Transition from superhydrophilic to superhydrophobic state of laser textured stainless steel surface and its effect on corrosion resistance

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\begin{abstract}
This work investigates the evolution from superhydrophilic to superhydrophobic surface state on corrosion behaviour of SS316L produced by Nd:YAG nanosecond direct laser texturing (DLT). Results confirm perfect correlation among wettability and corrosion, hence superhydrophobic surface with a contact angle of 168 ± 3.0° reflects in enhanced passivity, lower anodic dissolution and corrosion current reduction. Characterization of the corrosion attack by 3D microscopy reveals high sensitivity of superhydrophilic surfaces on corrosion propagation direction in regard to the laser beam passage (90°/0°). However, this trend completely diminishes with superhydrophobic development. Further, DLT also completely prohibits intergranular corrosion detected with the non-processed sample.
\end{abstract}

1. Introduction

Recently, intensive research efforts have been devoted to synthesize lotus-like, superhydrophobic, surfaces with water contact angle in excess of 150° and sliding angle below 5° \cite{1,2}. Such functionalized surfaces possess several unique beneficial properties, i.e. extreme water repellency \cite{3,4}, self-healing \cite{5}, self-cleaning \cite{6}, reduced drag in laminar and turbulent flows \cite{7,8}, enhanced heat transfer \cite{9,10} and improved corrosion resistance \cite{11–17}.

Artificial super-hydrophobic surfaces have been successfully fabricated via various chemical methods, such as plasma and chemical etching, anodic oxidation, chemical vapor deposition, sol-gel method, etc. \cite{11,15,16,18}. Nonetheless, in recent years laser surface texturing has emerged as a novel, versatile, clean and low waste nanotechnology for producing multi-modal surfaces with micro/nano structure due to laser ablation and melting \cite{2,5,7,19}. Emelyanenko et al. \cite{5} fabricated a superhydrophobic surface on 321H AISI stainless steel. Their results have confirmed extreme water repellency with excellent functional durability under prolonged abrasive wear and cavitation loads. Ta et al. \cite{20} demonstrated that superhydrophobic surfaces on SS304 with steady contact angle of 154° and contact angle hysteresis of 4° can be fabricated via direct laser texturing (DLT) with cost-effective, compact nanosecond fiber laser system. Further, it has been shown \cite{3,14} that nanosecond laser texturing of various Al alloys can greatly improve resistance to localized corrosion attack in a sodium chloride solution due to multimodal roughness with μ-cavities consisting of air entrapment hence preventing penetration of corrosive species at solution/metal interface.

However, despite considerable progress in this area, little attention has been paid to investigate transition from superhydrophilic to superhydrophobic effect on corrosion behaviour of laser textured stainless steel surface along with the influence of laser passage direction (90°/0°). Hence, the aim of this work is to study how the evolution of hydrophobicity, i.e. water repellency of direct laser textured (DLT) SS316L influences corrosion behaviour in an aggressive 0.6 M NaCl solution. Specific attention was focused on the collateral influence of bimodal surface topography to the initiation and propagation of corrosion.

2. Material and methods

2.1. Laser texturing

We textured surfaces of AISI 316L stainless steel samples with the following chemical composition (in wt.%): Cr 16.9, Ni 10.04, Mo 2.07, Mn 1.84, Si 0.57, Cu 0.41, P 0.036, C 0.019, S 0.0009, V 0.077, Nb 0.015, N 0.044, and Fe the rest. Commercial 1 mm thick sheet of AISI 316L alloy was cut in samples with diameter of 15 mm and textured by using a marking nanosecond Nd:YAG pulsed laser (LPKF, OK DP10) with a wavelength of 1064 nm, pulse duration of 40 ns (FWHM), pulse frequency of 25 kHz, and pulse energy of 0.22 mJ. A scanning head (Scanlab SCANgine 14) with an F-Theta focusing lens was used for...
The distance between adjacent laser scanning lines (90°) and then in the diameter of 0.03 mm and a constant speed of 150 mm/s, delivery of a focused laser beam over the sample surface with beam spot 2.2. Surface morphology and wettability measurements

Surface morphology of untreated and laser textured samples prior to rinsed by ethanol.

Surface morphology of untreated and laser textured samples prior to ultrasonically cleaned in distilled water for 12 min and rinsed by ethanol.

Fig. 1. SEM micrographs of laser textured surfaces.

delivery of a focused laser beam over the sample surface with beam spot diameter of 0.03 mm and a constant speed of 150 mm/s, first in the y (90°) and then in the x (0°) direction (e.g., see dashed lines in Fig. 1a). The distance between adjacent laser scanning lines – the so-called scan line separation – equalled 50 μm in both directions. Before processing, all samples were ultrasonically cleaned in distilled water for 12 min and rinsed by ethanol.

The transition from superhydrophilic to superhydrophobic state and its influence on corrosion behaviour was studied by using 4 samples (DLT#1-4), textured by same laser parameters, but exposed to ambient conditions (T = 25 °C, RH = 35%) for different time periods after laser texturing, i.e. 30 min (DLT#1), 24 h (DLT#2), 11 days (DLT#3) and 1 month (DLT#4), respectively. Before the transfer of samples to the electrolytic cell for corrosion experiments the contact angle measurements were performed and after that the samples were ultrasonically degreased in ethanol and rinsed in deionised water for 3 min each.

2.3. Electrochemical measurements

Electrochemical measurements were carried out with a PAR 263A potentiostat/galvanostat using a three-electrode component corrosion cell under static conditions. A saturated calomel electrode was used as a reference, graphite rod as a counter electrode along with the sample embedded in a Teflon PAR holder as the working electrode (1 cm²).

Test medium was a naturally aerated (pH = 6.8 ± 0.2; T = 23 ± 1 °C) 0.6 M NaCl solution prepared with deionised water. Corrosion was tested using linear polarization resistance (LPR) and cyclic polarization (CP) electrochemical techniques. Before LPR and CP experiments open circuit potential measurements (Ecorr = f(t)) was performed for 60 min in order to stabilize the surface, whereas corrosion potential Ecorr, was determined at the end of the stabilization process. LPR measurements were performed in the potential range ± 10 mV relative to Ecorr using 0.1 mV/s potential scan rate. CP scans were performed with a scan rate of 1 mV/s, started at −250 mV vs. Ecorr, and increased in anodic direction up to 600 mVcorr. Afterwards, the polarization direction was reversed and progressed in cathodic direction to the starting potential. All electrochemical corrosion techniques were pre-tested to ensure the repeatability of the experiments.

3. Results and discussion

3.1. The effect of laser texturing on surface morphology

Surface morphology of DLT sample (Fig. 1) clearly indicates the structuring effect due to laser irradiation. As shown in Fig. 1a multidirectional structure due to different laser scanning directions (90°/0°) is well pronounced. The μ-nets have 50 μm spacing corresponding to the scan line separation. The oriented structure along the second (last) laser texturing passage (Fig. 1b) indicates its primary solidification path (from left to right and vice versa) of the ablated/molten material. Further, SEM image at higher magnification (Fig. 1c) reveals multimodal oriented structures as a consequence of constant melting, ablation and deposition of the recast material during laser texturing.

In order to evaluate the influence of DLT on the surface topography and roughness in both the vertical (y) and horizontal (x) directions of laser-beam scan an optical 3D microscope was used. Fig. 2 shows the 3D topography of laser textured surface, where the distinctive influence of the second laser texturing path can be observed. Further, μ-channels are completely opened and parallel to the last laser scanning direction and closed to the opposite direction (first laser scanning direction).

The roughness parameters obtained along valleys (x1, y1) and crests (x2, y2) of the specific direction in regards to the first (e.g., see y1 and y2 lines in Fig. 2) and second (e.g., see x1 and x2 lines in Fig. 2) scan lines path are listed in Table 1. As can be seen from the results, roughness values parallel to the first
laser beam passage reflects in much higher values compared to those obtained in parallel to the second scanning direction. For example, the roughness \( R \) achieved the minimum value of 2.15 ± 0.13 \( \mu \)m along valleys of the \( \mu \)-channels (\( x_1 \)) produced during the second texturing path, whereas in the opposite direction (\( y_1 \)) it equals 3.20 ± 0.04 \( \mu \)m due to the metal ejection at the edges produced during the second DLT path. Similar trend was also obtained along crests, but with higher values of all roughness parameters in the first, i.e., \( y \) direction of laser passage path through the treated surface. Nonetheless, 5 separated measurements of 3D amplitude parameter on different DLT samples have confirmed good surface uniformity with an average \( S \) value of 4.62 ± 0.15 \( \mu \)m. For comparison, the non-processed sample achieved around 26 times lower \( S \) roughness with a value of 0.175 ± 0.02 \( \mu \)m.

3.2. Surface wettability development

The corrosion resistance of metals depends on several parameters, such as homogeneity and stability of the passive film, microstructural properties as well as surface roughness and wettability. Although, intrinsic wetting properties, namely, improves wetting for hydrophilic surfaces and increases the contact angle for hydrophobic ones, the influence of roughness on sensitivity to localized corrosion attack is very complex and sometimes for rough hydrophobic materials this sensitivity might be higher than for smooth surface [11,14]. To examine the isolated influence of wettability on corrosion behaviour we used the inherent property of laser textured metal surface, where a transition from hydrophilic to hydrophobic state appears if such a surface is exposed to the air at room conditions [11,12,21]. During this process the surface roughness on microscale stays the same.

The contact angle of non-processed and non-polished surface (as received sample, just ultrasonically cleaned in distilled water and rinsed by ethanol) equals 95.0 ± 6.4°, while the Young angle of the base material, measured on highly polished surface (\( R_s = 25 \pm 2 \) nm) as suggested in ref. [22,23] equals \( \theta_y = 81.6 \pm 5.7° \). Immediately after laser texturing the surface experiences a super-hydrophilic state with a contact angle \( \theta = 0° \), i.e., the water forms a thin film covering the whole sample. At this time the surface is in a saturated state [24] of a Wenzel regime [25], where the roughness gains the wettability of a base material. The hydrophilic behaviour immediately after texturing is additionally increased also due to metal oxides appearing on the surface. When the textured surface is exposed to air at ambient conditions, the hydrophobicity is developed [11,12]. In our case, the contact angle increased to \( \theta = 109 ± 6.7° \) in 11 days, while the superhydrophobic state in a Cassie-Baxter regime [26] with \( \theta = 168 ± 3.0° \) and sliding angle below 3° was achieved in 1 month. After superhydrophobicity was developed, the contact angle appeared stable by time.

Several mechanisms contributing to this transition in ambient air over time have been proposed by different authors, i.e. decomposition of carbon dioxide into carbon with active magnetite [21], airborne hydrocarbon contamination and the absorption of organic matters from the atmosphere [27,28], partial surface deoxidation [29] and the creation of hydrophobic functional groups [30]. However, it should be noted that the mechanisms responsible for hydrophilic-to-hydrophobic transition after DLT is still under debate [27] and there is still not fully accepted theory to explain this behaviour.

Nevertheless, our results, i.e., the achieved contact angles of superhydrophobic surface and the time period needed for development of stable superhydrophobicity, are very similar to the results obtained by other authors, who used nanosecond lasers without any additional surface treatment [31,32]. We, therefore, studied how this – experimentally observed – transition influences the corrosion behaviour.

3.3. Linear polarization resistance (LPR) measurements

LPR measurements were performed after one hour’s immersion at open circuit in the potential range ± 10 mV relative to \( E_{corr} \), using 0.1 mV/s scan rate. The corresponding values of polarization resistance \( R_p \), determined from the slope of \( E \)-\( i \) curves \( [R_p = (dE/di)] \), are given in Table 2.

The lowest \( R_p \) value in a 0.6 M NaCl solution was confirmed for the superhydrophilic samples DLT#1 & DLT#2, which achieved a value of 2.34 ± 0.15 kΩ cm² and 13.37 ± 0.86 kΩ cm², respectively. Both of

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sample/Condition</th>
<th>DLT#1 (after 30 min)</th>
<th>DLT#2 (after 1 day)</th>
<th>DLT#3 (after 11 days)</th>
<th>DLT#4 (after 1 month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta ) [°]</td>
<td>95 ± 6.4</td>
<td>0 (saturated)</td>
<td>109 ± 6.7</td>
<td>168 ± 3.0</td>
<td></td>
</tr>
<tr>
<td>( R_p ) [kΩ cm²]</td>
<td>67.57 ± 5.25</td>
<td>2.34 ± 0.15</td>
<td>13.37 ± 0.86</td>
<td>80.04 ± 4.70</td>
<td>94.24 ± 4.16</td>
</tr>
<tr>
<td>( E_{corr} ) [mV/dec]</td>
<td>-175 ± 8</td>
<td>-321 ± 12</td>
<td>-212 ± 18</td>
<td>16 ± 14</td>
<td>-162 ± 9</td>
</tr>
<tr>
<td>( i_{corr} ) [µA/cm²]</td>
<td>18 ± 9</td>
<td>-66 ± 5</td>
<td>-51 ± 7</td>
<td>-4 ± 3</td>
<td>219 ± 11</td>
</tr>
<tr>
<td>( R_p ) [mV/dec]</td>
<td>-195 ± 4</td>
<td>-316 ± 3</td>
<td>-214 ± 6</td>
<td>-159 ± 4</td>
<td>-197 ± 7</td>
</tr>
<tr>
<td>( i_{corr} ) [µA/cm²]</td>
<td>330 ± 29</td>
<td>178 ± 15</td>
<td>79 ± 11</td>
<td>269 ± 11</td>
<td>81 ± 9</td>
</tr>
</tbody>
</table>

![Table 2](https://example.com/table2.png)

Table 2 Characteristic results derived from contact angle measurements and electrochemical measurements of non-processed and DLT processed samples exposed to ambient conditions for different time periods: \( R_p \), \( E_{corr} \), \( R_p \), and \( i_{corr} \) from CP curves.
3.4. Cyclic polarization (CP) measurements

CP curves of non-processed SS316L and DLT samples are shown in Fig. 3a and b. All CP curves show typical active/passive behaviour in the forward (anodic) scan. Afterwards, a sharp increase in anodic current due to a stable pit growth or pit propagation at pitting potential \( E_{\text{pit}} \) is observed with a well-defined hysteresis in the reverse, i.e. cathodic scan. Further, no distinct primary passivation potential was determined with extrapolation to the potential at which the current abruptly increases in the forward anodic scan. On the other hand, the repassivation/ protection potential \( E_{\text{pass}} \) was obtained along the valleys of these channels (see Fig. 2 and Table 1). This phenomenon can be explained by an opened micro-channel along the last laser scanning direction and barriers in the perpendicular direction (see Fig. 2). However, the development of superhydrophobic state with entrapped air acts as an effective corrosion resistant coating thus making the penetration of water molecules and halide (Cl\(^{-}\)) ions adsorption to the surface more difficult [34].

The various characteristic potentials such as \( E_{\text{corr}}, E_{\text{pass}}, \) and \( E_{\text{fp}} \) obtained from the CP curves in a 0.6 M NaCl solution are presented in Table 2. The pitting potential \( E_{\text{pit}} \), at which a protective passive film is damaged as a result of pit initiation followed by pit propagation, was determined with extrapolation to the potential at which the current abruptly increases in the forward anodic scan. On the other hand, the repassivation/ protection potential \( E_{\text{pass}} \) where pits or crevices repassivate, was determined as the potential at which the curve in reverse scan intersects the curve in forward scan [34]. The current density \( i_{\text{corr}} \), in \( \mu A/cm^2 \) was calculated according to the Stern–Geary equation:

\[
i_{\text{corr}} = \frac{\beta_{a} \beta_{c}}{2.303R_{\beta}(\beta_{a} - \beta_{c})}
\]

where \( R_{\beta} \) is polarization resistance (determined from the LPR test) and \( \beta_{a} \) and \( \beta_{c} \) are the anodic and cathodic Tafel constants (in mV/dec) determined by the Tafel extrapolation method.

Experimental results presented in Fig. 3 and Table 2 confirms the tremendous effect of the surface state of direct laser textured 316L stainless steel on corrosion behaviour. From the CP scans it is clearly understood that DLT in the superhydrophilic state has inferior corrosion resistance, compared with the base material. On the contrary, laser processed samples with developed hydrophobic/superhydrophobic state indicate superior corrosion resistance compared to the non-processed sample. A distinctive shift of the pitting potential can be noticed with the DLT#4 superhydrophobic sample (\( \theta = 168 \pm 3.0^\circ \)), which was exposed to the ambient condition for 1 month. Here, \( E_{\text{pit}} \) is located at 219 ± 11 mV_SCE, which is 201 mV more positive than with the non-processed 316L stainless steel sample, suggesting that pitting corrosion is unlikely to occur. Further, the analysis of characteristic potentials obtained from the CP curves shows that among all the samples, the DLT#4 exhibits the highest passivity \( (E_{\text{pit}} - E_{\text{corr}}) \) with lowest anodic dissolution in the transpassive region. Moreover, the calculated values of \( i_{\text{corr}} \) confirm good accordance with the LPR measurements, indicating importance of transition from superhydrophilic to superhydrophobic state on the corrosion behaviour. Thus, \( i_{\text{corr}} \) values indicate the following order of the corrosion resistance: DLT#1 (18.61 ± 2.26 \( \mu A/cm^2 \)) < DLT#2 (2.53 ± 0.32 \( \mu A/cm^2 \)) < non-processed 316L (0.72 ± 0.07 \( \mu A/cm^2 \)) < DLT#3 (0.33 ± 0.02 \( \mu A/cm^2 \)) < DLT#4 (0.29 ± 0.03 \( \mu A/cm^2 \)).

3.5. Influence of wettability development on corrosion propagation

3D surface morphology after CP corrosion tests with the insert of wettability evolution (the contact angle measurement) are shown in Fig. 4. The corrosion without any preferred direction is developed on non-processed surface (Fig. 4a). Contrarily, the 3D measurement of corroded hydrophilic surface (Fig. 4b) clearly reveals high dependence of the corrosion attack propagating inside \( \mu \)-channels produced during the last laser beam passage, despite the fact that the lowest roughness was obtained along the valleys of these channels (see Fig. 2 and Table 1). This phenomenon can be explained by an opened \( \mu \)-channel along the last laser scanning direction and barriers in the perpendicular direction (see Fig. 2). However, the development of superhydrophobicity reduces the preferred direction of corrosion propagation, as clearly visible from Fig. 4c–d. With superhydrophobic state developed, this effect is completely eradicated, since in this case the \( \mu \)-channel along the last laser scanning direction does not act anymore as a channel for microfluidic. Instead, the developed superhydrophobicity increases a trapping air and reduces the fractional area of liquid–solid interface, as suggested by the Cassie-Baxter’s model [26]. Another possible effect contributing to improved corrosion resistance is a grain refinement of the top surface layer due sequential cycles of melting/rapid cooling and quenching during DLT [17,35]. Gupta et al. [36] reported significantly improved pitting and oxidation resistance due to greater Cr diffusion and ease of formation of compact Cr-oxide layer resistance of nanocrystalline surface compared to the conventional coarse grained 316L SS surface. Such hierarchical super-hydrophobic structure with entrapped air acts as an effective corrosion resistant coating thus making the penetration of water molecules and halide (Cl\(^{-}\)) ions adsorption to the surface more difficult [3,11,14].

Fig. 5 shows surface condition after the CP tests of non-processed and laser textured superhydrophilic sample (DLT#1), respectively.
Although, both SEM images confirms pitting attack in the form of spherical/non-oriented pits with the base sample and completely oriented pits with DLT#1 sample, only the base/non-processed sample exhibited intergranular corrosion (IGC) attack. This is an additional important benefit of DLT process, since austenitic chromium-nickel (300 series) stainless steels are prone to IGC in the proximity of chromium rich carbides [37]. The precipitation of Cr-rich M(Fe,Cr)\textsubscript{23}C\textsubscript{6} carbides at grain boundaries often leads to the appearance of Cr-depleted zones that are prone to corrosion [38]. Since these precipitates are nobler than the adjacent boundary the galvanic effect promotes the anodic dissolution of the more negative grain boundaries acting as the continuous anodes [39]. This is an important factor, since after the occurrence of IGC attack, the corrosion resistance and mechanical properties of the stainless steels are drastically reduced.

In contrast, as can be seen in Fig. 5b, laser texturing completely prevents IGC attack, even in superhydrophilic state. This phenomenon is most likely attributed to more homogeneous microstructure with smaller amount of galvanic cells inside the material as a consequence of melting and deposition of the recast material due to laser texturing. Similar results were reported previously also by other authors [35,36]. For example, Kwok et al. [35] confirmed complete elimination of Cr-rich carbide phases in various austenitic SS samples due to laser surface melting process. Double loop electrochemical potentiokinetic reactivation (DL-EPR) tests in 0.5 M H\textsubscript{2}SO\textsubscript{4} and 0.01 M KSCN solution have confirmed considerably higher resistance to IGC attack after laser surface melting as a result of more homogenous microstructure and the redissolution of Cr-rich carbides.

4. Conclusions

Direct laser texturing (DLT) using a nanosecond Nd:YAG laser was confirmed as an effective method for fabrication of superhydrophobic surfaces on 316L stainless steel. It was shown that the transition from superhydrophilic ($\theta = 0^\circ$) through hydrophobic ($\theta = 109 \pm 6.7^\circ$) to superhydrophobic ($\theta = 168 \pm 3.0^\circ$) state occurs due to exposure of the textured surface to ambient conditions, which enables examination
of the isolated influence of wettability on corrosion behaviour.

LPR and CP results confirmed perfect correlation with the development of water repellency. The highest corrosion resistance with the highest polarization resistance ($R_p = 94.24 \pm 4.16 \text{k}\Omega \text{cm}^2$), improved passivation ability, and lowest corrosion current density ($i_{corr} = 0.29 \pm 0.03 \text{\mu A/cm}^2$) was measured on the superhydrophobic sample. The electrochemical measurements clearly demonstrate that both the hydrophobic and superhydrophobic surface experience lower corrosion activity as the non-processed surface with 26 times lower roughness. Improved corrosion resistance is directly associated with entrapped air inside hierarchical hydrophobic structure, which reduces the fractional area of liquid–solid interface which makes the penetration of corrosive species to the surface more difficult.

Further, the 3D topography of superhydrophobic surface after corrosion test revealed a strong preferential direction of corrosion propagation along µ-channels that are oriented along the last texturing passage (0°). However, this effect is significantly reduced by development of water repellency, resulting in non-oriented pitting attack. More importantly, presented results indicate that laser texturing completely inhibits the initiation of inter-granular corrosion as a consequence of more homogeneous microstructure with smaller amount of galvanic cells, i.e. Cr-depleted grain boundaries/(Mn(Fe,Cr)$_{23}$Co carbides.

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References