm, in compliance with ASTM A240 standards [17]. Their chemical compositions, confirmed via manufacturer-provided certificates, are detailed in Table 1. The main compositional difference lies in the inclusion of molybdenum (2.0–3.0 wt%) in 316L, which is absent in 304L. Additionally, 316L contains a moderately higher concentration of nickel. These alloying elements are well-documented for enhancing resistance to localized corrosion mechanisms such as pitting and crevice attack, especially in chloride-rich physiological environments. Both steels are iron-based, with supplementary additions of chromium (Cr), manganese (Mn), and silicon (Si).

Sample preparation and tensile specimen geometry

Tensile specimens were manufactured using wire-cut electrical discharge machining (EDM), a non-conventional process employed to minimize thermal distortion and prevent microstructural alterations along the cutting edges. This method also ensured superior dimensional accuracy and surface quality. The specimen geometry conformed to the ASTM E8/E8M standard [18] for subsize tensile testing, incorporating a gauge length of 25 mm, a width of 6 mm, and a constant thickness of 3 mm. The specimen size was specifically chosen for complete compatibility with the universal testing system and to allow a uniform strain distribution within the gauge length under tensile loading. Standard surface preparation was performed for all samples prior to immersion and mechanical testing. It consisted of degreasing in analytical-grade ethanol, extensive rinsing in deionized water, and ambient drying. This preparatory phase was aimed at removing surface

impurities – like residual machining marks, organic films, and oxides – that might affect corrosion behavior or detract from the validity and reproducibility of mechanical test findings.

Immersion testing in simulated body fluid

In an effort to replicate the corrosive environment found in the human body, phosphate-buffered saline (PBS) was used as the immersion medium. The medium was prepared according to a close approximation of the ionic profile specified by the World Health Organization (WHO) [19], such that the composition was similar to extracellular fluids. Chemical formulation details are presented in Table 2. It should be noted here that the standard PBS solution was used without added proteins or carbonates, although real biofluids contain additional components to facilitate the simulation of extracellular fluids. The addition of proteins and carbonates may complicate electrochemical reactions and make it difficult to separate the effect of corrosion from the effect of other biological components. High-purity deionized water was utilized in the preparation and the pH was adjusted to the physiological range of about 7.4. To ensure experimental continuity, proteins and carbonate species were intentionally omitted. Each of the stainless steel samples was fully immersed in 250 mL of PBS in a sealed borosilicate glass container to minimize evaporation and any contamination. The immersion was conducted under static conditions at a constant temperature of 37 ± 1 °C for five months. In an effort to ensure chemical consistency of the solution and avoid excessive buildup of corrosion products, the PBS was replaced every 30 days. No mechanical agitation or pH adjustment was employed throughout this duration, with a quasi-static condition representative of true physiological conditions maintained. It is worth noting that static immersion was employed in this study to simulate the physiological medium, as it provides a standard and easily controlled reference environment. However, real body fluids are characterized by dynamics and continuous movement (such as blood flow), which requires complex and expensive equipment that was difficult to provide at this stage.

Table 1. Chemical composition of 304L and 316L stainless steels (wt%)

Alloy	Fe	Cr	Ni	Mo	Mn	Si	C	P
304L	Balance	18.0–20.0	8.0–12.0	—	≤2.0	≤1.0	≤0.03	≤0.045
316L	Balance	16.0–18.0	10.0–14.0	2.0–3.0	≤2.0	≤1.0	≤0.03	≤0.045

Table 2. Corrosion testing results for stainless steel 316L and 304 alloys over five months

W_n	SS304 weights (g)	SS316L weights (g)	Date (day)
W_0	16.0033	16.4568	0
W_1	16.0033	16.4427	5
W_2	16.0033	16.4427	10
W_3	16.0033	16.4569	14
W_4	16.0033	16.4569	14
W_5	15.9891	16.4569	14
W_6	16.0033	16.4143	14
W_7	16.0033	16.4568	14
W_8	16.0033	16.4852	14
W_9	16.0033	16.4568	14

Gravimetric corrosion evaluation

Corrosion resistance of stainless steel samples was appraised by the gravimetric technique, adhering to the standardized guidelines of ASTM G31-21 [20]. The initial mass measurements were made using a very precise analytical balance (± 0.1 mg resolution) to obtain accurate baseline values before immersion. After five months of exposure to phosphate-buffered saline, surface residues of corrosion were gently removed with a soft nylon brush to prevent damage to the intact metal underneath. Samples were subsequently rinsed with deionized water and dried under controlled laboratory conditions. This cleaning procedure was carefully executed to avoid unintentional modification of the surface, thus maintaining the accuracy, consistency, and reproducibility of the corrosion testing.

Mechanical testing procedure

In order to evaluate the mechanical performance of the alloys after prolonged corrosion exposure, uniaxial tensile tests were carried out using a precisely calibrated universal testing machine (UTM) equipped with a 50 kN load cell, ensuring accurate load application and reliable characterization of the tensile properties under post-corrosive conditions. The crosshead speed was maintained at 1 mm/min in accordance with ASTM E8/E8M standards. For each alloy type (304L and 316L), three specimens in the as-received (unexposed) condition and three specimens after immersion were tested to ensure statistical reliability. The key mechanical properties recorded included yield strength (YS), ultimate tensile strength (UTS), and total elongation at fracture (El%). Fracture surfaces

were visually documented, and the load–displacement data were used to construct corresponding engineering stress–strain curves.

RESULTS AND DISCUSSION

Gravimetric corrosion analysis

The corrosion performance of 304 and 316L stainless steels after five months of immersion in PBS, simulating physiological conditions, is summarized in Table 2 and Figure 1. The results indicate discernible variations in sample weight over time, reflecting differing degrees of corrosion for both materials. 316L stainless steel exhibited a more consistent weight evolution throughout the exposure period compared to 304L. The same trend was observed with [5]. A slight weight increase observed in the 316L specimens is attributed to the development of a passive oxide layer, formed through the alloy's interaction with the PBS medium, as illustrated in Figure 1. In contrast, 304L samples showed negligible weight variation, indicating that they largely remained in a passive state during the immersion and may require an extended exposure period to initiate active corrosion processes. While both alloys exhibited signs of corrosion, the more stable mass profile of 316L reflects its superior corrosion resistance. This enhanced performance is primarily attributed to its molybdenum content, which significantly improves localized corrosion resistance and facilitates repassivation, particularly in chloride-rich environments [5, 21, 22]. These findings are consistent with those of Zhang et al. [4], who reported that 316L demonstrates superior corrosion resistance over 304L under aggressive environmental conditions. In the

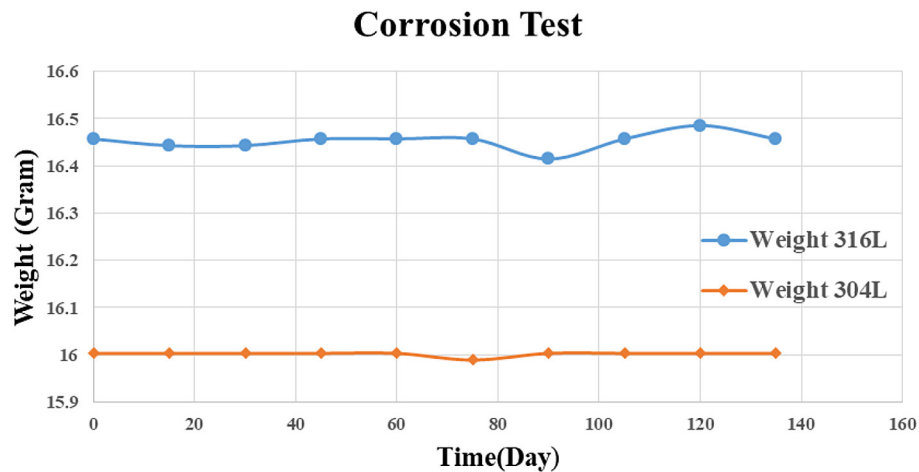


Figure 1. Variation of stainless steel (316L-304L) weight over five months

same context, Abdel-Majid and Hadi [23] demonstrated improved corrosion resistance performance of AISI 316L at 37 °C in simulated physiological solutions, highlighting the role of passive film stability under chloride exposure. The improved corrosion stability of 316L reinforces its applicability in biomedical and clinical applications requiring reliable long-term performance in physiological environments. However, it is important to note that a five-month exposure may not fully capture the long-term degradation behavior. Therefore, extended-duration experiments and comprehensive comparative analyses are necessary to thoroughly assess the corrosion behavior of these alloys in biologically relevant environments.

Mechanical performance degradation

Uniaxial tensile tests were employed to assess the extent of mechanical degradation resulting from corrosion. The average mechanical properties before and after exposure are presented in Table 3. In their uncorroded (as-received) state, 316L stainless steel exhibited slightly superior mechanical strength, with a yield strength (YS) of 294 MPa and an ultimate tensile strength (UTS) of 620 MPa, compared to 278 MPa and 600 MPa, respectively, for 304L. Following five months of immersion in PBS, both alloys experienced measurable reductions in strength, though the deterioration was more pronounced in 304L.

Specifically, the yield strength of 304L decreased by 10.8% to 248 MPa, while its UTS dropped by 8.8% to 547 MPa. In contrast, 316L retained more of its mechanical integrity, with post-corrosion values of 273 MPa for YS and

590 MPa for UTS, representing only 7.1% and 4.8% declines, respectively. These tensile results are consistent with the results observed in Ref. [24], which confirm the superior passivation behavior of 316L in chloride media. These findings highlight the beneficial influence of alloying elements such as molybdenum (Mo) and nickel (Ni) in enhancing the corrosion resistance and structural resilience of 316L during prolonged physiological exposure [25, 26].

Furthermore, elongation at fracture (El%) showed a more substantial decline in 304L – from 47.3% to 34.1% – indicating a notable loss in ductility. In comparison, 316L exhibited a less severe reduction, decreasing from 49.8% to 41.5%. This greater embrittlement in 304L can be attributed to localized corrosion effects, such as pitting, which introduce stress concentrators and impair ductile behavior. Similar observations have been reported in the literature, where exposure of stainless steels to PBS environments led to diminished ductility due to corrosion-induced microstructural damage [27].

Stress-strain behavior and failure characteristics

The stress–strain curves (Figures 2 and 3) of the corroded samples reveal distinct mechanical responses between the two stainless steel grades. The 304L alloy displayed a noticeable reduction in post-yield plastic deformation and an earlier onset of necking, characterized by a flatter stress–strain slope and diminished elongation at fracture. This behavior suggests a compromised strain-hardening capability, likely resulting from

Table 3. Mechanical properties of 316L and 304L alloys before and after corrosion exposure

Alloy	Condition	YS (MPa)	UTS (MPa)	Elongation (%)
304L	Uncorroded	278	600	47.3%
304L	Corroded	248	547	34.1%
316L	Uncorroded	294	620	49.8%
316L	Corroded	273	590	41.5%

microcrack formation along grain boundaries due to corrosion. In contrast, 316L stainless steel maintained a more ductile and continuous deformation pattern under load, reflecting superior resistance to corrosion-induced mechanical degradation. The present findings are in close agreement with observations made by Wu et al. (2024), where corrosion fatigue was found to significantly enhance crack initiation and cause a dramatic loss of ductility in 304L austenitic stainless steel, particularly in comparison with the more corrosion-resistant 316L grade [28]. This difference is also supported by Fracture surface morphology, which, despite both materials showing characteristics of ductile fracture, 304L samples manifested greater surface irregularity, extensive microvoid coalescence, and the presence of microcrack evolution – features often associated with pitting-related degradation. In contrast, the 316L alloy showed more homogeneous and smoother fracture surfaces, indicating a steadier and more uniform ductile failure response. These microstructural and mechanical distinctions are also in agreement with past comparative studies of welded 304L and 316L steels, which have shown a higher susceptibility of 304L to localized corrosion and premature failure, whereas 316L exhibits

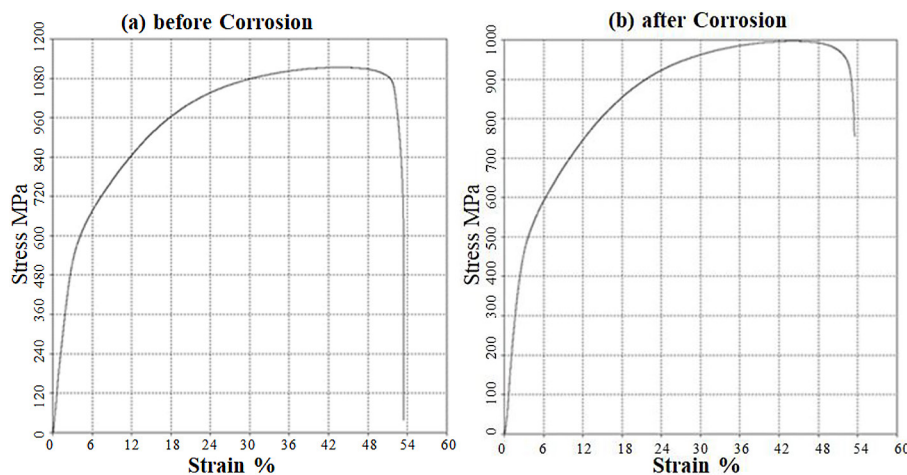
better structural robustness against combined corrosive and mechanical loading [27]. Collectively, the results confirm that 316L stainless steel not only retains superior tensile behavior following corrosion exposure but also exhibits more stable and predictable fracture behavior, reaffirming its suitability for long-term biomedical applications in corrosive physiological milieus.

Microstructure observation

Figure 4 shows the optical micrographs of 304L and 316L steel samples before and after immersion in PBS. It's clear from the figure that both alloys had a fine-grain structure of the size of about 10 to 45 μm , indicating that the samples had to undergo preheating to improve their mechanical properties.

After the corrosion test, no significant changes in the microstructure were observed, indicating that the two alloys maintained relative stability during the test period. This stability corresponds to the results of weight loss, where 316L alloys showed a small mass loss compared to 304L, which shows their greater resistance to local rust.

Mechanical test results also support this interpretation. Although both alloys showed a reduction in strength properties, the reduction in 316L


Figure 2. Stress-Strain diagram for 316L stainless steel sample

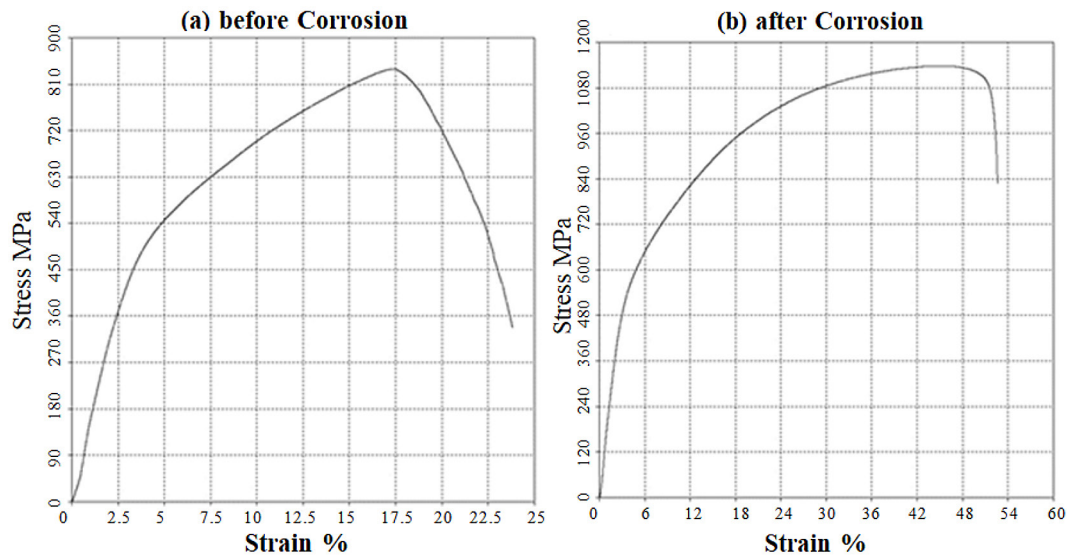


Figure 3. Stress-Strain diagram for 304L stainless steel sample

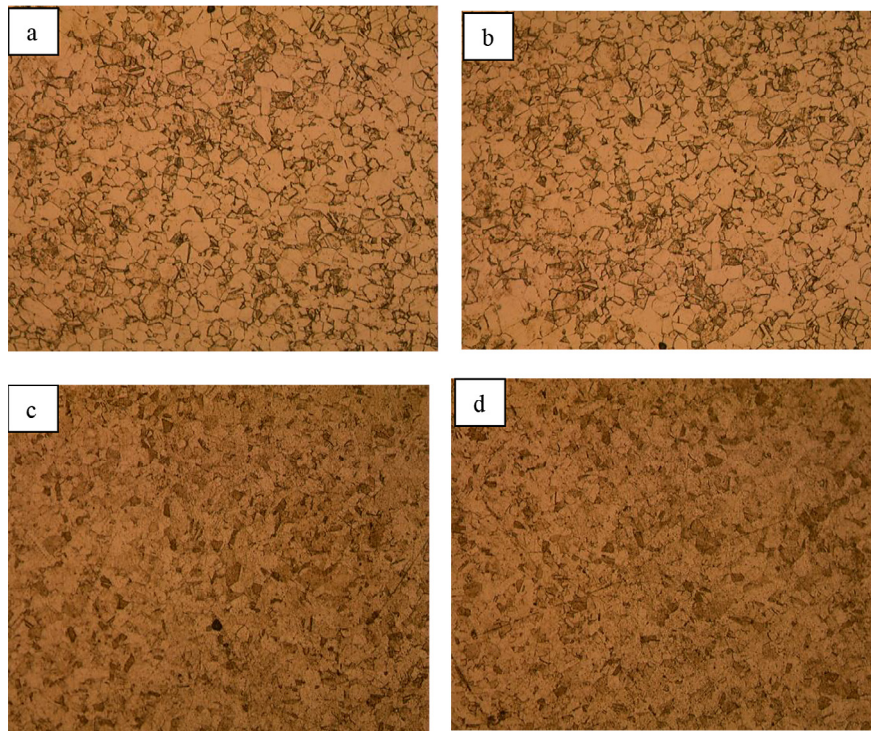


Figure 4. Microstructure of alloys before and after corrosion test (a) 316 stainless steel before corrosion (b) 316 stainless steel after corrosion (c) 304 stainless steel before corrosion (d) 304 stainless steel after corrosion

was quite small, supporting the idea that the presence of the molybdenum in its composition helps to speed up regeneration of the inactive film. On the other hand, 304L alloys showed a more pronounced deterioration, both in terms of weight loss and a greater decrease in mechanical properties.

By combining microstructure images with weight loss findings and mechanical tests, it can

be concluded that 316L exhibits better corrosion resistance while maintaining its toughness, whereas 304L shows relatively weaker performance under the same conditions.

It should be noted that although this research did not include examinations such as SEM, EDS, or XRD due to equipment limitations, optical microscopic images of both alloys before

and after corrosion were provided. These images support our observations on surface stability. The use of scanning electron microscopy/electrostatic discharge spectroscopy (EDS) will be considered in future work.

Discussion and comparisons

The enhanced alloying composition of 316L, characterized by higher molybdenum and nickel content, offers superior resistance to active-site corrosion compared to 304L, aligning with findings reported in the literature. Wang et al. [29], for example, demonstrated that chloride exposure alters the passive film on stainless steel surfaces, whereas the presence of molybdenum facilitates the formation of a thinner, more stable, and protective oxide layer. In addition, the 304L specimens exhibited a notably greater reduction in ductility, which is primarily attributed to surface degradation caused by corrosion, the accumulation of localized stresses, and the initiation of cracks linked to pitting corrosion mechanisms. When considered in totality, these observations reinforce the well-established scientific consensus favoring 316L stainless steel for applications requiring long-term implantation and for service in chloride-rich physiological environments. This preference is fundamentally based on its exceptional corrosion resistance and its proven ability to retain mechanical stability under extended exposure to simulated body fluids.

CONCLUSIONS

This investigation systematically examined the corrosion-induced deterioration in mechanical properties of 304L and 316L austenitic stainless steels following extended exposure to PBS, simulating physiological in vivo environments. Through an integrated approach involving gravimetric analysis, uniaxial tensile testing, and statistical evaluation, the study established the following primary conclusions:

316L stainless steel demonstrated a significantly lower corrosion rate and more stable mass retention throughout the immersion period relative to 304L. This improved corrosion resistance is primarily ascribed to the presence of molybdenum in its alloy composition, which enhances resistance to localized corrosion (e.g., pitting and

crevice attack) and facilitates rapid repassivation, particularly in chloride-rich environments.

Both alloys exhibited measurable reductions in yield strength, ultimate tensile strength, and ductility following corrosion exposure. Nevertheless, the mechanical deterioration was markedly more severe in 304L (the loss in yield strength, tensile strength, and elongation for 304L reached up to 10.8%, 8.8% and 27.9% respectively whereas for 316L it was limited to 7.1%, 4.8%, and 16.6% respectively), underscoring its higher susceptibility to corrosion-induced damage and loss of structural integrity under simulated physiological conditions.

Collectively, the findings substantiate the superior suitability of 316L stainless steel for biomedical and implantable applications requiring long-term exposure to corrosive biological media. While 304L may remain acceptable for temporary or low-risk scenarios, 316L is clearly favored in applications demanding sustained mechanical reliability and robust corrosion resistance.

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