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Influence of surface modifications on pitting corrosion behavior of nickel-base alloy 718. Part 1: Effect of machine hammer peening

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ABSTRACT

The effect of surface modifications induced by machine hammer peening on pitting corrosion behavior of nickel-base alloy 718 in a 3.5 wt.% NaCl solution is investigated. Severe work hardening and high compressive residual stress are generated with surface smoothing and microstructure evolution in terms of formation of nano-grains and nano-twins in the near surface region after machine hammer peening. Electrochemical tests results show that machine hammer peening has a beneficial influence on the corrosion resistance, indicated by a significant increase of the critical pitting potential (+134 mV) accompanied with lower corrosion current density and higher polarization resistance.

1. Introduction

Nickel-base alloy 718 has been recently used in the oil and gas industry for downhole drilling components especially for the parts of the bottom hole assembly because of its superior mechanical properties, good corrosion resistance and non-magnetic properties [1–5]. Due to the existence of high chloride content in the aqueous drilling fluids and the severe corrosive environments in the oil drilling wells, concern has been directed towards controlling or reducing failures from pitting corrosion, crevice corrosion, environmental assisted cracking including stress corrosion cracking, sulfide stress cracking and hydrogen embrittlement, as well as corrosion fatigue [6–11] in metallic materials utilized in the bottom hole assembly.

In recent years, surface treatments such as shot peening, ultrasonic peening, hammer peening, laser shock peening and roller peening [12–16] have been widely used for improving the mechanical properties, fatigue life and corrosion fatigue resistance by introducing a compressive residual stress layer in the near surface region through the work hardening from the surface treatments [17–20]. In the mean time, the surface modifications, in terms of surface roughness, surface morphology, surface passive/oxide film, near surface microstructure and residual stress induced by surface finishing processes, can affect the corrosion properties, especially pitting corrosion which is usually considered to be a precursor to stress corrosion cracking and corrosion fatigue crack initiation in chloride solutions [21–24]. Numerous studies have been focused on the influence of peening treatments on the corrosion resistance of alloys [25–35], regardless of their applications be it oilfield drilling or otherwise. It has been reported by Azar et al. [26] that surface roughening, which was considered to be deleterious to the corrosion resistance by increasing the corrosion current density and decreasing the break-down potential, could be produced by the shot peening treatment. According to Lee et al. [25], ultrasonically peened AISI 304 stainless steel showed better corrosion resistance than the shot-peened specimen due to the rendering of a smoother surface and the creation of strain-induced martensite. Peyre et al. [23,32] have pointed out that the deleterious roughened surface state produced by shot peening could counterbalance the beneficial effect of compressive residual stress on the pitting corrosion resistance of 316L steel.

Machine hammer peening (MHP) is a mechanical surface treatment which can induce deep penetration of compressive residual stress and a strain hardened layer below the surface as well as a strong reduction of surface roughness on work pieces with complex shapes [36–39]. During MHP processes, the metal work piece is hammered with a tungsten carbide ball, which is moved by a machine tool or robot along the surface, thereby creating a uniformly smooth surface by well-directed impacts with a controlled distance between each impact. However, this method is not well

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covered in the literature since it is relatively novel. Recent research has focused attention on how deep machine hammer peening can smooth machined surfaces and thus achieve compressive residual stress by adjusting hammer peening parameters. Therefore, it is logical to expect that MHP would result in an increase in corrosion resistance. Nevertheless, published data on MHP is limited, focusing on the effect of surface modifications on the corrosion behavior of alloy 718. Thus, it is meaningful to determine whether the MHP surface treatment can improve corrosion resistance.

The objective of this research is to study the effect of MHP on surface modified properties including microhardness, residual stress, surface chemistry, surface morphology, surface rougenss and the near surface microstructure of nickel-base alloy 718. The research goal would relate surface modifications induced by MHP on the pitting corrosion behavior of nickel-base alloy 718 in a 3.5 wt.% NaCl solution at room temperature.

2. Materials and methods

2.1. Materials and specimen preparation

The nickel-base alloy 718 studied in this paper was provided by Baker Hughes Inc. The chemical composition is 0.02C–18.47Cr–52.55Ni–19.41Fe–3.00Mo–0.97Ti–5.09Nb–0.49Al (wt.%). The as-received alloy was solution annealed at 1032 °C for 2 h. Before MHP the specimen surface was prepared by mill finishing (MF). During MHP, a tungsten carbide ball with a diameter of 8 mm was used to treat one side of the milled surface at a frequency of 140 Hz and feed rates of 2 m/min (MHP1) and 4 m/min (MHP2), respectively.

2.2. Specimen characterization

Vickers micro-hardness tests conforming to the ASTM E384-05 standard were carried out using 0.3 N (300 g) load with an indentation cycle time of 15 s on cross-sections of the MF and MHP specimens. An average of ten indentation measurements was used to determine each data point.

Surface residual stress induced on the MF and MHP samples was obtained according to the $\sin^2\Psi$ method [40] by using X-ray Diffraction (XRD, Bruker D8 Discovery).

X-ray photoelectron spectroscopy (XPS) analysis was carried out using a PHI 5000 VersaProbe System, utilizing monochromatic Al Kα radiation to examine the oxide film formed on the surface of specimens. The C1s peak from carbon contamination at 284.8 eV was used as a reference to correct for charging shifts. Depth profiling of oxide films was performed over an area of 2 mm × 2 mm using Argon ion bombardment with an ion energy of 2 kV. Sputtering rate was determined to be 18.5 nm/min with reference to the Ta_2O_5 layer. Therefore, it should be noted that the thickness change after the MHP treatment rather than the absolute thickness values of the oxide film was meaningful. The quantification of the species in the oxide films was performed via XPSpeak 4.1 peak fitting software.

The surface roughness and surface topography of the MF and MHP specimens were measured by using an optical profiler (Bruker Contour GT K0). The vertical scanning interferometry type was chose based on the samples surface conditions. A 5× objective lens and 1× field of view multiplier were used to give a measurement area of 1.257 mm × 0.942 mm. The tilt was removed from the measurement during data analysis because it could alter the surface profile. R_a, R_q, R_p, R_v, R_t are arithmetic average roughness, root mean squared roughness, maxim peak height, maximum valley depth, maximum height of the profile ($R_t = R_p - R_v$). These roughness parameters of each specimen are the average values of five measurements.

The near surface microstructure of all the specimens was examined by means of optical microscopy (OM, Meiji MT 7000), scanning electron microscopy (SEM, JEOL JSM-7600F) and transmission electron microscopy (TEM, JEOL JEM-2010). Cross-sectional specimens mounted in epoxy were mechanically ground using a series of abrasive SiC grit sizes, i.e., 120–1200 grit, with final polishing using 3 μm and 1 μm diamond suspension. Chemical etching using a mixture of 200 ml methanol, 200 ml hydrochloric acid and 10 g $CuCl_2$ for 4 min produced the final surface for OM and SEM examination. For TEM analysis, specimens were first ground to 50 μm thickness and then thinned electrolytically using a twin jet polishing unit. The electropolishing solution was consisted of 10% perchloric acid in 90% ethanol. Electropolishing was performed using a current of 90 mA at −20 °C.

2.3. Electrochemical measurements

Electrochemical measurements were performed at room temperature using an aerated 3.5 wt.% NaCl solution, prepared with deionized water. Specimens for electrochemical testing were mounted in epoxy leaving only 0.5 cm × 0.5 cm surface area of the MF or MHP exposed. Immediately prior to each testing, the specimens were rinsed with acetone, ethanol and deionized water, and dried in air at room temperature, then transferred into the test solution. None of the specimens were ground as is usually the case in electrochemical testing because doing so might lead to information loss on corrosion behavior differences due to different surface treatment conditions. Electrochemical testing was carried out using a standard three electrode system in a 1.5 L glass cell. A three-electrode cell setup was employed that consisted of a pair of graphite counter electrodes, a saturated calomel electrode (SCE) reference electrode and specimen as working electrode. Experiments for each specimen condition were conducted at least three times with the results averaged. At the beginning of each experiment, the working electrode was first cathodically polarized at $-1\ V_{SCE}$ for 10 min to remove the air-formed surface oxides because it has been proved that the reproducibility of electrochemical measurements performed on passive films was improved after cathodic polarization [41–44].

The test specimens were then immersed in the test solution for up to 48 h to attain a relatively stable value of open-circuit potential (OCP) after cathodic pretreatment. Potentiodynamic polarization curves were performed using a Solartron SI 1287. For this series of tests, the test specimens were excited from $-0.5\ V_{SCE}$ towards the anodic direction at a scanning rate of 0.5 mV/s. Electrochemical impedance spectroscopy (EIS) measurements were carried out with a Solartron SI 1287 electrochemical interface and a SI 1260 impedance analyzer. EIS measurements were conducted at OCP after the specimens had been immersed for 1, 6, 12, 24 and 48 h, respectively, in a 3.5 wt.% NaCl solution. The testing frequency ranged from 10 kHz to 10 mHz while the AC amplitudes were 10 mV (rms–root mean square). The resulting impedance spectra obtained during testing were then fitted using ZSimpWin software.

3. Results and discussion

3.1. Mechanical modifications

3.1.1. Microhardness

Microhardness measurements were carried out on the cross-section of the MF and MHP specimens to determine the hardness at different layers from the treated surface in order to assess the