

<https://doi.org/10.1038/s41529-025-00622-6>

The influence of texture density and free surface energy on the corrosion resistance of laser-textured 316L stainless steel



J. I. Ahuir-Torres¹ ✉, A. Al-Mahdy¹, M. C. Sharp¹, T. T. Opoz¹, G. Zhu², M. Bashir³ ✉ & H. R. Kotadia¹ ✉

316L stainless steel, despite its widespread industrial use, exhibits moderate corrosion resistance. Laser surface texturing has emerged as a promising technique to enhance this property. Specifically, laser texturing using dimples can effectively increase the corrosion resistance and surface free energy of the material. However, the influence of dimple density on these properties has been insufficiently explored. This study investigates the impact of texture density on the corrosion resistance and surface free energy of 316L stainless steel. Surfaces were textured with an infrared nanosecond fibre laser, and their corrosion behaviour and surface free energy were subsequently assessed. The results demonstrate a clear correlation between increased texture density and enhanced corrosion resistance, alongside a rise in surface free energy. Notably, surfaces textured with densities of 75% and 91% exhibited spontaneous repassivation, indicating a significant improvement in corrosion resistance due to the high texture density.

316L stainless steel finds widespread application across diverse industries, including maritime, offshore, power generation, aerospace, automotive, biomedical, and construction, owing to its advantageous properties such as biocompatibility, non-magnetic behaviour, and corrosion resistance superior to many other metallic alloys^{1–4}. However, 316L stainless steel exhibits moderate corrosion resistance, particularly in aggressive environments such as seawater, elevated temperatures, and under mechanical stress^{5–7}. While surface texturing is a technique employed to modify material properties, it can potentially compromise the corrosion resistance of 316L stainless steel^{3,8,9}.

Laser surface texturing (LST) offers a highly effective method for creating precise texture patterns. Employing laser technology to generate surface cavities, LST is characterised by its environmentally friendly nature, ease of automation, tool non-wear, and exceptional reproducibility^{2,10–12}. LST is primarily used to enhance friction and wear resistance. However, it can also influence corrosion resistance by inducing microstructural, chemical, and topographical changes in the material^{1,2,10–14}. The laser texturing process creates a highly compacted oxidised layer, effectively shielding exposed materials from corrosive environments². Additionally, laser-textured surfaces exhibiting superhydrophobic characteristics significantly enhance corrosion resistance^{10–14}.

Previous studies have investigated the influence of laser texturing on the corrosion resistance and wettability of stainless steel. For instance, Singh et al.¹⁰ found that femtosecond laser-textured stainless steel exhibited enhanced corrosion resistance, which was attributed to the induced super hydrophobicity of the textured samples. The laser texturing process generated a super hydrophobic surface through topographic modifications and thermal oxidised layer formation. The super hydrophobicity reduced the contact of the saltwater, thereby hindering the exposure of the samples to the corrosive agents (e.g., chloride ions, oxygen and water), leading to a corrosion resistance reduction. However, the hydrophobicity was reduced over time, potentially decreasing the corrosion resistance. The reduction in the hydrophobicity was linked to the chemical evolution of the thermal oxidised layer. Yue et al.¹⁴ observed that nanosecond laser texturing can reduce corrosion resistance due to crack formation and chemical changes. The exposed material in the crack became vulnerable to corrosive environment, leading to rapid corrosion. The high cathode/anode area ratio caused the corrosion due to the microgalvanic cell formation between exposed and oxidised regions. The chemical heterogeneity of the surface also encouraged the corrosion by the microgalvanic cell generation between the diverse types of oxidised products. Difference in the nobility of the oxidised products

¹School of Engineering, Liverpool John Moores University, Byrom Street, Liverpool, UK. ²The School of Electrical Engineering, Chongqing University of Arts and Sciences, Chongqing, China. ³Civil and Environmental Engineering, University of Liverpool, Liverpool, UK. ✉e-mail: j.i.ahuirtorres@liverpool.ac.uk; M.B.Bashir@liverpool.ac.uk; h.r.kotadia@liverpool.ac.uk

provoked the formation of the microgalvanic cell. The crack formation was attributed to the mechanical stress generated by the thermal oxidised layer formation and the shock wave induced by the plasma formed by laser. The Gaussian spatial distribution of the laser beam energy produced uneven heating across the textured area, resulting in an oxidised layer constituted of diverse oxidation products. Trdan et al.¹³ demonstrated that laser-induced dimple patterns can improve corrosion resistance of the samples with time due to the transition from super hydrophilic to super hydrophobic. The chemical evolution of the textured surface over time could lead to the passive film formation. The chemical evolution was attributed to the chemical activation of the surface produced by the laser texturing. Although the corrosion resistance improved with time, it was lower than that observed in the non-textured sample. Lu et al.¹² successfully created super hydrophobic surfaces with enhanced corrosion resistance using ultraviolet nanosecond laser texturing. The high corrosion resistance was also attributed to the super hydrophobic nature of the textured samples. LST created “brain like” nanostructures, which imported the super hydrophobicity to the textured surface. The super hydrophobic capacity was attributed to the air channels formed within the nanostructures, which repelled the water. Kedia et al.² also achieved super hydrophobicity and improved corrosion resistance in stainless steel via nanosecond laser texturing for biomedical applications. The high corrosion resistance observed in textured samples was attributed to both super hydrophobicity and dense thermal oxidised layer generated by LST. The dense thermal layer exhibited a reduction of the chemical active due to the less donor electron number. Lou et al.¹⁵ also enhanced the hydrophobicity of the 316L by creating of the dimples overlapped using a nanosecond pulsed laser. The study attributed the increase in hydrophobicity to the formation of the air channel within the textures. The corrosion resistance of the textured samples in 3.5% NaCl solution was also evaluated. The results indicated that the textured samples with the highest degree of overlap exhibited higher corrosion resistance compared to the non-textured sample. However, the textured samples with lower overlap demonstrated a reduction in the corrosion resistance compared to non-textured sample.

Although the influence of various LST parameters, such as laser settings, texture overlapping, and testing conditions, on the corrosion resistance of metallic alloys, including 316L, has been extensively studied, a significant gap remains regarding the corrosion behaviour of textured 316L with dimple patterns. Notably, the effect of texture density (TD) on the temporal evolution of corrosion mechanisms for dimple patterns on 316L is absent in previous studies. It is important to clarify that TD refers to the percentage of surface area covered by laser-induced textures. Overlapped dimple patterns can be considered a distinct texture type due to the altered individual texture morphology. Furthermore, the role of free surface energy in the corrosion behaviour of textured samples has been scarcely discussed.

To investigate the impact of TD on the surface free energy, wettability, and corrosion resistance of laser-textured stainless steel, we generated dimple patterns on 316L using an infra-red (1064 nm) nanosecond (200 ns) pulsed fibre laser. The TD ranged from 25% to 91%. Surface free energy was assessed using contact angle measurements, while corrosion resistance was evaluated using asymmetric electrochemical noise (AEN), potentiodynamic polarisation curves (PPC), and electrochemical impedance spectroscopy (EIS). Scanning electron microscopy (SEM) with secondary (SE) and backscattered electrons (BSE) and energy dispersive spectroscopy (EDS) mapping were employed to characterise the surface morphology and elemental composition before and after corrosion. This comprehensive study aims to provide valuable insights into the underlying mechanisms governing the relationship between TD, surface properties, and corrosion behaviour. By understanding these factors, it can optimise the laser texturing process for enhanced corrosion protection in stainless steel and similar materials.

Results

Analysis of the laser textured samples

Figure 1 presents surface and cross-sectional micrographs of both non-textured samples (Fig. 1a) and laser-textured samples with TD ranging from

25% to 91% (Fig. 1b–e). The single pulse laser exposure creates dimples characterised by a crest on the edge and ejected material outside the laser impact area (Fig. 1b–e). This morphology suggests a phase explosion as ablation mechanism, which involves the formation, growth, and explosion of a liquid–vapour bubble. The vapour pressure from the bubble pushes molten material to the edges of the dimple, forming the crest^{2,16}. Additionally, the explosive ejection of molten material occurs outside the laser-impacted zone¹⁷. Figure 1a–e presents SEM images of the non-textured (Fig. 1a) and textured (Fig. 1b–e) surfaces at varying texture depths (TD): 25% (Fig. 1b), 50% (Fig. 1c), 75% (Fig. 1d), and 91% (Fig. 1e). The micrographs reveal non-overlapping dimples across all patterns. Dimple areal density exhibits a direct proportionality to target TD, except for the 91% TD condition, which shows minor dimple overlap resulting in near-complete surface coverage. Cross-sectional micrographs reveal a refined microstructure beneath the laser-induced dimples. When metallic materials are processed using a near-infra-red laser (1064 nm), the incident laser energy is efficiently converted into thermal energy at the surface. Depending on the laser energy density, the metallic alloy undergoes heating, melting, and potentially even vaporisation. Following the laser pulse, rapid heat dissipation into the bulk material occurs, resulting in the formation of a heat affected zone (HAZ) characterised by a refined microstructure (Fig. 1f)^{2,16}. The HAZ thickness surrounding the dimple was around 3–5 µm, which was the same for all textured samples.

A consistent thermal oxide layer, measuring up to 1 µm in thickness (as shown in Fig. 2), was observed in the HAZ across all TD. This layer's composition, as determined by Kedia et al.² in their study of 316L, includes NiCr₂O₄, FeCr₂O₄, Fe₃O₄, Fe₂O₃, and Cr₂O₇^{2−}, formed during LST. From these identified compounds, specific chemical reactions can be inferred:

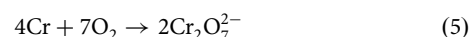
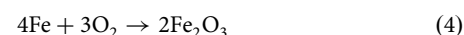
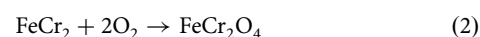
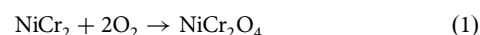


Table 1 reveals a notable increase in Ni and O concentration and a corresponding decrease in C content specifically at the dimple crests when compared to the surrounding non-textured areas. This observation aligns with previously published research¹⁸. Consequently, the observed enrichment of Ni within the laser-processed regions is expected to enhance the material's corrosion resistance.

Surface free energy evaluation

The wettability of the samples, along with the adhesion work, is shown in Fig. 3. The contact angles of the diiodine methane (Θ_{dm}) and distilled water (Θ_{dw}) on the surfaces, Fig. 3a, were used to calculate the dispersive (γ_s^{D}) and polar (γ_s^{P}) components of the surface free energy of the samples by employing Eqs. (6)^{11,19,20} and (7)^{11,19,20}.

$$\gamma_s^{\text{D}} = \frac{1}{\gamma_{\text{dm}}^{\text{D}}} \times \left(\frac{\gamma_{\text{dm}}^{\text{D}} \times (\cos\Theta_{\text{dm}} + 1)}{2} \right)^2 \quad (6)$$

$$\gamma_s^{\text{P}} = \frac{1}{\gamma_{\text{dw}}^{\text{D}}} \times \left(\frac{(\gamma_{\text{dw}}^{\text{P}} + \gamma_{\text{dw}}^{\text{D}}) \times (\cos(\Theta_{\text{dw}}) + 1)}{2} - \sqrt{\gamma_{\text{dw}}^{\text{D}} \gamma_{\text{dw}}^{\text{P}}} \right)^2 \quad (7)$$

where $\gamma_{\text{dm}}^{\text{D}}$ is dispersive free surface energy of the diiodine methane, the polar and dispersive components of the distilled water surface free energy are $\gamma_{\text{dw}}^{\text{P}}$ and $\gamma_{\text{dw}}^{\text{D}}$, respectively. The dispersive surface free energy of the samples

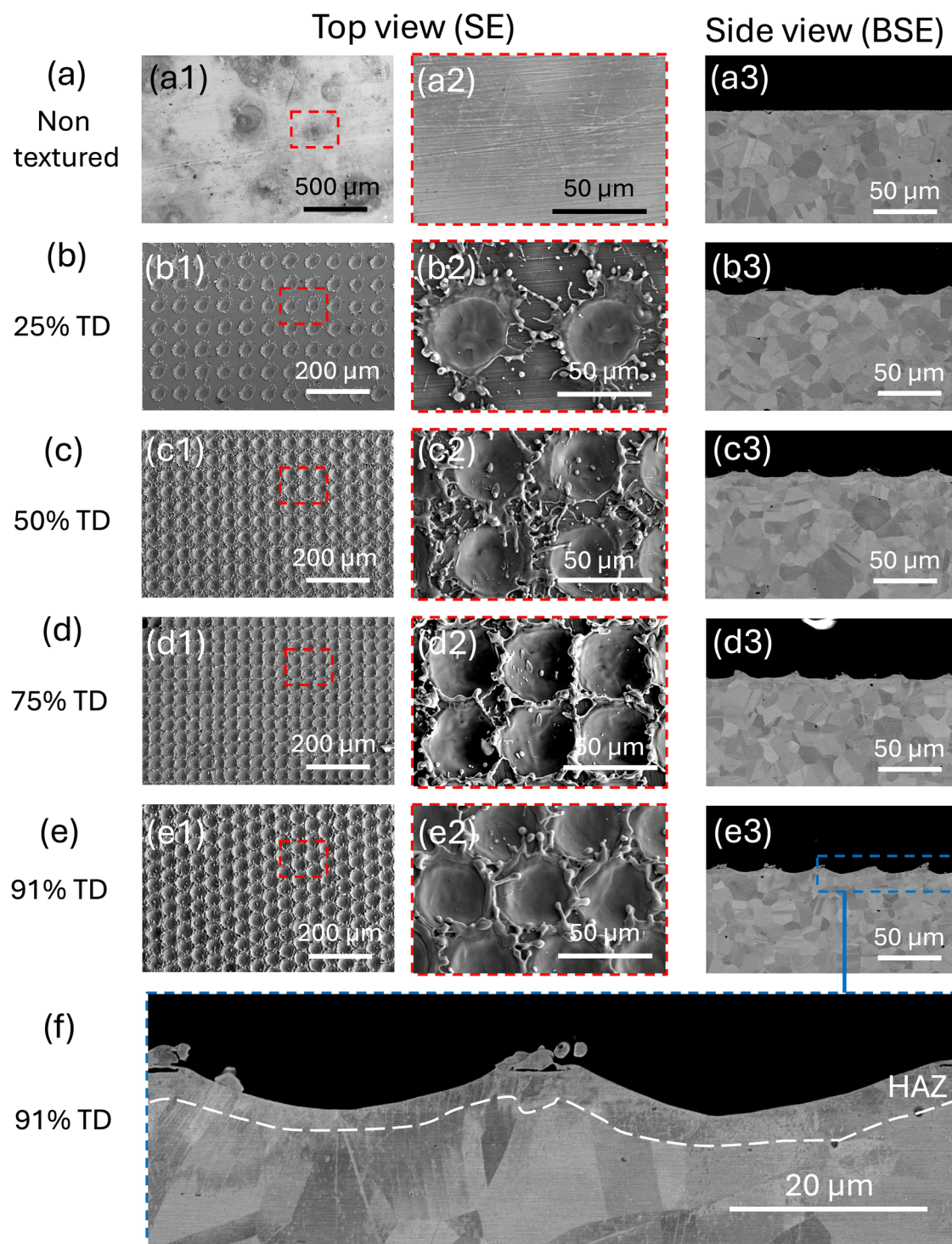


Fig. 1 | Top and side view micrographs of laser-textured 316L with varying texture densities. **a** Non-textured samples, textured dimple pattern with **b** 25%, **c** 50%, **d** 75%, and **e** 91% texture density. Surface texture analysis: **a1–e1** low

magnification, **a2–e2** high magnification images, and **a3–e3** side views comparing textured and non-textured surfaces. **f** HAZ of the dimple pattern with 91%. HAZ zones marked with white dash lines on the cross-section images.

increased with TD with a slight decrease for dimple pattern with 91% TD. The dimples increase the contact area with the liquid, increasing the surface free energy^{11,16}. The dimples have u-type shape (methodology)^{3,21,22}, which for a wide dimple texture allows the liquid access to the bottom of the texture. Regarding the dimple pattern with 91% TD, the dimple between dimples generates a sharp microstructure on the surface with a continuous crest formed of dimple crests, which limits the liquid contact¹¹. The polar surface free energy fluctuated around 18 J/cm² with TD, indicating the similar polarity of the samples.

Electrochemical analyses

AEN (ZRA and OCP). AEN of the samples can be observed in Fig. 4 (Supplementary Figs. 1–10 demonstrate the consistency of the results). The reduction of the current density (Fig. 4a) and the increase of the potential (Fig. 4b) with time for all samples means that chemical inactivity increased over time. The passive film growth over time diminishes the chemical activity of the material^{18,23}. Both output signals showed fluctuations owing to the metastable micropitting generation that produces an activation/passivation cycling process^{23–25}. At 7000 s, a sharp

Fig. 2 | Oxide rich layer on dimple surface. **a** SEM-SE image of a FIB cross-section, with **b** EDS analysis, revealing the thermal oxide layer on dimple patterns at 25% texture density sample.

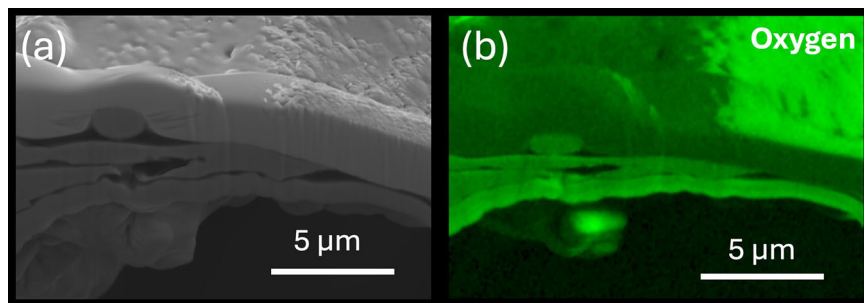


Table 1 | 316L composition (wt%) in textured and non-textured regions

Samples	Fe	Cr	Mn	Mo	Ni	C	O
Non-textured region	55.3 ± 0.5	15.0 ± 0.2	1.4 ± 0.2	1.9 ± 0.2	7.9 ± 0.3	16.2 ± 0.5	2.3 ± 0.2
Crest of the dimple	62.2 ± 0.5	15.0 ± 0.2	1.5 ± 0.2	1.7 ± 0.2	11.4 ± 0.3	3.6 ± 0.5	4.6 ± 0.1

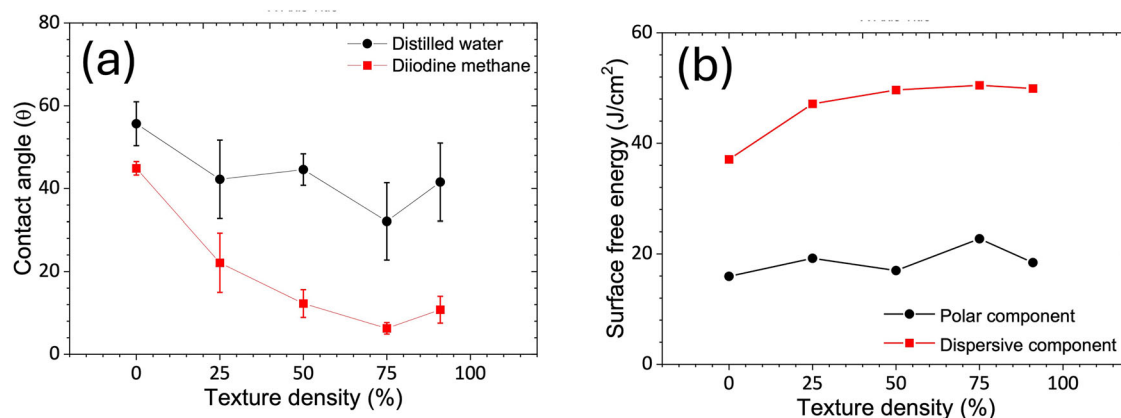


Fig. 3 | Effect of texture density on contact angle and surface free energy of 316L. **a** Contact angle with distilled water and methanol. **b** Surface energy components (polar and dispersive).

potential drop was recorded for the 91% TD dimple patterns, signifying the onset of large and deep metastable pitting. Furthermore, the size of these metastable pits is directly proportional to the area under the current density peak, as supported by previous research^{24,25}. The potential was higher for the dimple patterns with larger TD. This shows the HAZ is nobler than the native passive film¹⁸. The enlargement of the textured area increases this HAZ effect on specimens.

The corrosion features of the samples obtained with AEN outputs are summarised in Table 2. The kinetic characteristics of the samples were asymmetric electrochemical noise corrosion rate (C.R._{AEN}), resistance (R_{AEN}) and oxidised material concentration (O.M.C.) that were calculated using AEN data in combination with Eq. (8)^{26–28}, Eq. (9)^{29–31}, and Eq. (10)²⁵.

$$C.R._{AEN} = \frac{I_{R.M.S.}}{Fn_e\rho} \quad (8)$$

$$R_{AEN} = \frac{\sigma_E}{\sigma_I} \quad (9)$$

$$O.M.C. = \frac{QM}{n_eF} \quad (10)$$

Here, $I_{R.M.S.}$ is the root mean square current density, M is iron molar mass, F is Faraday's constant²⁷, n_e is the number of transferred electrons in the corrosion reaction (3), ρ is the density of the 316L, σ_E and σ_I are the standard

deviation of the potential and current density, respectively, and Q is the total transferred charge that was estimated with quick integration²⁵. Textured samples presented lower C.R. and O.M.C., and higher R_{AEN} than non-textured samples, indicating the higher chemical inactivity of the HAZ. R_{AEN} was increased with TD because the increased HAZ effect on the corrosion features.

The localised index (L.I.) values show that the corrosion for all samples was localised. General corrosion has values < 0.01, mixture corrosion is for values from 0.01 to 0.10, while localised corrosion has values > 0.10³². L.I. was calculated using ZRA data and Eq. (11)²⁹.

$$L.I. = \frac{\sigma_I}{I_{R.M.S.}} \quad (11)$$

PPC. The PPC shape was the same for all samples (Fig. 5) (Supplementary Figs. 11–15 demonstrate the consistency of the results). The cathodic branch was tilted, which indicates an activation control of the reduction reactions³³. The anodic branch is formed by a vertical curve that means the passive film control of the oxidation reactions^{33,34}. This vertical curve changed to a horizontal curve at the highest potentials, showing the passive film breaking. The large cathodic area (intact passive film) and small anodic area (pitting) produces a quick increase of the current density. The vertical curve of the anodic branch had fluctuations due to the metastable micropitting generation. The mechanism of metastable pitting initiation involves a dynamic interaction between the

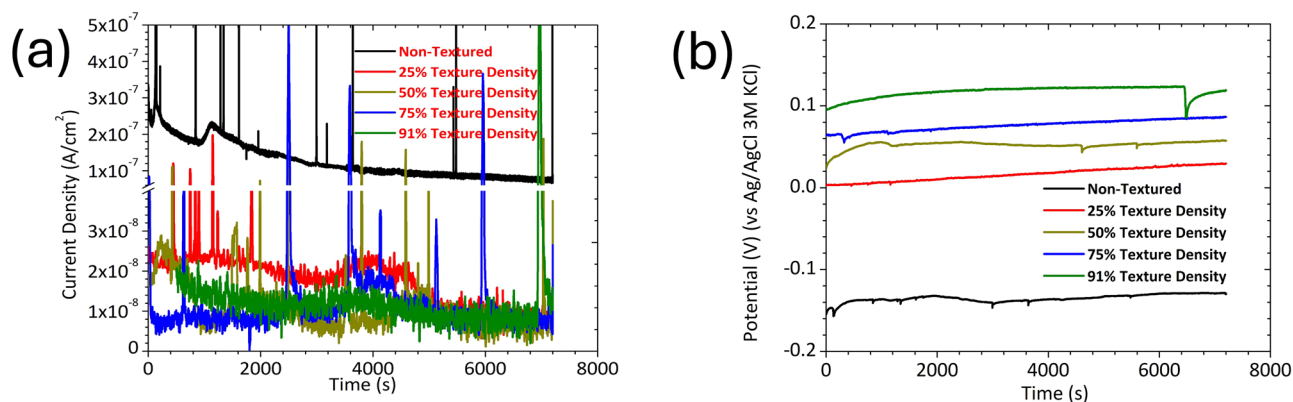


Fig. 4 | ZRA and OCP results. Evolution of the **a** current density and **b** potential over the time of the samples.

Table 2 | Summary of the corrosion features calculated with AEN outputs

TD (%)	$I_{R.M.S.}$ (nA/cm ²)	C.R. _{AEN} (nm/year)	σ_i (nA/cm ²)	σ_E (μV)	L.I.	R_{AEN} (kΩ/cm ²)	Q (μC/cm ²)	O.M.C. (ng/cm ²)
0	129	988	71	448	0.55	62	433	83
25	18	141	22	7985	1.22	355	132	25
50	27	211	25	4202	0.91	169	196	38
75	20	153	11	6789	0.56	609	80	15
91	15	113	5	6844	0.33	1369	107	21

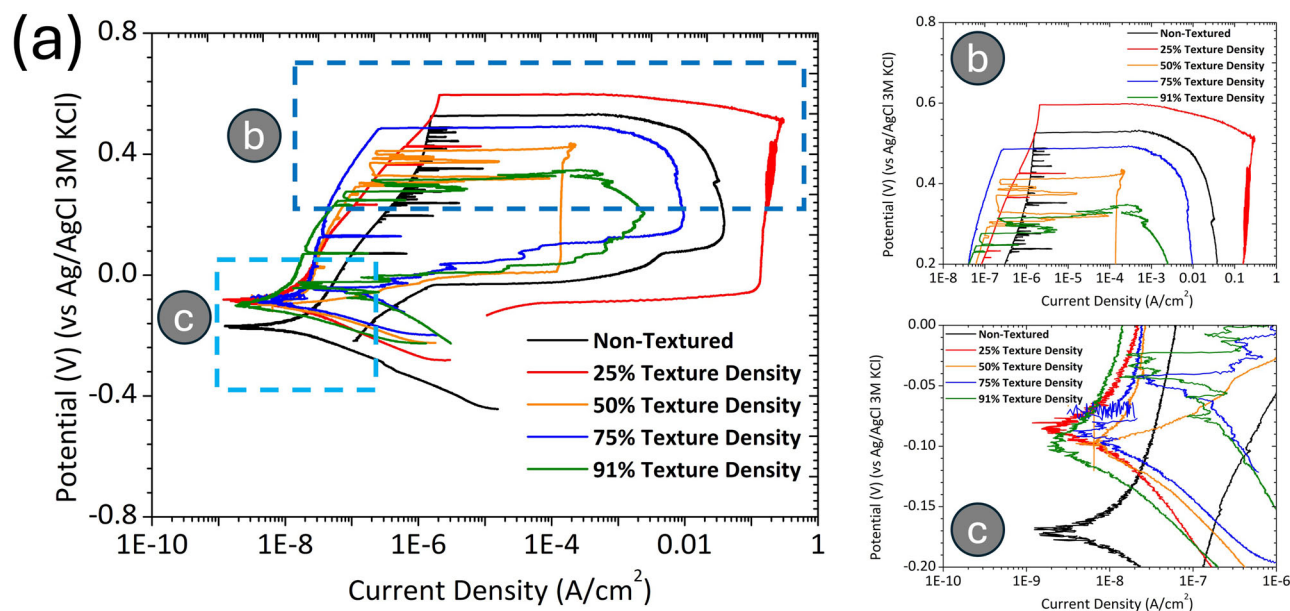


Fig. 5 | PPC results for samples immersed in 0.6 M NaCl for 2 h. **a** Full graph, magnified, **b** anodic branch, and **c** corrosion potential difference between samples.

breakdown and repair of the passive film, as showed in Fig. 5b. Localised dissolution of the passive film exposes the underlying metal, triggering its oxidation. This oxidation process manifests as a transient increase in current density at a fixed potential. Subsequently, the newly formed oxide layer repassivates the exposed area, resulting in a corresponding decrease in current density. This repetitive cycle of passive film dissolution, metal oxidation, and repassivation contributes to the stochastic nature and formation of metastable pits^{33,35}. The PPC exhibited a consistent profile across all samples, with the exception of the return curves for the 75% and 91% texture density dimple patterns. Notably, these specific patterns displayed an inflection point on the return curve at a potential significantly higher than the corrosion potential (the transition point between the anodic and cathodic branches). This characteristic indicates

that, following passive film breakdown and subsequent potential reduction, spontaneous repassivation of the film occurs. The potential at this inflection point is recognised as the repassivation potential^{13,36}. In contrast, the remaining samples exhibited inflection points on their return curves at potentials lower than the corrosion potential, suggesting an inability for spontaneous passive film recovery. Furthermore, the 91% TD dimple patterns displayed an inflection point at a higher potential than the 75% TD patterns. This observation signifies that repassivation can occur over a wider potential range for the 91% TD samples, indicating enhanced resistance to passive film breakdown.

Table 3 summarises the thermodynamic (corrosion and passive film breakdown potentials) and kinetic (corrosion current density and rate, cathodic and anodic Tafel slopes, passive current density and rate)

Table 3 | List of the corrosion characteristics got with PPC data

TD (%)	E_{corr} (V)	i_{corr} (nA/cm ²)	C.R. _{corr} (nm/year)	β_c (V/decade)	β_a (V/decade)	R_p (k Ω cm ²)	E_{bp} (V)	i_{pass} (nA/cm ²)	C.R. _{pass} (nm/year)
0	−0.172	9.26	99	−0.028	0.069	1253	0.528	1860	19,000
25	−0.128	5.59	60	−0.039	0.021	3648	0.588	150	2000
50	−0.110	1.92	21	−0.027	0.011	4496	0.414	67	684
75	−0.080	0.91	10	−0.013	0.007	7066	0.484	39	415
91	−0.070	0.80	9	−0.017	0.007	7858	0.384	39	415

parameters derived from the PPC of the specimens, providing a comprehensive characterisation of their corrosion behaviour in 0.6 M NaCl.

The corrosion potential (E_{corr}) is the potentials where the cathodic and anodic branches matched (Fig. 5c). E_{corr} increased with increasing texture density as the HAZ is nobler than the native passive film²⁶. This has a greater effect on the corrosion features of the samples when TD is larger. The breaking passive film potentials (E_{bp}) are the potentials where the current density quickly increased in the anodic branch¹⁰. E_{bp} lowers with increasing TD, indicating HAZ is less thermodynamically stable than the native passive film²⁶. The only exception to this is the dimple pattern with 25% TD that had a similar E_{bp} to the non-textured sample E_{bp} . The low texture density exhibits low influence on non-textured sample E_{bp} .

The corrosion current density (i_{corr}), cathodic (β_c) and anodic slope (β_a) were estimated using Tafel lines^{27,37}. The corrosion rate (C.R._{corr}) was calculated using the Eq. (8)^{26,27} and replacing $I_{\text{R.M.S.}}$ by i_{corr} . C.R._{corr} was lower at higher TD, indicating the lower kinetic activity of the HAZ. The polarisation resistance (R_p) was calculated with the Eq. (12)^{13,27,37,38}.

$$R_p = \frac{\beta_c \beta_a}{2.303 \times (\beta_c + \beta_a) i_{\text{corr}}} \quad (12)$$

Increasing TD increases R_p because it is inversely proportional to i_{corr} . The passive film current density (i_{pass}) was measured on the vertical curve of the anodic branch. The passive film corrosion film (C.R._{pass}) is also estimated with Eq. (3)^{26,27} but $I_{\text{R.M.S.}}$ was replaced by i_{pass} in this case. C.R._{pass} is lower at higher TD, confirming the excellent kinetic chemical inactivity of the HAZ^{2,12}.

EIS. EIS data for each sample and according to immersion time were represented with Nyquist and Bode plots (Fig. 6). Equivalent circuits (Fig. 7) were proposed to represent the corrosion mechanisms according to the data presented in Fig. 6. Supplementary Figs. 16–40 demonstrate the consistency of the results.

The first equivalent circuit (Fig. 7a) was formed of three time constants. The horizontal curve at high frequency range (from 10³ to 10⁵ Hz) of the impedance modulus (Z) vs. frequency (F) Bode plots (Fig. 6) indicated that the first constant is a resistance (R_1)²⁸. The loop of the Nyquist plots, peak of the phase angle (α) vs. F Bode plots and the tilted curve of the Z vs. F Bode plots showed that the second time constant is a contact phase element (CPE₂) in parallel with a resistance (R_2)². The third time constant was similar to the second time constant, indicating the loss of the loop curvature at high real impedance (Nyquist plots), the rounding of the peak (α vs. F Bode plots) and the slope change of the tilted curve (Z vs. F Bode)²⁸. According to this, R_1 was in serial with CPE₂ and R_2 , while CPE₃ was in parallel with R_2 . This circuit has been suggested for the SS316L corrosion mechanism in previous works^{1,39}.

The second equivalent circuit, (Fig. 7b) was similar to the first equivalent circuit but a Warburg impedance was added in series with R_3 . The tail at low frequency ($\approx 10^{-2}$ Hz) for α vs. F Bode plots and high real impedance for Nyquist plots are the signals of this element. Diffusion processes are associated with the Warburg impedance (W)⁴⁰. This circuit has been employed in previous studies¹.

The first equivalent circuit was proposed to represent the corrosion mechanisms for the non-textured samples at all immersion times. The

second equivalent circuit was employed to simulate the corrosion mechanisms of the textured samples.

The excellent Chi-square (χ^2) ($\approx 10^{-4}$ 28,41) and good fit the equivalent circuit with the experimental data (Fig. 8) confirmed the validity of these equivalent circuits to represent the sample corrosion mechanism. χ^2 represents the deviation of the equivalent circuit data from the experimental results^{28,41}. The equivalent circuit element values are summarised in Table 4. R_1 was constant over the time and similar for all samples (3–10 Ω cm²), meaning that this element can be related with the solution²⁸. R_2 and R_3 were decreased with the immersion time for the non-textured sample, meaning the reduction of the corrosion resistance. These elements remained constant over time or even increased for the dimple texture patterns. This indicates higher stability for the corrosion resistance in textured samples. CPE₂ was constant over time for all samples and similar between most of the samples (the order of 10⁵ s μ S sⁿ cm^{−2}). The only exception was the dimple pattern with 91% of texture density, where CPE₂ was in the order of μ S sⁿ cm^{−2}. This means this corrosion process is thicker for this dimple pattern as the process thickness is inversely proportional to CPE₂²⁷. The same behaviour for CPE₃ is observed. The non-textured samples exhibited the lowest CPE₃ (μ S sⁿ cm^{−2}). n_2 was close to 1 for non-textured samples, indicating good flatness of the surface. For the textured surfaces, this element was ≈ 0.8 because of the relief of the surface. n_2 is inversely proportional to the surface roughness^{2,28}. For 91% texture density at 24 h immersion or more, n_2 is closer to 0.5, due to the roughness^{28,41} or electrical relaxation effects⁴². This was also observed for n_3 in the case of the non-textured samples at ≥ 24 h of immersion. The Warburg impedance, W , and the diffusion time root (t), fluctuated with the immersion time and reduced as the texture density increases. This indicates a reduction of the diffusion length (l_d) as determined by the Eq. (13)⁴³.

$$l_d = \sqrt{Dt} \quad (13)$$

Here, D is the diffusion coefficient of the oxygen or water in salt water.

Notably, R_2 and R_3 values measured for the textured samples were lower than those observed for non-textured counterpart, suggesting a reduced corrosion resistance in the textured samples. This reduction is attributed to increase surface area generated by the texturing process. However, the presence of the diffusion impedance in the textured samples also contributed in the corrosion resistance. Specially, the enhanced diffusion impedance improved the overall protective behaviour of the dimple textures, resulting corrosion resistance values exceeded those of the non-textured samples.

Corroded sample assessments

The effect of corrosion on the sample surfaces can be seen in Fig. 9. The non-textured specimens (Fig. 9a) had a corroded surface characterised by central pitting surrounded by smaller pitting in circular position to this. 316L filaments were also observed on the pitting surface. The inner pitting exhibited a polygonal structure similar to the grain. The filaments and inner polygonal structure indicates the direct corrosion of the inner grain, remaining intact the grain boundary, which are the filament. The corrosion in the inner grain leads the dissolution of the utterly grain (i.e., inner grain and boundary grain). The 316L dissolution reveals its microstructure. The preferential corrosion of the inner grain is attributed to the dissolution of the grain^{25,31,34,44}.

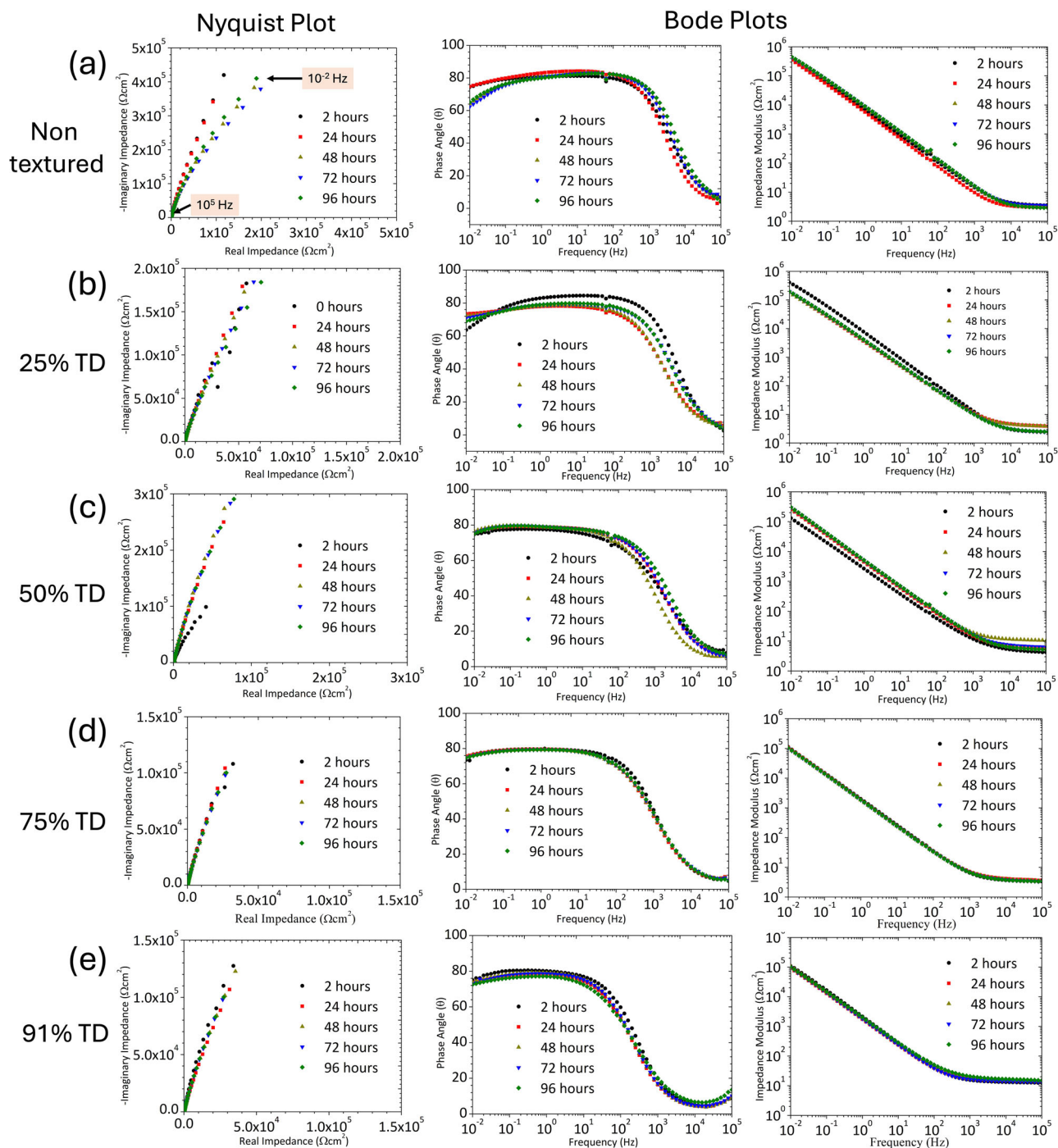
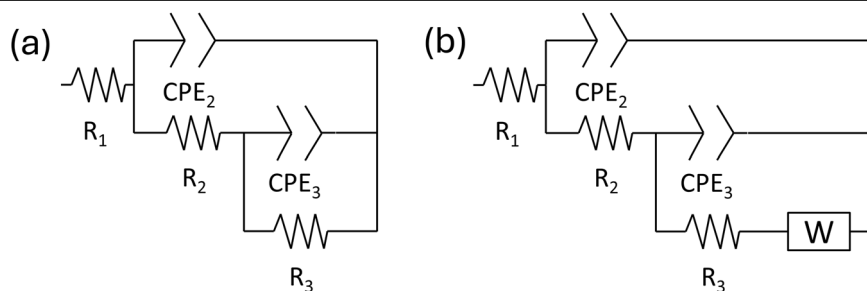


Fig. 6 | EIS results. Nyquist and Bode plots of the **a** non-textured sample and the dimple patterns with **b** 25%, **c** 50%, **d** 75%, and **e** 91% of texture density at 2, 24, 48, 72 and 96 h of immersion in 0.6 M NaCl. Notably, low impedance corresponds to high frequency, while high real impedance corresponds to low frequency.

Fig. 7 | Equivalent circuit. **a** First and **b** second equivalent circuit proposed to represent the corrosion mechanism of the samples.



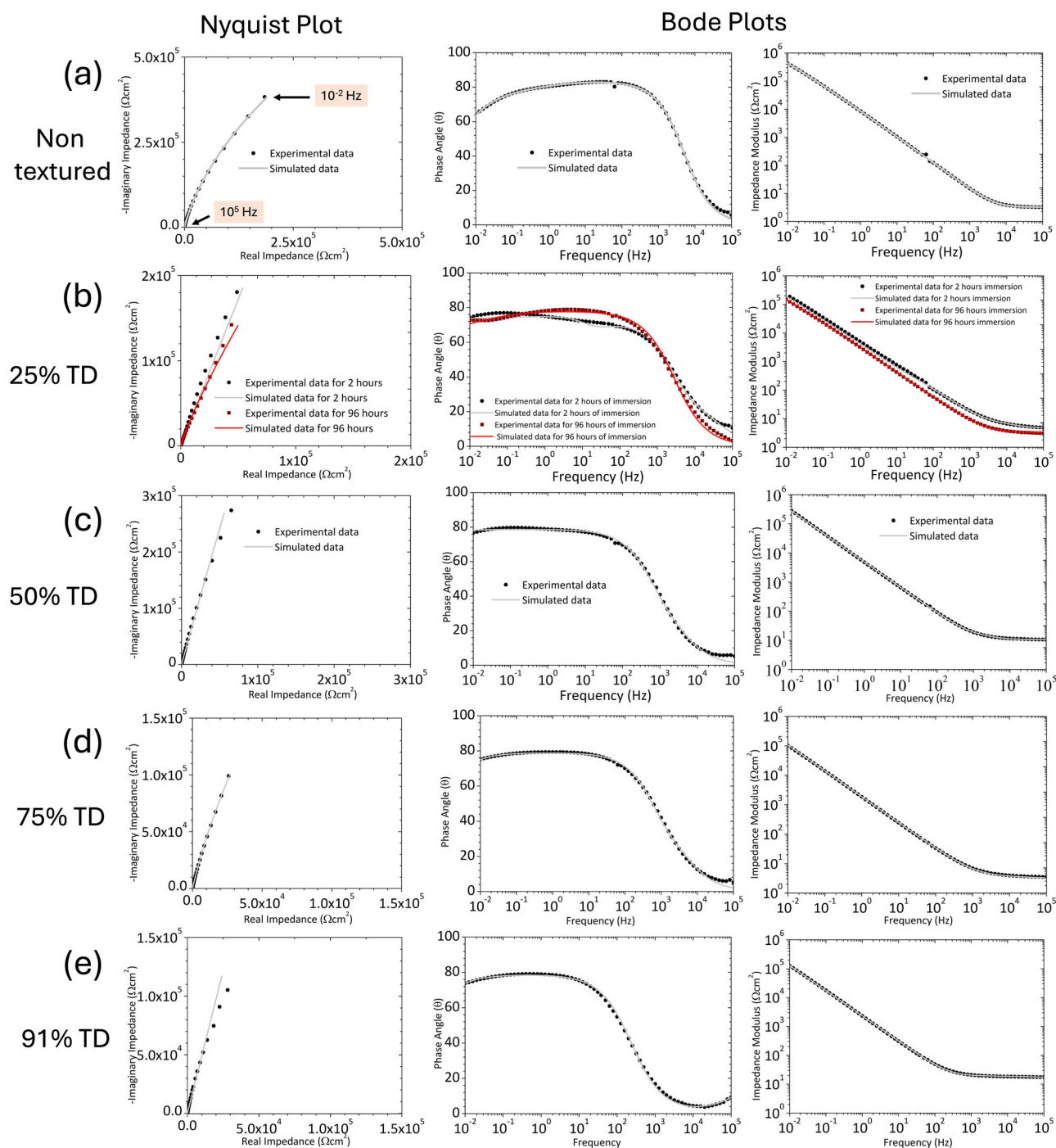


Fig. 8 | Equivalent circuit vs. experimental data. Comparison between the equivalent circuit and experimental data, **a** non-textured sample and the dimple patterns with **b** 25%, **c** 50%, **d** 75%, and **e** 91% of texture density.

This corrosion morphology was also observed on the dimple patterns (Fig. 9b–e), a corroded surface with another morphology was also found in the textured specimens. However, the corrosion only consists of small localised pitting in the dimple valley. Most of the crests were free from the corrosion due to the presence of the thicker melted layer on this region^{2,16}. Melted metallic materials are highly reactive with the atmospheric oxygen, which resulted in the generation of the thermal oxidised layer with superior corrosion resistance^{1,15,18}. This suggests the thickening of the thermal oxidised layer improves the corrosion resistance.

The chemical analyses of the corroded surface (Fig. 10) show a high concentration of iron and chromium on the pitting both non-textured sample (Fig. 10a) and dimple pattern (Fig. 10b). The concentrations of the

other alloy elements (nickel and carbon) and oxygen were lower in this area, indicating the removal of the passive film. The Fe_2O_3 and $\text{Fe}(\text{OH})_3$ components of the passive film exhibit an affinity for the chloride ions, leading to the formation of the chemical products (FeCl_3 , FeO_2Cl and $\text{Fe}(\text{OH})_2\text{Cl}$) with high solubility. The dissolution of these products in the water degrades and removes the oxidised layer⁴⁴. The chemical reaction between passive film with chloride ions are following:

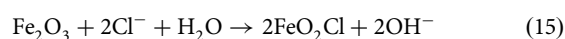
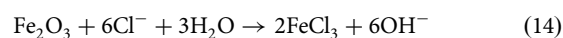
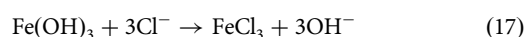
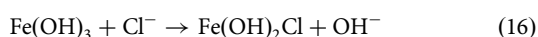


Table 4 | Summary of the equivalent element values according to the immersion time in 0.6 M NaCl and the sample

TD (%)	Time (h)	R_1 ($\Omega \text{ cm}^2$)	CPE_2 ($\mu\text{S s}^n \text{ cm}^{-2}$)	n_2	R_2 ($\Omega \text{ cm}^2$)	CPE_3 ($\mu\text{S s}^n \text{ cm}^{-2}$)	n_3	R_3 ($\text{M}\Omega \text{ cm}^2$)	W ($\text{S s}^{1/2} \text{ m}^{-2}$)	t ($\text{s}^{1/2}$)	χ^2 (10^{-4})
0	2	3.0	32.6	0.92	2.2×10^5	9.5	0.90	5.1	–	–	6.08
	24	3.2	22.0	0.92	1.5×10^5	4.4	0.66	1.7	–	–	4.31
	48	3.1	20.5	0.93	6.6×10^4	3.9	0.58	2.4	–	–	2.74
	72	3.5	19.7	0.93	7.7×10^4	3.7	0.51	3.0	–	–	4.19
	96	2.9	19.2	0.92	6.3×10^4	3.6	0.61	2.5	–	–	2.76
25	2	4.4	36.8	0.79	7.7	12.8	0.87	2.3×10^{-3}	1.2×10^{-4}	2.9×10^{-2}	8.55
	24	3.8	25.1	0.86	10.2	30.3	0.85	77.0	2.3×10^{-6}	12.0	4.38
	48	3.4	32.6	0.88	7.7	35.0	0.84	0.5	3.2×10^{-6}	263.0	3.40
	72	2.9	39.7	0.88	11.8	23.2	0.85	0.1	5.5×10^{-6}	∞	2.65
	96	3.2	64.0	0.87	16.2	12.8	0.87	0.3	6.3×10^{-6}	∞	14.80
50	2	3.2	12.5	0.82	2.0	46.0	0.86	0.2	9.7×10^{-6}	4.6	5.60
	24	5.8	27.2	0.88	14.0	17.0	0.87	9.0	1.6×10^{-3}	331.0	7.93
	48	10.6	25.7	0.88	23.9	15.2	0.86	36.0	5.0×10^{-6}	6.0	8.17
	72	6.2	21.6	0.87	5.9	15.8	0.87	3.0×10^{-2}	1.4×10^{-2}	1.2×10^{-4}	3.28
	96	5.0	21.6	0.86	4.8	14.5	0.88	0.4	3.2×10^{-3}	5.5×10^{-4}	3.72
75	2	3.4	86.1	0.87	12.3	12.8	0.94	1.4	5.3×10^{-4}	4.5×10^{-2}	4.61
	24	3.8	44.5	0.92	7.3	9.4	0.85	1.9	1.6×10^{-3}	2.4×10^{-2}	6.59
	48	3.5	62.2	0.88	7.2	45.3	0.87	1.4	1.8×10^{-3}	0.4	4.88
	72	3.4	72.3	0.87	9.4	35.0	0.89	1.2	2.2×10^{-4}	0.2	4.83
	96	3.4	65.2	0.88	8.2	40.1	0.87	1.2	3.3×10^{-3}	1.6×10^{-2}	3.80
91	2	6.2	1.7	0.80	7.1	74.7	0.88	1.3	1.1×10^{-2}	1.3×10^{-3}	7.23
	24	3.6	1.6	0.66	19.0	94.1	0.87	1.6	19.3	1.2×10^{-4}	5.42
	48	4.3	1.1	0.68	19.0	84.6	0.88	1.5	0.5	5.9×10^{-4}	5.30
	72	3.2	1.4	0.68	17.9	90.3	0.87	1.2	0.3	3.5×10^{-4}	4.86
	96	7.0	0.9	0.78	10.9	84.9	0.88	1.1	1.0×10^{-2}	1.0×10^{-2}	4.51



The filaments exhibited high Ni concentration, indicating the accumulation of this element at the grain boundary. Ni is known as one of the key elements responsible for the high corrosion resistance of the stainless steels³⁴. While Cr enrichment is known to impart greater corrosion resistance to stainless steel than Ni, the presence of Ni also contributes significantly to improved corrosion performance. Nickel promotes the formation of a dense and adherent Cr_2O_3 passive layer, which is characterised by its exceptional resistance to corrosion⁴⁵. Consequently, the observed enrichment of nickel specifically at the grain boundaries resulted in superior corrosion resistance compared to the inner grain regions.

Discussion

LST exhibited the ability to change the surface properties (surface free energy and corrosion behaviour) of the 316L. The extent and nature of these changes were defined by the type of surface property and the TD percent.

With respect of the surface free energy, this surface property comprised of the polar and dispersive part, which were evaluated with water and diiodine methyl, respectively. The wettability is increased with increasing TD up to 75%. This is due to the increase in the dispersive component of surface free energy. Water is a liquid with polar and dispersive components²⁰. The topography of the dimple pattern encourages the contact of the water with the textured surface as a result of the wide dimple (u-type)¹⁶. Notably, the oil-ability is moreover increased with the texture density increment. The dimples patterns with 91% TD have lower dispersive

free surface energy than the dimple patterns with 75% TD owing to the specific topography. The inclusion of an extra dimple on the non-textured area between dimples produces a continuous narrow crest chain that limits the contact of the liquid inside the dimple^{29,11–13,46}. Figure 11 shows a schematic drawing of both processes, being increasing wettability ($\leq 75\%$ TD) and reduction (91% TD).

In respect of the corrosion behaviour, the controls of the cathodic and anodic branches (PPC) are the same for all samples, being activation and passive film, respectively. The type of the corrosion (AEN-ZRA) was also similar for all specimens, being a mixture of general and localised. The corrosion and passive film rate decreases with the increasing TD (PPC and AEN-ZRA), showing higher corrosion resistance for the textured samples. The oxidised layer generated by the laser in the HAZ is more chemically inert than the native passive film. The laser oxidised layer can be n-type oxidation that hinders the transfer of cations from metallic alloy matrix, reducing the chlorine reaction with the passive film². The enhanced nobility of the textured samples can be attributed to the increased chemical inertness of the HAZ. Specifically, the surface area covered by the laser-induced oxide layer increases proportionally with TD^{10,13}. It is noted that the C.R._{AEN} (AEN-ZRA) value was similar to the $\text{C.R.}_{\text{pass}}$ (PPC) value as the passive film controls the corrosion kinetics of the samples⁴⁷. The laser surface texturing ennobles the 316L as indicated by the higher corrosion potential (PPC and AEN-OCP) of the textured surface compared to the non-textured specimen. LST can generate a thermal oxidised layer with higher nobility than native passive films due to the thicker of the thermal layer^{1,18}. The difference between AEN-OCP and PPC potential is due to the partial elimination of the passive film by the cathodic branch (PPC)³⁷. E_{bp} (PPC) decreases with increasing TD because of the less thermodynamic stability of the laser oxidised layer¹⁸. However, the surfaces textured with dimple patterns at 75% and 91% TDs presented a new function, spontaneous repassivation. The

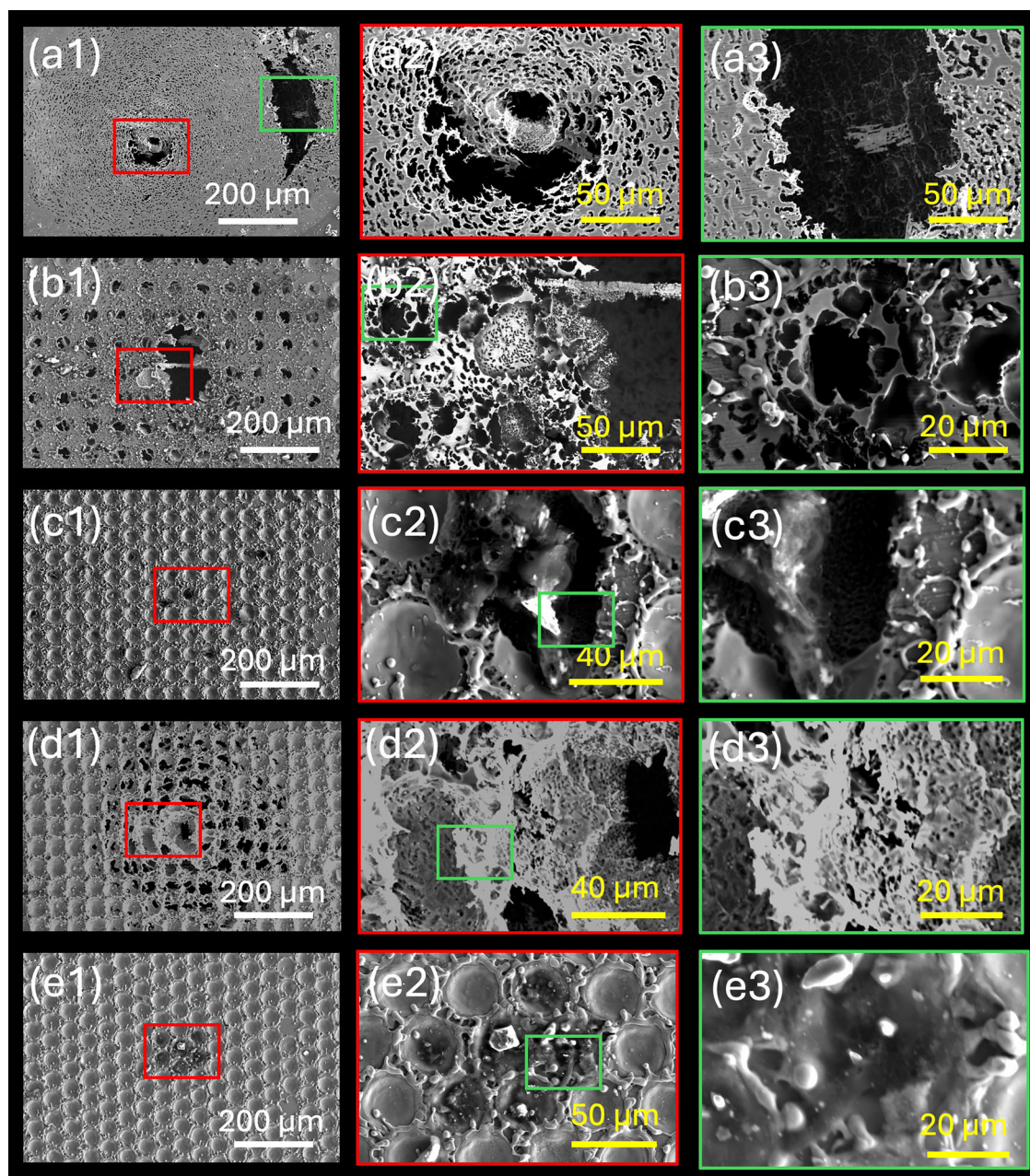


Fig. 9 | Corrosion analysis using SEM imaging of 0.6 M NaCl-induced pitting (after PPC) on. a Non-textured surface and dimple-patterned surfaces with texture densities of **b** 25%, **c** 50%, **d** 75%, and **e** 91%. Surface degradation on non-textured

and textured areas: **a1–e1** low magnification overview, **a2–e2** high magnification of the red-boxed area, and **a3–e3** high magnification of the green-boxed area.

crests of the dimples exhibit high nickel concentration, which is one of the key elements in the chemical inert of the stainless steel¹⁸. The effect of the crest on corrosion characteristics are enhanced with the TD increase. Consequently, the influence of the laser-oxidised layer on the corrosion behaviour of the samples is more dominant with increasing TD because this layer covers more surface.

The electrochemical impedance spectroscopy (EIS) data, the chemical analyses and metallographic evaluation define the corrosion mechanisms of the samples according to the immersion time. R_1 constancy ($\sim 3\text{--}6\ \Omega\ \text{cm}^2$) against immersion time and surface condition shows that this time constant is the solution resistance (R_s)^{34,39,44}. The second time constant is associated with the passive film process (CPE_f , n_f and R_f)^{34,39}. The third time constant is related to the bared material process. CPE_3 is the double layer formed by the alignment of the solution and alloy charges (CPE_{dl})^{34,39}. R_3 is associated with charge transference (R_{ct})^{34,39}. W represented a diffusion process, caused by

the rough topography of the dimple patterns. This hinders the access of the chlorine, oxygen and water to metallic alloy surface⁴⁸. The samples maintained the same corrosion mechanism type over time. The non-textured samples had similar corrosion mechanism to the dimple textured samples, but without the diffusion process. The low relief of the surface avoids the impedances of mass transference.

Although the corrosion mechanism remains the same over time, the following values change over time and between the samples. R_f and R_{ct} diminishes with time for non-textured specimens. The chloride anions of the solution can locally dissolve the native passive film, causing pores and cracks that decrease the corrosion resistance of the material³⁴. These resistances are constant or increase over time for dimple patterns, showing higher stability of the laser oxidised layer against time. The sum of these resistances is in the order ($10^6\ \Omega\ \text{cm}^2$) of R_{AEN} (AEN) and R_p (PPC), validating the results. CPE_f is similar for the immersion time and specimen

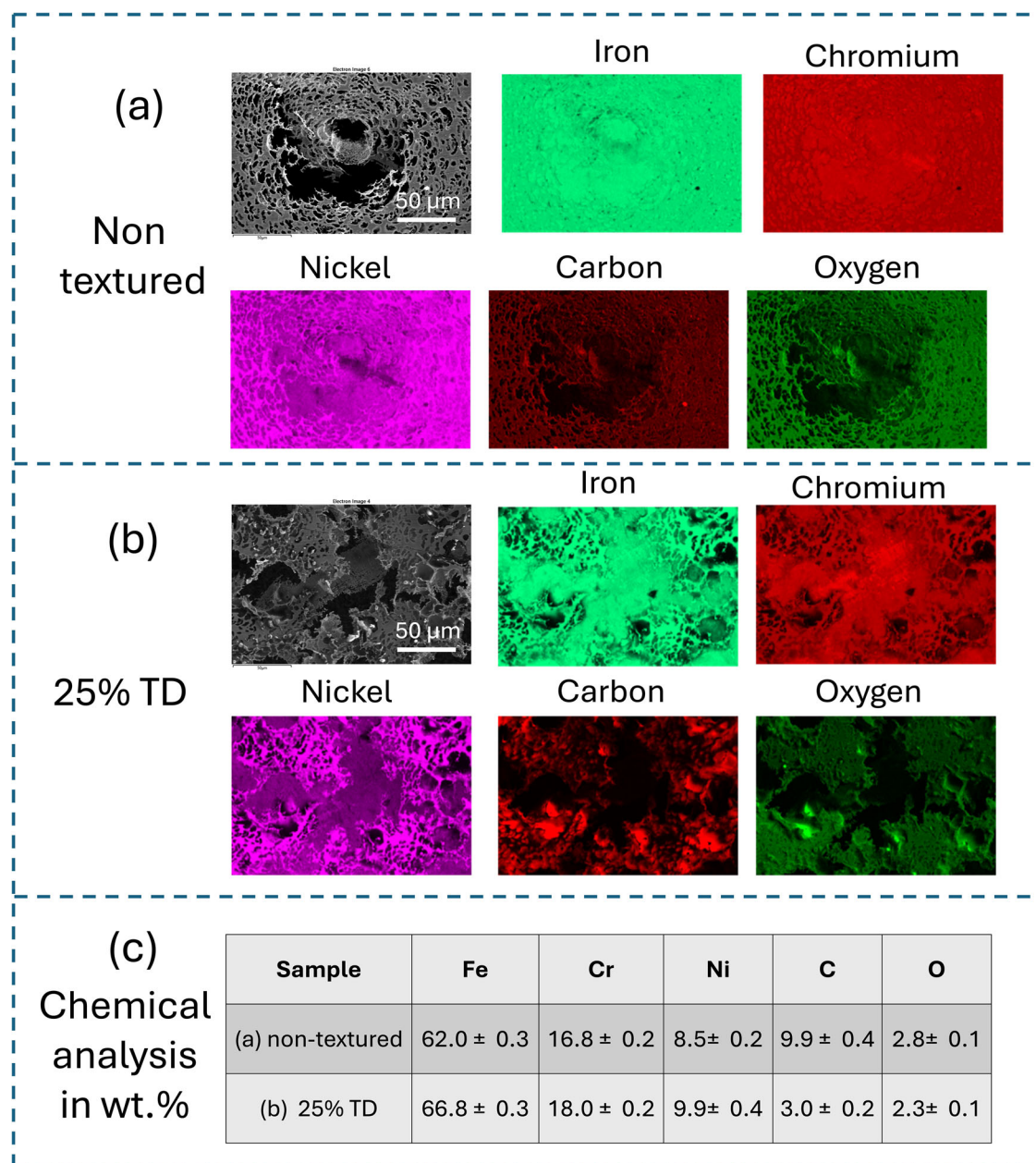
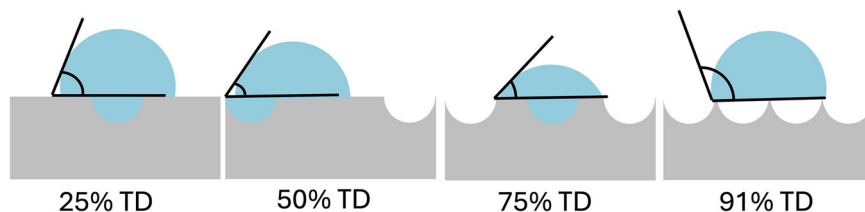


Fig. 10 | EDS analysis of corroded surfaces in 0.6 M NaCl after PPC. **a** Non-textured surface and **b** pitting on a dimple-patterned surface with 25% texture density, **c** chemical composition analysis in wt% of samples (a) and (b).

Fig. 11 | Contact angle vs. texture density. Schematic drawing of the liquid contact on dimple patterns according to texture density from 25% to 91% (a–d).



kind, with the exception of the dimple pattern with 91% texture density. This textured sample shows the lowest CPE_6 , indicating a thicker laser oxidised layer²⁷. This is observed for this dimple pattern as a result of the complete surface cover being oxidised by the laser. The low n_f and W of the dimple patterns are caused by the high relief of the dimple patterns (Fig. 12).

Increased surface roughness results in a decrease in the exponent ' n ' of the CPE. This reduction signifies a greater deviation from ideal capacitive behaviour, which is characteristic of smooth and uniform surfaces⁴¹. The relief increase associated with increasing TD raises the Warburg impedance and reduces the diffusion time.

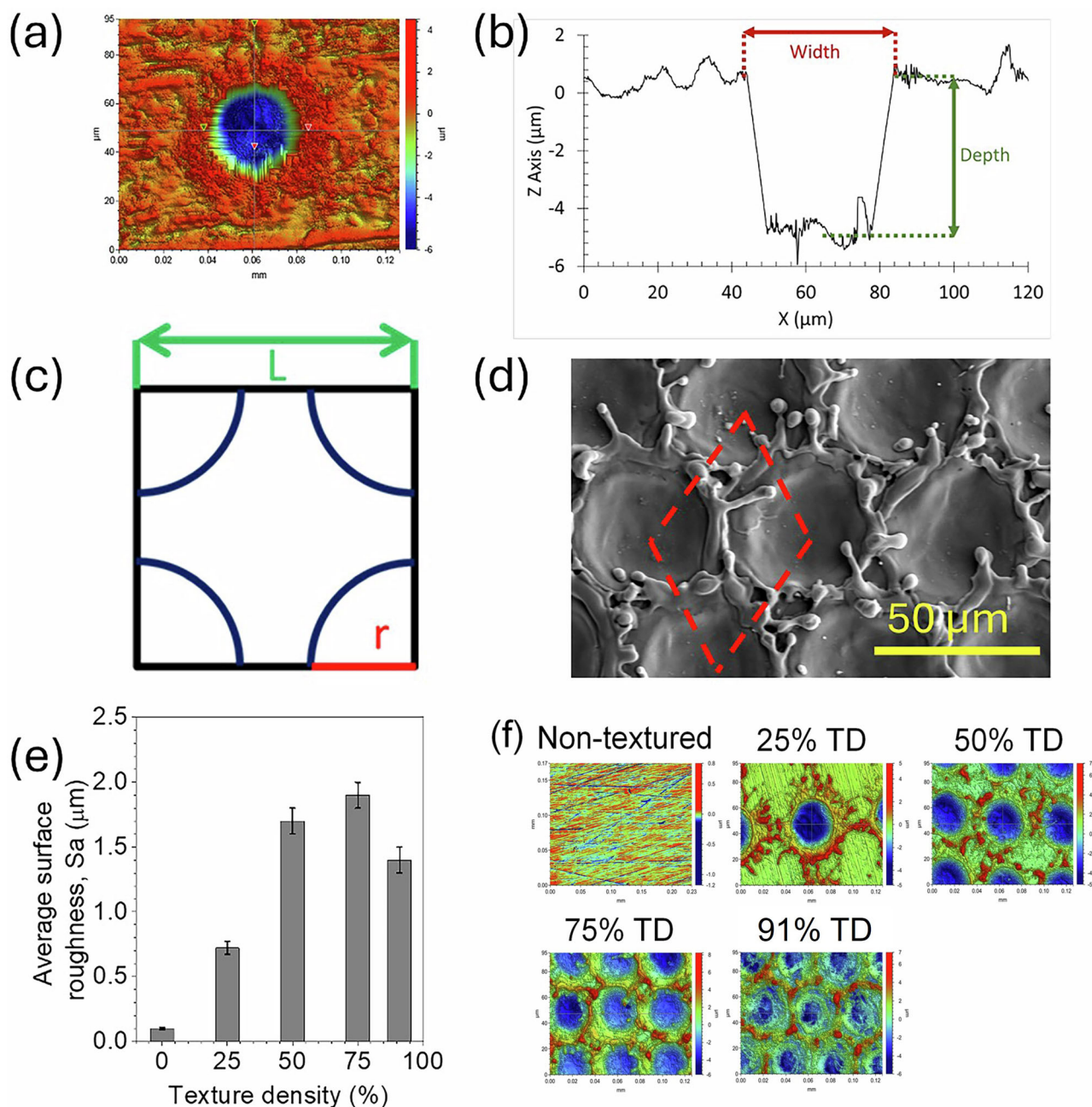


Fig. 12 | Topographical texture analysis. Optical profilometry images showing **a** the topography and **b** the profile of a single dimple created on 316L using a single laser pulse, with an aspect ratio of 0.1, a width of 36 μm , and a depth of 3.6 μm . **c** Schematic illustration of the method used to determine TD based on L and r for dimple

patterns. **d** SE-SEM image of the dimple pattern with 91% TD. Dashed box shows area used for TD calculation. **e** Average surface roughness and **f** corresponding topography image.

Table 5 | Summary of the corrosion resistance of the samples obtained using AEN, PPC and EIS. Notably, R_{ct} measured at 96 h of immersion

Sample	Electrochemical analysis		
	R_{AEN} ($\text{k}\Omega \text{ cm}^2$) (AEN)	R_p ($\text{k}\Omega \text{ cm}^2$) (PPC)	R_{ct} ($\text{k}\Omega \text{ cm}^2$) (EIS)
Non-textured	62	1253	2563
Dimple pattern at 25% TD	355	3648	300
Dimple pattern at 50% TD	169	4496	400
Dimple pattern at 75% TD	609	7066	1200
Dimple pattern at 91% TD	1369	7858	1100

Table 6 | 316 L chemical composition in weight percent (wt%)

Elements	Fe	C	Cr	Cu	Mn	Mo	Ni
wt%	Bal	0.025	16.200	0.120	1.660	2.057	10.070

Table 7 | Laser parameters for dimple generation with aspect ratio of 0.1

Parameter	Pulse rate frequency	Focused laser beam diameter	Pulse energy	Pulse length
Value	25 kHz	50.88 μm	402 μJ	200 ns

Table 8 | Selected inter-dimple distances for various texture densities

L (μm)	99.8	81.1	72.8	33.00
TD (%)	25	50	75	91

Table 9 | Details of the laser system

Parameter	Value
Type of laser	SPI laser G3 20 W
Wavelength	1064 nm
Focal length	100 mm
Beam quality	2.16
Atmosphere	Natural air
Distance to focal point	0 μm
Scanning mirror	Nutfield extreme-15-YAG
Three axes automatic table	Aerotech limited

The CPE_{dl} exhibited the lowest value for non-textured samples, while the dimple-patterned samples displayed comparable CPE_{dl} values. Although a lower CPE_{dl} value can sometimes suggest enhanced corrosion resistance, the observed low exponent value ($n_{\text{dl}} \approx 0.6$) counteracts this interpretation. This is because n_{dl} values in this range are indicative of relaxation processes⁴². Consequently, the decrease in CPE_{dl} is attributed to internal oxidation within the material, rather than an improvement in corrosion resistance.

An increase in TD resulted in enhanced R_{AEN} and R_p (Table 5), demonstrating the beneficial effect of LST on corrosion resistance. This improvement can be attributed to the larger surface area covered by the laser-melted material. While increased wettability typically leads to reduced corrosion resistance due to an enlarged contact area between water and the sample^{10,12,13,15}, potentially offsetting the benefits of LST, the observed increase in wettability did not correlate with a decrease in corrosion resistance. Although microstructural refinement can promote repassivation⁴⁹, the textured surface region exhibited a thermally oxidised layer that effectively isolates the refined microstructure from the corrosive environment. This oxide layer, formed by the reaction of the laser-melted material with atmospheric oxygen during LST, possesses high chemical inertness^{1,15,18}. Furthermore, the observed enrichment of nickel in the laser-textured regions contributes to improved corrosion resistance³⁴. Consequently, the increased coverage of the textured region resulted in an overall enhancement of corrosion resistance. The variation in charge R_{ct} with TD can be attributed to the system not having reached a stable electrochemical state during the measurements.

In conclusion, laser surface texturing effectively functionalised 316L, demonstrating a direct correlation between increased TD and enhanced surface free energy, with the exception of 91% density patterns due to continuous crest formation. This manipulation allows for tailored

wettability and oil-ability. Notably, dimple patterns significantly improved corrosion resistance, evidenced by increased nobility and decreased corrosion rates at higher TD, with 75% and 91% patterns exhibiting spontaneous passive film recovery. The corrosion mechanism transitioned from a solution resistance/passive film/bare material model for non-textured samples to a diffusion-controlled process in dimple patterns, with diffusion increasing with TD. While non-textured samples showed time-dependent degradation, dimple patterns maintained stable resistance. Critically, this study reveals that increased surface free energy does not compromise corrosion resistance, showcasing the potential of laser surface texturing to produce 316L surfaces with both high corrosion resilience and desired surface energy characteristics. This finding is particularly relevant for off-shore industries where robust materials are essential, such as in wind turbines, naval systems, and tidal power generation.

Methods

Laser surface texturing

316L rolled sheet were obtained from Columbus Stainless Ltd. with 20 mm $\times$ 20 mm and 0.8 mm thickness. The chemical composition of the 316L samples, is listed in Table 6. Before the laser texturing, samples were polished to achieve an average surface roughness of ~ 100 nm, which is considered optimal for LST³.

Dimples were the texturing unit used to create patterns on the sample surface. A single laser pulse with the parameters specified in Table 7 was employed to produce each dimple (Fig. 12). These parameters were chosen to generate dimples with an aspect ratio of 0.1 (depth/width), which is considered optimal for tribological applications under lubrication⁵⁰. The resulting dimples had an approximate width of 36 μm and a depth of 3.6 μm .

The samples were non-textured and textured where the dimple patterns (textured samples) had four different TDs, being 25%, 50%, 75% and 91%. TDs were set with the distance between dimple centres (L) and dimple radius (r) using Eq. (18)⁵¹. These TDs encompass the range commonly utilised in tribological applications. A schematic drawing of the calculation can be seen in Fig. 12c. The selected distance between dimples is summarised in Table 8.

$$\text{TD} = \frac{\pi r^2}{L^2} \times 100 \quad (18)$$

Note that the 91% TD was produced by texturing on a hexagonal pattern to achieve the highest TD, rather than the square pattern used for lower TDs (Fig. 12d).

The details of the laser equipment can be found in previous work (Table 9)³.

Before all electrochemical testing and analyses, the samples were cleaned firstly with commercial detergent and fresh water, then rinsed with distilled water, finally isopropanol spraying and drying using a warm air drier. The chemical products employed in the cleaning process were provided by RS Components (UK).

Surface free energy measurement

The polar and dispersive surface free energies of the samples were determined by measuring their contact angles with distilled water and diiodine methane using a goniometer (CAM 101 from KSV Instruments Ltd.). The volume of the drops used was 1.767 μl , the total measurement time was 3.200 s, and the frame number and time were 200 and 16 ms, respectively. The free surface energy of the water consisted of polar and dispersive components, measured 51.0 and 21.8 J/cm², respectively. The diiodine methane, in contrast, exhibited only a dispersive component that was 50.8 J/cm²²⁰. The contact angles of the samples were measured one month after the LST, as they remain constant over time beyond this period⁵².

Electrochemical testing

Electrochemical testing were conducted using a potentio/galvanostat device (Interface1010E), controlled by Gamry Framework software, and with data analysis performed using Gamry Echem Analyst software. The trials were carried out with three-electrodes cells formed of a 3 M KCl silver/silver chloride (3 M KCl Ag/AgCl) as reference electrode and a platinum wire, diameter 0.7 mm, counter electrode. The working electrodes were the samples. All corrosion experiments were conducted in 0.6 M (3.5% in weight) NaCl, naturally aerated, at room temperature. The exposed area was defined using an adhesive tape containing a hole, and epoxy resin, to shield any crevices.

The EN (non-perturbative test) was conducted with the OCP and ZRA tests carried out at the same time. EN was called as AEN owing to the electrochemical cell consisting of reference, counter and working electrodes³⁰. The output signals were measured for 2 h with 0.05 s acquisition time.

PPC (Potentiodynamic polarisation curves) (perturbative technique of direct current) was conducted with the following specific conditions. The initial potential and potential scan rate were at the open circuit potential of -0.3 V and 0.167 mV s⁻¹, respectively. The current density was limited to 10 mA cm⁻², and the reversal potential was set to 3 V vs. 3 M KCl Ag/AgCl potential. The final potential was the same as the initial potential. The open circuit potential was determined after two hours of immersion.

EIS (perturbative testing of alternating current) was set at 10 mV root mean square (RMS) of potential amplitude, frequency range from 10^{-2} to 10^5 Hz and 10 points per frequency decade. EIS trials were conducted at 2, 24, 48, 72 and 96 h of immersion in 0.6 M NaCl to assess the corrosion mechanism evolution over time. The equivalent circuit of the EIS data were obtained through Gamry Echem Analyst software to analyse the corrosion mechanism.

To ensure the consistency of results, all electrochemical experiments were conducted at least three times. This data are collected in the supplementary document, being Supplementary Figs. 1–10 for EAN results, Supplementary Figs. 11–15 for PPC testing, and Supplementary Figs. 16–40 for EIS.

Microstructural characterisation

The topographies of the non-corroded samples were assessed with optical light profilometer (Bruker, ContourGT optical profiler) using green light and $\times 2.5$ magnification. High-resolution imaging and chemical mapping were performed using an FEI Versa SEM equipped with EDS and FIB for elemental analysis and cross-section, respectively. SEM micrographs were captured using SE and BSE detectors to distinguish topographical and microstructural features. Imaging was conducted at an accelerating voltage of 20 kV and a current of 16 nA.

Data availability

Data is provided within the manuscript or supplementary information files.

Received: 28 November 2024; Accepted: 3 June 2025;

Published online: 24 September 2025

References

- Dashtbozorg, B. et al. A study on the effect of ultrashort pulsed laser texturing on the microstructure and properties of metastable S phase layer formed on AISI 316L surfaces. *Appl. Surf. Sci.* **511**, 145557 (2020).
- Kedia, S. et al. Nanosecond laser surface texturing of type 316L stainless steel for contact guidance of bone cells and superior corrosion resistance. *Colloid Interface Sci. Commun.* **42**, 100419 (2021).
- Al-Mahdy, A. et al. Effect of surface roughness on the surface texturing of 316 L stainless steel by nanosecond pulsed laser. *Lasers Manuf. Mater. Process.* **10**, 141–164 (2023).
- Gil, L. et al. Corrosion performance of the plasma nitrided 316L stainless steel. *Surf. Coat. Technol.* **201**, 4424–4429 (2006).
- Azzi, M., Paquette, M., Szpunar, J., Klemberg-Sapieha, J. & Martinu, L. Tribocorrosion behaviour of DLC-coated 316L stainless steel. *Wear* **267**, 860–866 (2009).
- Henry, P., Takadom, J. & Berçot, P. Tribocorrosion of 316L stainless steel and TA₆V₄ alloy in H₂SO₄ media. *Corros. Sci.* **51**, 1308–1314 (2009).
- Sun, Y. & Haruman, E. Tribocorrosion behaviour of low temperature plasma carburised 316L stainless steel in 0.5 M NaCl solution. *Corros. Sci.* **53**, 4131–4140 (2011).
- Etsion, I. State of the art in laser surface texturing. *J. Trib.* **127**, 248–253 (2005).
- Singh, A., Patel, D. S., Ramkumar, J. & Balani, K. Single step laser surface texturing for enhancing contact angle and tribological properties. *Int. J. Adv. Manuf. Technol.* **100**, 1253–1267 (2019).
- Singh, A. et al. Surface micro-structuring of type 304 stainless steel by femtosecond pulsed laser: effect on surface wettability and corrosion resistance. *Appl. Phys. A* **124**, 1–9 (2018).
- Zhang, L. et al. Super-hydrophobicity and corrosion resistance of laser surface textured AISI 304 stainless steel decorated with hexadecyltrimethoxysilane (HDTMS). *Opt. Laser Technol.* **127**, 106146 (2020).
- Lu, Y. et al. Nanosecond laser fabrication of superhydrophobic surface on 316L stainless steel and corrosion protection application. *Colloids Surf. A: Physicochem. Eng. Asp.* **604**, 125259 (2020).
- Trdan, U., Hočevár, M. & Gregorčič, P. Transition from superhydrophilic to superhydrophobic state of laser textured stainless steel surface and its effect on corrosion resistance. *Corros. Sci.* **123**, 21–26 (2017).
- Yue, T. M., Yu, J. & Man, H. C. The effect of excimer laser surface treatment on pitting corrosion resistance of 316LS stainless steel. *Surf. Coat. Technol.* **137**, 65–71 (2001).
- Lou, D. et al. The effect of dimple overlap on wettability and corrosion resistance of laser-textured stainless steel. *Crystals* **12**, 695 (2022).
- Kasman, Ş., Uçar, I. & Ozan, S. The effects of laser surface texturing parameters on the surface characteristics of biomedical-grade stainless steel. *J. Mater. Eng. Perform.* **33**, 1–14 (2023).
- Wang, Y. et al. Evolution of nanosecond laser-induced phase explosion based on a high-speed continuous imaging system. *Results Phys.* **29**, 104782 (2021).
- Gupta, R. K. et al. Corrosion study on laser shock peened 316L stainless steel in simulated body fluid and chloride medium. *Lasers Manuf. Mater. Process.* **5**, 270–282 (2018).
- Palencia, M. Surface free energy of solids by contact angle measurements. *J. Sci. Technol. Appl.* **2**, 84 (2017).
- Matykina, E., García, I., De Damborenea, J. & Arenas, M. Comparative determination of TiO₂ surface free energies for adhesive bonding application. *Int. J. Adhes. Adhes.* **31**, 832–839 (2011).
- Nanbu, T., Ren, N., Yasuda, Y., Zhu, D. & Wang, Q. J. Micro-textures in concentrated conformal-contact lubrication: effects of texture bottom shape and surface relative motion. *Tribology Lett.* **29**, 241–252 (2008).
- Ahuir-Torres, J. I., Sharp, M. & Seddighi, M. Influence of the surface roughness and pulse energy in the production of dimple features on Cr₂O₃ surfaces. *Procedia CIRP* **94**, 930–935 (2020).
- Li, Y., Wang, X. & Zhang, G. Corrosion behaviour of 13Cr stainless steel under stress and crevice in 3.5 wt% NaCl solution. *Corros. Sci.* **163**, 108290 (2020).
- Wharton, J. & Wood, R. Influence of flow conditions on the corrosion of AISI 304L stainless steel. *Wear* **256**, 525–536 (2004).
- Zhang, Z. et al. Electrochemical noise comparative study of pitting corrosion of 316L stainless steel fabricated by selective laser melting and wrought. *J. Electroanal. Chem.* **894**, 115351 (2021).

26. Rafieezad, M., Jaffer, J. A., Cui, C., Duan, X. & Nasiri, A. Nanosecond laser fabrication of hydrophobic stainless steel surfaces: the impact on microstructure and corrosion resistance. *Materials* **11**, 1577 (2018).
27. Kakaei, K., Esrafil, M. D. & Ehsani, A. Graphene and anticorrosive properties. In *Interface Science and Technology*, Vol. 27 (ed. Hubbard, A.) 303–337 (Elsevier, 2019).
28. Avstenitnih, P. K. L. Comparison of the corrosion behaviour of austenitic stainless steel in seawater and in a 3.5% NaCl solution. *Mater. Technol.* **48**, 937–942 (2014).
29. Mansfeld, F., Sun, Z. & Hsu, C. Electrochemical noise analysis (ENA) for active and passive systems in chloride media. *Electrochim. Acta* **46**, 3651–3664 (2001).
30. Xia, D.-H. et al. electrochemical noise applied in corrosion science: theoretical and mathematical models towards quantitative analysis. *J. Electrochem. Soc.* **167**, 081507 (2020).
31. Chandrasatheesh, C., Jayapriya, J., George, R. & Mudali, U. K. Detection and analysis of microbiologically influenced corrosion of 316L stainless steel with electrochemical noise technique. *Eng. Fail. Anal.* **42**, 133–142 (2014).
32. García-Ochoa, E. et al. Application of electrochemical noise to evaluate outdoor atmospheric corrosion of copper after relatively short exposure periods. *J. Appl. Electrochem.* **38**, 1363–1368 (2008).
33. Esmailzadeh, S., Aliofkhaezai, M. & Sarlak, H. Interpretation of cyclic potentiodynamic polarization test results for study of corrosion behavior of metals: a review. *Prot. Met. Phys. Chem. Surf.* **54**, 976–989 (2018).
34. Ni, X. et al. Corrosion behavior of 316L stainless steel fabricated by selective laser melting under different scanning speeds. *J. Mater. Eng. Perform.* **27**, 3667–3677 (2018).
35. Hara, N., Hirabayashi, K., Sugawara, Y. & Muto, I. Improvement of pitting corrosion resistance of type 316L stainless steel by potentiostatic removal of surface MnS inclusions. *Int. J. Corros.* **2012**, 1–6 (2012).
36. Cai, B. et al. An experimental study of crevice corrosion behaviour of 316L stainless steel in artificial seawater. *Corros. Sci.* **52**, 3235–3242 (2010).
37. Zhang, X., Jiang, Z. H., Yao, Z. P., Song, Y. & Wu, Z. D. Effects of scan rate on the potentiodynamic polarization curve obtained to determine the Tafel slopes and corrosion current density. *Corros. Sci.* **51**, 581–587 (2009).
38. Singh, P., Dixit, K. & Sinha, N. A sol–gel based bioactive glass coating on laser textured 316L stainless steel substrate for enhanced biocompatibility and anti-corrosion properties. *Ceram. Int.* **48**, 18704–18715 (2022).
39. Hoseinie, S., Hornborg, A., Shahrabi, T., Mol, J. & Ramezanzadeh, B. A novel approach for the evaluation of under deposit corrosion in marine environments using combined analysis by electrochemical impedance spectroscopy and electrochemical noise. *Electrochim. Acta* **217**, 226–241 (2016).
40. Macdonald, D. D. Reflections on the history of electrochemical impedance spectroscopy. *Electrochim. Acta* **51**, 1376–1388 (2006).
41. Xu, F. -I., Duan, J. -Z., Lin, C. -G. & Hou, B. -R. Influence of marine aerobic biofilms on corrosion of 316L stainless steel. *J. Iron Steel Res. Int.* **22**, 715–720 (2015).
42. Jimenez-Morales, A., Galvan, J., Rodriguez, R. & De Damborenea, J. Electrochemical study of the corrosion behaviour of copper surfaces modified by nitrogen ion implantation. *J. Appl. Electrochem.* **27**, 550–557 (1997).
43. Nguyen, T. Q. & Breitkopf, C. Determination of diffusion coefficients using impedance spectroscopy data. *J. Electrochem. Soc.* **165**, E826–E831 (2018).
44. Sobral, A. V., Ristow, W. Jr., Azambuja, D. S., Costa, I. & Franco, C. V. Potentiodynamic tests and electrochemical impedance spectroscopy of injection molded 316L steel in NaCl solution. *Corros. Sci.* **43**, 1019–1030 (2001).
45. Liu, M., Zeng, Y. & Luo, J. -L. Roles of major alloying elements in steels and alloys on corrosion under biomass hydrothermal liquefaction (HTL) conversion. *Corros. Sci.* **218**, 111148 (2023).
46. Cai, Y. et al. Superhydrophobic structures on 316L stainless steel surfaces machined by nanosecond pulsed laser. *Precis. Eng.* **52**, 266–275 (2018).
47. Cottis, R. Interpretation of electrochemical noise data. *Corrosion* **57**, 265–285 (2001).
48. Kant, R. & Singh, M. B. Generalization of Randles–Ershler admittance for an arbitrary topography electrode: application to random finite fractal roughness. *Electrochim. Acta* **163**, 310–322 (2015).
49. Ura-Bińczyk, E. Effect of grain refinement on the corrosion resistance of 316L stainless steel. *Materials* **14**, 7517 (2021).
50. Ronen, A., Etsion, I. & Kligerman, Y. Friction-reducing surface-texturing in reciprocating automotive components. *Tribol. Trans.* **44**, 359–366 (2001).
51. Ahuir-Torres, J. I., Arenas, M., Perrie, W., Dearden, G. & De Damborenea, J. Surface texturing of aluminium alloy AA2024-T3 by picosecond laser: effect on wettability and corrosion properties. *Surf. Coat. Technol.* **321**, 279–291 (2017).
52. Liu, Z., Niu, T., Lei, Y. & Luo, Y. Metal surface wettability modification by nanosecond laser surface texturing: a review. *Biosurf. Biotribol.* **8**, 95–120 (2022).

Acknowledgements

The authors gratefully acknowledge the use of the research facilities at Liverpool John Moores University (LJMU) for their support in this work.

Author contributions

All authors contributed to the study conception and design. Data collection of the surface free energy (Fig. 2) and optical profilometry analyses (Fig. 10a and b) were carried out by A.A. The analysis and discussion of the results were developed by J.I.A.-T. H.R.K. conducted the scanning electron microscopy (Figs. 1, 7 and 10d) and energy dispersive spectroscopy analyses (Fig. 8). J.I.A.-T. produced the laser surface texturing samples and evaluated the corrosion resistance of specimens with electrochemical testing (Figs. 3–6). H.R.K. conducted the microstructural analysis. H.R.K. and M.B. secured resources for this research. The first draft of the manuscript was written by J.I.A.-T. and all authors (J.I.A.-T., A.A., M.C.S., T.T.O., G.Z., M.B., and H.R.K.) commented on, and developed, subsequent versions of the manuscript. All authors have read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41529-025-00622-6>.

Correspondence and requests for materials should be addressed to J. I. Ahuir-Torres, M. Bashir or H. R. Kotadia.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2025