Microstructure evolution and corrosion behavior of 316L stainless steel subjected to torsion

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Abstract

The microstructure evolution of 316L stainless steels subjected to torsion deformation and its corrosion resistance in 1 M H₂SO₄ solutions were studied. Microstructure evolution of the annealed and torsion-processed samples was characterized by x-ray diffraction and electron backscatter diffraction techniques. The results showed that no martensitic transformation occurred during torsion deformation, while dynamic recrystallization occurred within the samples slowing down the tendency of increasing dislocation density and storage energy. Electrochemical tests including potentiodynamic polarization tests and electrochemical impedance spectroscopy (EIS) were used in the 1 M H₂SO₄ solution to evaluate the corrosion resistance of the annealed and torsion-processed samples. The results illustrated that small deformation (torsion for 1 turn) could enhance the corrosion resistance of the 316L stainless steels by increasing the stability of the passive film, the medium deformation (torsion for 3 turns) will deteriorate the corrosion resistance due to high-density dislocations formed during torsion deformation, while large deformation (torsion for 5 turns) could improve the corrosion resistance compared with the medium deformation due to the occurrence of dynamic recrystallization and the high-density deformation twins formed.

1. Introduction

Austenitic stainless steels are extensively applied in nuclear power, petrochemical, boilers and other industries due to their excellent comprehensive performance including good weldability, excellent corrosion resistance and suitable formability [1, 2]. However, the low strength of the annealed samples severely restricts their application. Grain refinement can not only improve the comprehensive mechanical properties of metal materials, but also improve their corrosion resistance [3–6]. Severe plastic deformation (SPD) such as equal channel angular pressing (ECAP) [7, 8], surface mechanical attrition treatment (SMAT) [8–10] has attracted more and more attention among materials scientists as effective methods for grain refinement. Those techniques have successfully fabricated numerous metallic materials with nano/ultrafine grains. During SPD process, the changed microstructures and introduced defects will affect the corrosion resistance of metallic materials.

Austenitic stainless steels subjected to SPD will accompany with dislocation slips, twinning and strain induced martensite. There is no doubt that different microstructures have different effects on its corrosion resistance [11, 12]. The martensite formed during SPD process will significantly weaken the corrosion resistance of metastable austenitic stainless steel (MASS) [11, 13]. Solomon et al [11] found the martensitic formed during cold plastic deformation can destroy the integrity of the passivation film due to the formation of numerous defects and the generation of residual stress. What’s more, the formed martensite during tension deformation and the austenite can cause a galvanic effect leading to different corrosion potentials [14]. Similarly, a high density of dislocations will also significantly deteriorate the corrosion resistance of 316L stainless steels. Maric et al [12] found that the corrosion behavior of the 316L stainless steels subjected to cold rolling in molten salt was governed by the high angle grain boundaries and dislocations. The greater the number of large angle grain
and dislocations, the worse the corrosion resistance of 316L stainless steel. On the contrary, the deformation twins formed during SPD process can improve the corrosion resistance of MASS. Therefore, it is very necessary to investigate the influence of the deformed microstructures of stainless steel on its corrosion resistance.

Recently, numerous studies have focused on the influence of SPD on the corrosion resistance of stainless steel. Tao et al.[15] used electrochemical methods to investigate the effect of cold rolling on the corrosion resistance of 316L stainless steel. They found that the cold rolling can change the composition of the passive film, especially the oxide content, which can combine with chromium to generate chromium oxide to modify the corrosion resistance of the passive film. The results showed that the cold rolling was detrimental to the corrosion resistance of 316L stainless steel. However, Yusuf et al.[16] investigated the effect of high-pressure torsion (HPT) on the corrosion resistant of a 316L stainless steels prepared by Selective Laser Melting (SLM) in a 3.5 wt % NaCl solution. The results showed that HPT-processed samples with stronger corrosion resistance compared with the SLM samples. They believed that the significant improvement in corrosion resistance of the HPT-processed samples can be attributed to the significant reduction of the pores in the SLM-fabricated samples due to HPT process, as well as the increase in the thickness and compactness of the passivation film on the HPT-processed sample surfaces. Similarly, Ghaleh et al.[17] found that ECAP can improve the corrosion resistance of 316L stainless steel in Ringer’s solution. They thought the high density of grain boundaries makes the sample have a thicker natural oxide layer, and the thicker the natural oxide layer, the stronger the corrosion resistance. In addition, the ECAP processing will also increase the chromium content of the passivated film on the surface of the 316L stainless steel thereby improving its corrosion resistance. Olugbade et al.[18] prepared surface nanostructured 316L stainless steel using SMAT technique, and investigated its corrosion behavior in 0.6 M NaCl solution. The results found that the corrosion resistance of SMAT-processed samples was deteriorated instead of improved compared to the as-received samples, which can be ascribed to the high residual stress and strain energy stored formed during SMAT process rather than to the difference in chromium content in the passivation film on the sample surfaces.

Up to now, there is no clear conclusion about the influence of severe plastic deformation, especially torsion deformation, on the corrosion resistance of 316L stainless steel. Therefore, the microstructure evolution of 316L stainless steel during torsion deformation were studied, and the effect of the microstructures on the corrosion resistance in 1 M H2SO4 solution was also discussed in this study.

2. Materials and Methods

2.1. Materials and processing

Chemical composition of the 316L samples used in this study was (wt%) 0.027% C, 17.71% Cr, 10.76 Ni, 2.21% Mo, 0.311% Si, 1.50 Mn and Fe (balance), which were determined by a Spark Emission Spectrometer. Noting that the chemical analysis of the 316L stainless steels were the ASTM E1086-14 standard. The 316L stainless steel cylindrical samples, 8 mm in diameter and 50 mm of length, were preconditioned by annealing at 1050 °C for 1 h prior to the torsion, followed by water cooling. The average grain sizes of the annealed sample were shown in figure 1. The torsion deformation is carried out using a wire torsion (XC-10) at a torsion speed of 0.25 turns/min at room temperature[19], and the 316L rods were designed to twist 1, 3 and 5 respectively. Following torsion, the disc samples were cut from the middle position of the annealed and torsion-processed samples, and then were polished using SiC paper from 200 to 2000 #. To prepare for microstructure characterization, all the polished disc samples were further polished using a smooth polishing cloth and cleaned using absolute ethanol. The corresponding equivalent strain can be described as

\[
\gamma = 2\pi nr/l \quad (1)
\]

\[
\varepsilon = \gamma / \sqrt{3} \quad (2)
\]

Where \(\gamma\) is shear strain obtained from the torsion, \(n\) is the torsion turn, \(l\) and \(r\) represent the position from the center of the circle and the length of the sample, respectively, and \(\varepsilon\) is the shear strain. Based on the above equation, we can obtain the maximum equivalent strain on the surface of the deformed sample to be 0.091, 0.270 and 0.443, respectively.

2.2. Microstructure Analysis

The phase composition of the annealed and the torsion-processed samples was characterized by x-ray diffraction (XRD) technique. The XRD experiment was carried out using a Cu-K\(\alpha\) radiation (20 Kv and 200 \(\mu\)A), and the scanning range from 40 to 100° with 4°/min. The microstructures of the annealed and the torsion-processed samples were also investigated using electron backscatter diffraction (EBSD) technique. For EBSD observation, the polished samples used in this study were electropolished in a solution of 10 \(g\) oxalic acid and 90...
ml deionized water at room temperature using a DC power with 12 V and 30 s to eliminate the surface stresses layer introduced by polishing. For EBSD testing, the step sizes of the annealed and the torsion-processed samples were 1 μm and 0.5 μm, respectively. The boundaries with a misorientation more than 15° can be regarded as high angle grain boundaries (HAGBs), and the misorientation angle range from 2° to 15° can be considered as low angle grain boundaries (LAGBs).

2.3. Electrochemical tests
A 1 M H₂SO₄ solution composed of deionized water and 98% sulfuric acid was used for the electrochemical tests. All the electrochemical tests were made by an electrochemical workstation (CHI660E) using a typical three-electrode. The three-electrode consists of a saturated calomel electrode, the surface of the exposed samples and platinum electrode, which can be regarded as reference electrode, working electrode and auxiliary electrode, respectively. The potentiodynamic polarization (PDP) and electrochemical impedance spectroscopy (EIS) were used to evaluate the corrosion resistance of the annealed and the torsion-processed samples. For PDP tests, the polarization curves were obtained via scanning the potential from −1.2 V relative to the open circuit potential in a positive direction with constant scan rate of 1 mV s⁻¹. EIS tests were carried out after the tested samples immersed for 60 min in 1 M H₂SO₄ solution with a frequency range from 10⁵ Hz to 10⁻² Hz. All the samples for electrochemical tests were polished using SiC paper and diamond paste. To ensure reproducibility, all the electrochemical tests were carried out at ambient temperature.

3. Results and Discussion

3.1. Microstructure evolution
Figure 2 shows the XRD patterns of the 316L stainless steels subjected to torsion for different turns, from which we can observe that no martensite transformation occurred in the 316L stainless steels during torsion deformation. This phenomenon has been reported in a 316L stainless steel subjected to dynamic plastic deformation [20]. It is worth noting that the peak of the (111) and (200) plane for the torsion-processed samples decreased compared with the as-annealed sample, while the peak of the (220) and (311) plane for the torsion-processed samples increased. In addition, all the peaks of the samples twisted 5 turns were broaden compared to the others, which can be attributed to the grain refinement.

The typical EBSD map of 316L stainless steels subjected to torsion for different turns is shown in figure 3. It can be seen from figure 3(a) that the grains around the surface of the samples twisted 1 turn were refined significantly, while the grains inside the samples were hardly refined, and only a small amount of deformation twins were generated. From figure 3(b) we can observe that the grains on the surface were further refined and numerous deformation twins were formed with the increase of the equivalent strain. In addition, the increase of equivalent strain inside the samples lead to the grains refined, and a large number of deformation twins were generated inside the grains. With the equivalent strain further increasing from 0.27 to 0.443, the grains inside the samples were refined obviously, and the grain sizes around the surface of the samples had little changes. From the figure 3 (a)–(c), we can conclude that the grain sizes on the surface of the samples were decreased drastically after 1 turn of torsion, and the grain sizes changes less with the increase of the equivalent strain.
Figure 3 displays the grain boundary misorientation (GBM) distributions in the torsion-processed 316L stainless steels. After the 316L stainless steel subjected to torsion for 1 turn, the low angle grain boundaries (LAGBs) were increased dramatically from 18.94% to 72.56%, which can be attributable to the torsion deformation introducing numerous dislocations and defects. With the equivalent strain further increasing, the fraction of LAGBs in the 316L stainless steel increased from 72.56% to 78.82%. It is worth noting that the fraction of misorientation angle around 60° were also increased in the sample subjected to 3 turns compared with the samples twisted 1 turn. Interestingly, the fraction of LAGBs increased only slightly in the samples subjected to torsion for 5 turns, from 78.82% to 81.43%. What’s more, the fraction of misorientation angle...
around 60° had little change. In previous studies, the fraction of misorientation angle around 60° increasing can be ascribed to the formation of deformation twins \([21]\). We can conclude that dislocation slips may be as the main deformation mechanism in the 316L stainless steels twisted 1 turns, and twinning will play an important role in the samples twisted 3 and 5 turns.

Figure 4 shows the pole figures of the 316L stainless steels processed by torsion for different turns. From figure 4(a), we can observe that the annealed samples have strong Cube (\(100\)) texture and Copper (\(112\)) texture, and the relatively weak Goss (\(110\)) texture is also found. The Cube is considered to be the typical annealing texture, while the Copper, Goss and Brass (\(110\)) texture are regarded as deformation texture, which indicate that the as-received 316L stainless steel annealed at 1050 °C for 1 h cannot completely eliminate the deformation textures \([22]\). After the samples subjected to torsion for 1 turn, the Copper and Goss texture were included, and the Brass texture were also formed. In addition, the pole strength increased significantly from 4.0 to 9.0, indicating that the texture strength increased. With the torsion increasing to 3 turns, the texture mainly comprised of \(111\) //\(ND\), and the strength of Brass and Copper texture is weaken slightly. With the torsion further increasing to 5 turns, all the texture strength is weakened which can be concluded from the pole strength decreased drastically from 8.0 to 3.0. However, the preferred orientation in the samples twisted 5 turns still retains. It is worth noting that the pole strength increased significantly after 1 turn of torsion, while the pole strength decreased gradually with the increase of equivalent strain. This phenomenon can be explained that the annealed samples subjected severe cold plastic deformation formed numerous deformed grains with preferred orientation, while the dynamic recrystallization were formed with the deformation increasing leading to the pole strength decreased.

The distributions of the recrystallization grains in the 316L stainless steels subjected to torsion for different turns are shown in figure 5, from which the blue grains indicate the recrystallization grains; the grains with yellow are substructured grains, and the grains with red represent deformation grains. The types of the grains can be classified by the average misorientation angle \([23]\). Generally, misorientation angle less than 1° are considered to be recrystallized grains; the misorientation angle is in the range of 1° and 7.5° are considered substructured grains; and the misorientation angle exceeds 7.5° are regarded as deformation grains. It can be seen in figure 5(a) that numerous deformation grains were introduced in the sample after torsion for 1 turn, while the recrystallized...
grains disappeared almost completely. Interestingly, with the torsion increasing to 3 turns, not only the fraction of deformation grains increased, but a small amount of recrystallized grains appeared inside the samples. What’s more, the fraction of recrystallized grains increases with the torsion increasing to 5 turns. This indicate that dynamic recrystallization occurred during the samples twisted 3 and 5 turns, and the fraction of the recrystallized grains increase from 6.35% to 16.76% (figure 5(d)), which is consistent with the dynamic recrystallization preferred to occur under larger deformation process.

Figure 6 shows the distribution and the average of Schmid factors in 316L stainless steels subjected to torsion for different turns, from which we can observe that the average of Schmid factors first decrease from 0.450 to 0.446 and then increase from 0.446 to 0.456. Based on the previous studies, the lower the average of Schmid factors is, the higher yielding stress and lower plasticity [24]. Numerous dislocations and defects were formed leading to the dislocations entangle with each other after torsion for 1 turn. Thus, the dislocation slips become more difficult resulting in higher yielding stress and lower plasticity. Despite the presence of dynamic recrystallization (only 6.35%) in the samples twisted 3 turns, work hardening dominates, leading to the average of Schmid factors decreased. With the torsion increasing to 5 turns, the formation of numerous dynamic recrystallization grains make the samples soften leading to the average of Schmid factors increased. In fact, although the average of the Schmid factor increases in the samples subjected to torsion for 5 turns, the plasticity decreases significantly instead of increasing due to the large number of defects and microcracks introduced during the deformation process.

To investigate the changes of dislocation density, especially geometrically necessary dislocations (GNDs), in the 316L stainless steels subjected to torsion for different turns, the strain gradient model theory is used to calculate the density of the GNDs [25, 26]. Based on the theory, the kernel average misorientation (KAM) value is used to estimate the GNDs density, and the calculation formula is as follows:

\[
\rho_{\text{GND}} = \frac{2\theta}{\mu b}
\]

where \(\theta\) represents the average local misorientation, \(\mu\) represents the step sizes used in EBSD tests, and \(b\) represents the Burger’s vector of the 316L stainless steels used in this study (\(b = 0.258\) nm) [27]. Figure 7 shows the distributions of KAM and the corresponding specific value in the torsion-processed 316L stainless steels. It can be seen from figure 7(a)–(c) that the KAM value at the grain boundary is larger than that within the grains, which illustrate higher dislocation density formed around the grain boundaries during the torsion deformation. In addition, we can observe from figure 7(d) that the KAM peak values of the samples gradually increase with the increase of equivalent strain. Figure 8 shows the average GNDs density calculated by equation (3) in the samples subjected to torsion for different turns. For the samples twisted 3 turns, the GNDs density increase from \(1.278 \times 10^{16} \text{m}^{-2}\) to \(1.802 \times 10^{16} \text{m}^{-2}\). Interestingly, with the torsion further increasing to 5 turns, the GNDs
Figure 6. The Schmid Factor distribution and the average of 316L stainless steels processed by torsion with different turns: (a) and (d) for 1 turn, (b) and (e) for 3 turns, and (c) and (f) for 5 turns.

Figure 7. The kernel average misorientation (KAM) maps of 316L stainless steels processed by torsion with different turns: (a) 1 turn, (b) 3 turns, and (c) 5 turns; (d) KAM value distributions of the twisted 316L stainless steels.
density only increase from $1.802 \times 10^{16} \text{ m}^{-2}$ to $2.88 \times 10^{16} \text{ m}^{-2}$. It can be attributed to the 316L stainless steels with low stacking fault energy leading to the dynamic recrystallization occurred during torsion process, which have been confirmed by figure 5.

The stored energy is also closely related to the local misorientation during the severe plastic deformation [28, 29], which can be calculated by the following equation:

$$E = \frac{\alpha \theta G b}{2d}$$

where $\alpha$ is a constant that depends on the type of lattice, and $\theta$ is the average local misorientation, $G$ represents shear modulus, and 79GPa for the samples, $b$ represents the Burger’s vector, and $d$ represents step sizes. Figure 8 shows the changes of the stored energy with the torsion turns, from which we can observe that the stored energy increased obviously with the increase of equivalent strain. After the samples twisted 3 turns, the stored energy increase from $4 \times 10^8 \text{ J.m}^{-3}$ to $7.02 \times 10^8 \text{ J.m}^{-3}$. It is worth noting that the stored energy only increase from $7.02 \times 10^8 \text{ J.m}^{-3}$ to $11.24 \times 10^8 \text{ J.m}^{-3}$ after the torsion turns increasing from 3 turns to 5 turns, which can be attributed to numerous stored energy was annihilated as a heat during the 5 turns-torsion process. From the description above, we can observe that the increase of the stored energy became slower with the increase of the torsion turns, which may be caused by the dynamic recrystallization.

3.2. Electrochemical corrosion behavior

3.2.1. Potentiodynamic polarization study

Figure 9 shows the potentiodynamic polarisation curves of the annealed and torsion-processed 316L stainless steels in 1 M H$_2$SO$_4$ solution, from which we can observe that the polarisation curves for all the samples is similar with each other, and contain two passivation zones although the two passivation zones are quite different. From the polarisation curves, we can obtain that the corrosion parameters, corrosion potentials ($E_{corr}$) and corrosion current densities ($I_{corr}$), which can be seen in table 1. It can be seen fro table 1 that the samples twisted 1 turn have lower $I_{corr}$ than that of annealed samples. However, it is worth noting that the value of $I_{corr}$ does not always decrease with the increase of equivalent strain, but first increases and then decreases with the increase of equivalent strain. The lower $I_{corr}$ represents the lower corrosion rate, which means that the samples have stronger corrosion resistance [30, 31]. In addition, the $E_{corr}$ in the samples twisted 1 turn is more positive than that of annealed and the samples twisted 3 turns, and is similar with that of the samples twisted 5 turns. Noting that the higher the $E_{corr}$, the stronger the corrosion resistance. Based on the polarisation results, we can find that the samples subjected to torsion for 1 turn have the best corrosion resistance among all the samples, and the samples subjected to torsion for 3 turns is the worst. On the other hand, we can find from the potentiodynamic polarization curve that all samples have similar constant current density. Generally, the corrosion mechanism of the samples in potentiodynamic polarization tests can be determined by the current density [30, 32]. Therefore, we can conclude that all samples have the same corrosion mechanism due to the almost the same constant current density.
3.2.2. EIS characterization

The EIS measures were performed to further study the corrosion resistance of the annealed and torsion-processed samples. Figure 10 illustrates the typical Nyquist and Bode plots of the samples in 1.0 M H₂SO₄ solution, from which the points represent the experimental data obtained from the EIS measures and the lines represent the fitting data. Obviously, the shape of the Nyquist plots for the samples annealed and twisted 1 turn is similar, but the radius of the capacitive arc for the samples twisted 1 turn is significantly larger than that of the annealed samples. In addition, the radius of the capacitive arc for the samples twisted 3 and 5 turns is also similar, the capacitive arc radius of the samples twisted 5 turns is larger than that of the samples twisted 3 turns. Noting that the largest capacitive arc belongs to the samples twisted 1 turn. In previous studies, the authors have associated the capacitive arc radius with the corrosion resistance, and they believe that the larger the arc radius, the stronger the corrosion resistance [33–36]. Therefore, we speculate that the samples twisted 1 turn have the best corrosion resistance among all the samples. This speculation is in full agreement with the results obtained by the polarization curves. For the Bode plots, we can observe that the peak phase angle of all samples except the samples twisted 3 turns is between 60 and 80°. The higher the peak phase angle, the higher the capacitive film formed on the sample surfaces [31, 37], and the higher the corrosion resistance of the 316L stainless steels [35]. In addition, the peak width of the phase angle also affects the stability of the metallic materials in corrosive environments, and the wider the peak the greater the stability [38]. The phase angles at low frequency can be described the charge transfer behavior of the passive oxide film formed on the surface of the samples [38, 39]. From the Bode plots, we can observe the samples twisted 1 turn with higher phase angles at low frequency than that of the others, which means the passive oxide of the samples with the highest electrochemical stability. The positive phase angles increased significantly after the samples twisted 1 turn, indicating that the oxide stability on the surface was improved. In addition, a slight fluctuation around the low frequency occurred can also be observed in figure 10(b), which can be attributed to the hydrogen absorption and desorption occurred on the sample surfaces.

To further investigate the corrosion resistance determining the oxide film capacitance, these curves were fitted using the equivalent circuit, as shown in figure 10(c). The CPE in the circuit represent the constant phase element used to characterize the dispersion behavior resulting from the heterogeneity of the sample surfaces, and its impedance can be expressed as:

\[
Z_{\text{CPE}} = \frac{1}{C_{\text{P}}(j\omega)^{n}}
\]

where \( C_{\text{P}} \) is the capacitance, \( n \) is the angular frequency exponent, and \( j \) is the imaginary unit.

Table 1. Corrosion parameters of the annealed and torsion-processed 316L stainless steels in 1.0 M H₂SO₄ solution.

|                | Annealed | 1 turn | 3 turns | 5 turns |
|----------------|----------|--------|---------|---------|
| \( I_{\text{corr}} \) A cm⁻² | \( 7.168 \times 10^{-5} \) | \( 4.874 \times 10^{-6} \) | \( 1.444 \times 10^{-4} \) | \( 1.868 \times 10^{-5} \) |
| \( E_{\text{corr}} \) V | \( -0.42 \) | \( -0.261 \) | \( -0.441 \) | \( -0.231 \) |
and the capacitance \( (C_{\text{CPE}}) \) can be obtained by the following equations \([40, 41]\).

\[
C_{\text{CPE}} = \frac{gQ}{\varepsilon_0 \varepsilon_0} (\varepsilon_0) \omega^{-n} \tag{6}
\]

\[
g = 1 + 2.88(1 - n)^{2.375} \tag{7}
\]

where \( Q, n, \omega \) and \( i(\omega) = -1 \) represent the magnitude, experience index, angular frequency and imaginary number of the CPE, respectively; \( \varepsilon \) represents the dielectric constant taking the value of 15.6 for stainless steels; \( \varepsilon_0 \) represents the vacuum permittivity taking the value of \( 8.85 \times 10^{-12} \text{F.m}^{-1} \), and \( \rho_d \) represents the resistivity taking the value of \( 500 \Omega \cdot \text{m}^{-1}[41]\). For the circuit, the \( R_a \), \( R_b \) and \( R_c \) represent the electrolyte resistance, passive film resistance, and the resistance of the charge-transfer, respectively; CPE1 and CPE2 represent the capacitance of the passive film and the electrochemical response of the outer ion channel terminal bilayer.

Table 2 lists the typical fitted parameters for EIS of the annealed and torsion-processed 316L stainless steels in 1 M H\textsubscript{2}SO\textsubscript{4}. From table 2, we can find that the \( R_b \) value is much larger than the \( R_b \) value, which means that the charge transfer plays an important role in the passive film system. In electrochemical system, the polarization resistance \( (R_p) \) is often used to evaluate the stability of the passivation film, which can be described as:

\[
R_p = R_b + R_c \tag{8}
\]

From table 2, we can observe that the \( R_p \) of the samples twisted 1 turn is the largest among all the samples, while the samples twisted 3 turns have the smallest value. The results indicated that the stability of the passive film for the samples twisted 1 turn is the highest, and the samples twisted 3 turns have the worst stability.

Severe plastic deformation will introduce numerous dislocations, defects and high microstrain, which play different roles in the corrosion resistance of the materials. In previous studies \([42, 43]\), the authors found that small deformation can enhance the corrosion resistance of the austenite stainless steels, while the corrosion resistance became worse with deformation increasing. They thought that dislocations can increase the corrosion rate by reducing the electron work function, therefore, with the increase in deformation, dislocation density...
Table 2. Typical fitted parameters for EIS of the annealed and torsion-processed 316L stainless steels in 1 M H$_2$SO$_4$.

| Samples  | $R_0$(Ω·cm$^2$) | CPE1(μF·cm$^{-2}$) | $n_1$ | $R_0$(Ω·cm$^2$) | CPE2(μF·cm$^{-2}$) | $n_2$ | $R_p$(Ω·cm$^2$) | CPE(μF·cm$^{-2}$) | RP(Ω·cm$^2$) |
|----------|------------------|---------------------|-------|------------------|---------------------|-------|----------------|------------------|-------------|
| Annealed | 1.18             | 19.2                | 0.92  | 26.45            | 4.39                | 152   | 0.63           | 1695            | 0.43        | 1721.45     |
| 1 turn   | 0.60495          | 68.1                | 0.84  | 516.3            | 5.04                | 650   | 0.82           | 15280          | 35.05       | 15796.3     |
| 3 turns  | 0.80             | 59.5                | 0.82  | 31.58            | 3.21                | 110   | 0.81           | 152.6          | 5.06        | 184.18      |
| 5 turns  | 0.82             | 41.2                | 0.85  | 57.11            | 3.58                | 54.0  | 0.79           | 1178           | 1.81        | 1235.11     |
increases leading to an increase in corrosion rate. The formation of martensite in the deformation can also increase the corrosion rate, while no martensite was generated in this study. Obviously, the best corrosion resistance was achieved by torsion for 1 turn, and with further increase in deformation, the corrosion resistance first decrease and then increase. Therefore, we can conclude that although the dislocation density is an important factor affecting the corrosion resistance of 316L stainless steel, it is not the only factor. It is worth noting that grain refinement can be regarded as an important method to improve the corrosion resistance [13]. In addition, a large number of dynamically recrystallized grains were formed in the sample with 5 turns of torsion, which can eliminate the defects in the samples formed by torsion deformation improving the corrosion resistance of the samples. What’s more, numerous twins formed in the samples twisted 5 turns can also enhance the corrosion resistance. Therefore, the corrosion resistance of the samples twisted 5 turns is higher than that of the samples twisted 3 turns.

4. Conclusions

The effect of torsion deformation on the microstructure evolution and the corrosion resistance of the 316L stainless steels subjected to torsion for different turn in 1 M H2SO4 solution were investigated. From the findings, we can obtain the following conclusions:

(1) The 316L stainless steels undergoes dynamic recrystallization behavior during the torsion deformation, and the fraction of the recrystallized grains increases from 6.35% to 16.76% as the torsion deformation increase from 3 turns to 5 turns. There is no martensitic transformation during the torsion deformation.

(2) Due to the dynamic recrystallization, the texture strength is weakened (the pole strength decreased from 9.0 to 3.0) as the torsion deformation increase from 1 turn to 5 turns. In addition, the increasing trend of the average GNDs density and storage energy slows down with the increase of the torsion deformation.

(3) Potentiodynamic polarization test illustrates that the samples subjected to torsion for 1 turn has the highest $E_{\text{corr}}$ ($-0.261 \text{ V}$) and the lowest $I_{\text{corr}}$ ($4.874 \times 10^{-6}\text{ A.cm}^{-2}$) compared with other samples, which indicate that the samples subjected to torsion for 1 turn possess the highest corrosion resistance.

(4) Torsion deformation can modify the stability of the passive film. Small deformation, torsion for 1 turn, makes the passivation film formed on the sample surface more stable compared with other samples, leading to the corrosion resistance enhanced.

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Data availability statement

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

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