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Effects of Surface Preparation on Pitting Resistance, Residual Stress, and Stress Corrosion Cracking in Austenitic Stainless Steels

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Surface finishing treatments such as shot blasting and wire brushing can be beneficial in improving the integrity of machined surfaces of austenitic stainless steels. These operations optimize in-service properties such as resistance to pitting corrosion and stress corrosion cracking (SCC). In this study, ground steel surfaces were subjected to a series of sand blasting and wire brushing treatments. The surfaces were then characterized by their hardness, surface residual stress state, and resistance to stress corrosion and pitting corrosion. Some samples were selected for depth profiling of residual stress. It is found that surface hardening and the generation of near-surface compressive residual stress are the benefits that can be introduced by sand blasting and brushing operations.

Keywords austenite stainless steel, shot blasting, stress corrosion cracking, surface preparation, wire brushing

Introduction

Surface finishing operations such as grinding, wire brushing, and peening of mechanical components produce surface states that can compromise corrosion resistance (pitting corrosion and stress corrosion cracking (SCC)) of stainless steels. These processes affect the electrochemical and mechanical stabilities of passive film and near-surface layers, by changing the surface reactivity[1,2] and altering the near-surface residual stress state.[3,4] The surface roughness resulting from these treatments can be an important factor in subsequent corrosion behavior.[5] As a result, surface preparation operations can alter the steel's susceptibility to SCC and its resistance to the initiation and propagation of pitting.

Careful control of machining parameters and the application of secondary surface treatments after machining can improve appreciably the durability of these materials by reducing the surface electrochemical reactivity and their susceptibility to SCC. Finishing processes to protect or to improve the in-service properties of these stainless steels have been the subject of several studies.[6–9]

In this paper, we present results showing the influence of various mechanical treatments such as wire brushing, sand blasting, and polishing on the pitting and SCC resistance of ground surfaces in an AISI 316L stainless steel.

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Materials and Testing

Materials and Sample Preparation

In this study, an austenitic stainless steel of type 316L was investigated. The chemical composition is given in Table 1.

The steel was supplied in bar form of 12 mm diameter. It was cut and milled to form small cylindrical samples ~10 mm in length. One of the flat surfaces was ground, and then the samples were examined either as-ground, or after a wire brushing, sand blasting, or polishing treatment. Two different grinding conditions were used, along with three wire brushing and three sand blasting treatments, and mechanical or electrochemical polishing. Details of all the samples that were prepared, along with a summary of some of the results, are given in Table 2.

Wire brushing was carried out using a cylindrical stainless steel brush wheel of 150 mm external diameter. This technique is often applied as a cleaning technique, to remove surface scales and dirt from metals after rolling treatments, for example. The experimental setup is shown in Fig. 1. The diameter of each wire on the brush was 0.1 mm, with a length of 30 mm. During the brushing process, the wires were effectively compressed by 10% of their length (the sample surface was 27 mm from the inner end of the wires). The brush was rotated between 280 and 900 rpm (revolutions per minute).

Sand shot blasting was carried out with quartz particles of various diameters: QZ40 (<50 μm), QZ100 (80 to 120 μm), and QZ160 (120 to 200 μm), at a pressure of 4 bars, an incident angle onto the sample of 45°, and a distance from emission to sample of 40 mm. In each case, the samples were exposed for 10 min.

Table 1 Chemical composition of the AISI316L stainless steel (wt.%)

C	S	P	Mn	Ni	Cr	Mo	Cu	V	Fe
0.02	0.041	0.041	1.68	11.14	17.24	2	0.05	0.05	balance

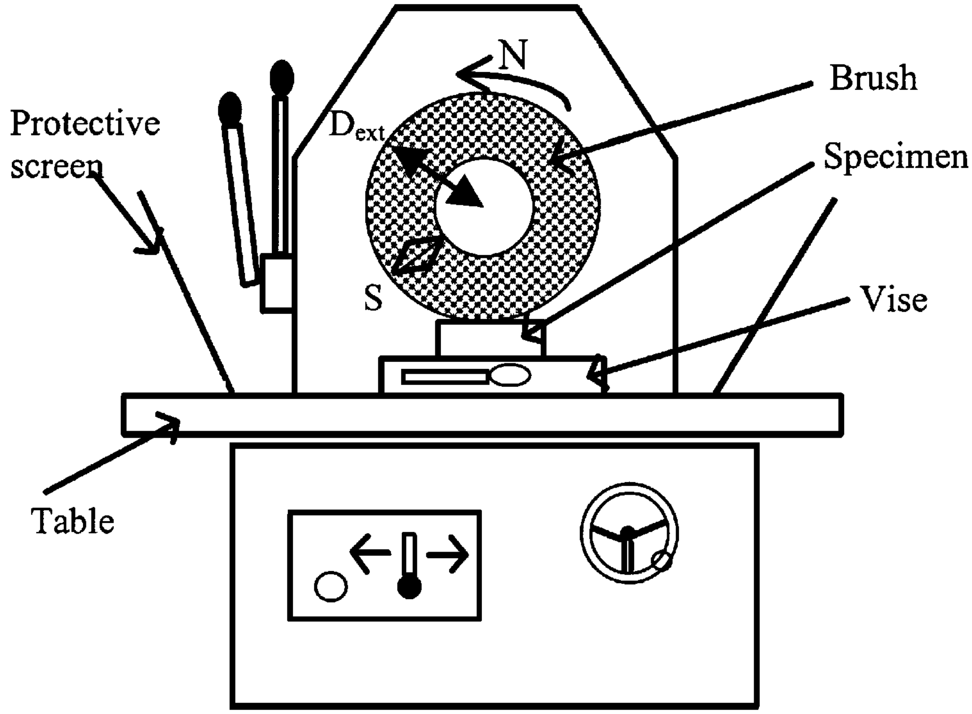

Fig. 1 Setup of the wire brushing operation

Table 2 Influence of grinding and finishing conditions on roughness and corrosion resistance of the AISI316L stainless steel

Grinding conditions (a)	Finishing conditions				Surface profile				Pitting corrosion resistance		
					Ra/μm		Rt/μm				
Workpiece speed/ $mmin^{-1}$	Type	Conditions			//	⊥	//	⊥	Ep (mV/SCE)	Er (mV/SCE)	SCC resistance
2	Reference		As ground		0.68	1.12	5.9	9.8	110	−200	Cracks
	Sand blasted	Angle/°	T/min	Shot size							
		45	10	Qz 40	1.18	1.18	8.2	8.2	320	−110	No cracks
				Qz 100	0.92	0.92	8.1	8.1	360	−150	No cracks
				Qz 160	0.78	0.78	7.5	7.5	360	−150	No cracks
	Wire brushed	Wire compression/%	No. of passes	Brush speed/rpm							
		10	3	280	0.51	0.69	6.2	5.3	500	−130	Cracks
				500	0.61	1.17	10.9	10.2	550	−100	Cracks
				900	0.37	0.38	4.2	4.1	500	−150	No Cracks
6	Reference		As ground		0.55	0.95	5.7	8.8	80	−180	Cracks
	Sand blasted	Angle/°	T/min	Shot size							
		45	10	Qz 40	1.08	1.08	8.2	8.2	460	−110	No cracks
				Qz 100	1.01	1.01	7.8	7.8	360	−110	No cracks
				Qz 160	0.81	0.81	7.7	7.7	360	−110	No cracks
	Wire brushed	Wire compression/%	No. of passes	Brush speed/rpm							
		10	3	280	1.08	1.6	7.8	12.1	450	−160	Cracks
				500	0.34	1.09	4.2	9.1	500	−100	Cracks
				900	0.54	1.06	6.3	9.8	500	−150	Cracks
2 or 6 (not relevant owing to large layer removal by secondary treatment)	Mechanical polishing	Abrasive paper to 0.5μm alumina			0.32	0.32	6.0	6.0	400	−200	No cracks
	Electrolytic polishing	90% $C_6H_{14}O_2$ + 10% $HClO_4$			0.28	0.28	5.7	5.7	550	120	No cracks

(a) Grinding conditions—wheel speed/rpm: 1500; depth of cut/mm: 0.03; no. of passes: 10

Mechanical polishing was undertaken using a series of abrasive papers, finishing with 0.5 μm alumina. Electrolytic polishing was performed in a solution of perchloric acid under a voltage of 10 V and a current density of 1 A cm^{-2}. Under these conditions, polishing during 10 min removes around 0.03 mm of material.

Table 3 The used x-ray diffraction parameters for the 316 L steel

	Experimental parameters				
Radiation	λMn $K_\alpha \times \lambda = 0.2102$ nm				
Voltage	20 kV				
Current	5 mA				
X-ray diffraction planes	{3 1 1} $2\theta \approx 152°$				
Beam diameter	2 mm				
ϕ angles (°)	0 and 90				
ψ oscillation	±3°				
ψ angles (°)	−42.95	−38.81	−34.54	−30.00	−25.00
	−19.11	−10.89	0.00	15.50	22.21
	27.58	32.31	36.70	40.89	45.00

Test Methods. The surfaces were characterized by roughness measurement, giving the mean surface deviation, R_a, and the maximum deviation, R_t. The surface hardening by cold work was characterized by Vickers microhardness testing, using a load of 50 gf (HV 50).

Profiles of the residual stress in the sample were made near the surface using x-ray diffraction and were made in depth using the hole drilling method. X-ray diffraction analysis measurements were performed using a Set-X x-ray diffractometer, with the multiple psi (ψ) tilt method. The appropriate diffraction parameters are presented in Table 3. The hole drilling method was performed using strain rosettes type TEA-06-062RK-120 (from Micro-Measurement Group, Inc., U.S.A.). The drill diameter was 2 mm. The holes were drilled incrementally with varying steps. A high drilling speed (2500 rpm) was used in order to avoid inducing additional residual stress. For each increment, the surface strain values in the three strain gauges were recorded. The calculation of the residual stresses was then performed from the measured strain values.

The corrosion resistance of the surfaces in synthetic sea water was evaluated by cyclic potentiodynamic tests. The tests give values for the pitting corrosion potential E_p and the repassivation potential E_r. The tests were carried out at a voltage rate of $dE/dt = 2.5$mV s^{-1}. The susceptibility of the samples to SCC owing to the residual stress state was determined by accelerated immersion tests of 48 h in a medium containing 40% $MgCl_2$ heated to 140 °C.

Results

Surface Characterization

Roughness. Roughness measurements (R_a, R_t), resulting from the different surface preparation operations, are performed using a MITUTOYO SURFTEST profilometer (Japan), following French Standard NFE05-015. The results are shown in Table 2. The measurements indicate the following general trends: sand blasting under the chosen conditions always increases the surface roughness relative to the ground initial surface; wire brushing produces a rather variable effect, but seems to be better at higher speeds in terms of producing a smoother surface finish; and polishing is the best method of improving the finish, as might be expected.

The roughness of the as-ground sample decreases slightly as the work speed is increased. Figure 2 shows micrographs of the surface states of the as-ground, wire brushed, sand blasted, and electrochemically polished surfaces.

Characterization of the Near-Surface Work Hardened Layer

Profiles of microhardness variation near the surfaces were measured using a microindenter with a load of 50 gf, carried out on a cross section of the sample. The results are shown in Fig. 3 and show that the depth of the hardened layers varies between 200 and 350 μm depending on the conditions. The depth of the cold worked layer initially introduced by grinding is approximately 200 μm. The hardness of this layer increases as the grinding workpiece speed is increased.

Figure 3(a) shows that the polishing treatments effectively remove the surface hardened layer, without adding any additional damage; they provide a method for removing the effects of the grinding treatment.

Figure 3(b) shows the effect of the sand blasting operation. For the sand blasting technique, the depth of the cold worked layer, and the level of hardness at the surface, increases as the size of projectiles gets larger. The largest particles give an increase in hardness to 350 Hv and extend the hardened layer to ~350 μm.

Figures 3(c) and (d) show the effects of wire brushing, for surfaces ground initially at either 2 or 6 m/min. The wire brushing treatment is less severe than the sand blasting one, with the fastest brush speed giving an increase to 300 Hv. The depth of the hardened layer is not greatly increased. A larger final hardness is obtained for the workpiece ground at 6 m/min (which had a higher initial hardness before the brushing operation).

Results of Residual Stress Measurements

Surface residual stress measurements were made, using the x-ray method, on a series of samples. The results are summarized in Table 4.

The results show that all the finishing treatments leave the surface in a state of compression, following the grinding treatment, which induces tension in the grinding direction and compression perpendicular to it. It is difficult to detect any trends in the data from the sample ground at 2 m/min, but the sample ground at 6 m/min shows, for subsequent wire brushing, that a higher brush speed generates a higher level of compressive residual stress. A more detailed set of measurements were performed on selected samples, to determine the subsurface stress profiles. These are shown in Fig. 4. Grinding with a work speed of 2 m/min generates tensile near-surface residual stresses (Fig. 4a), with the peak stress (about 500 MPa) found between 100 and 200 μm below the surface. The depth of the peak stress induced is equivalent to the depth over which the hardness is altered.

Surface treatment (sand blasting and wire brushing) following grinding modifies the residual stress distribution. In all cases, these treatments generate compressive near-surface stresses, the profile of which has a depth comparable to that obtained after grinding. The maximum values found at the surface are about −175 MPa for sand blasting by quartz 160 (Fig. 4b) and about −125 MPa for wire brushing (900 rpm) (Fig. 4c). In both cases, the maximum stress is now at the surface itself, rather than below it.

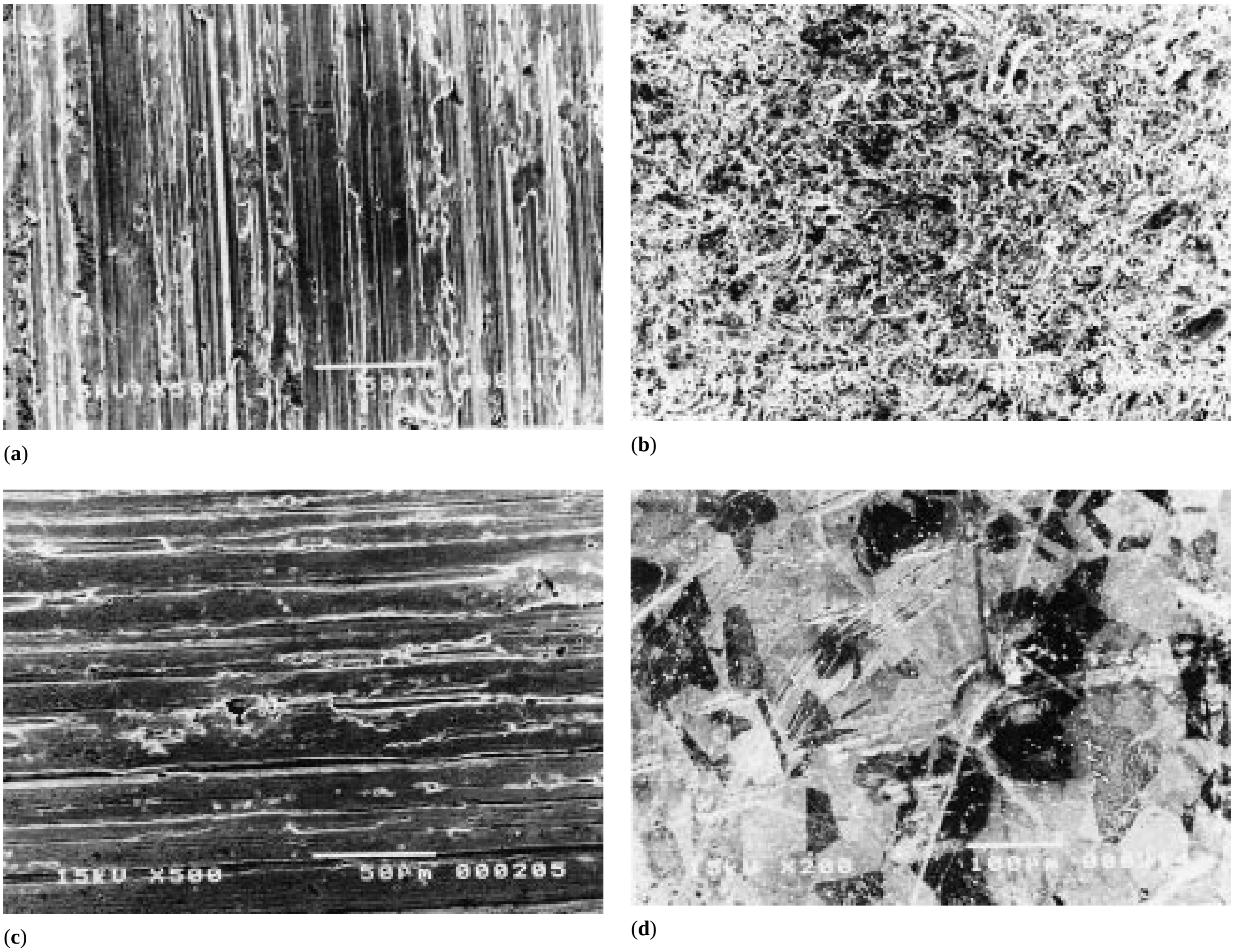

Fig. 2 Micrographs of the ground and finished surfaces. (**a**) Ground steel surface: $\nu = 2$ m/min. (**b**) Sand blasted (Qz100) after grinding. (**c**) Wire brushed (280 rpm) after grinding. (**d**) Electrolytically polished after grinding

Surface Integrity

Pitting Corrosion in Sea Water

Experimental results of the cyclic potentiodynamic tests are shown in Table 2. The tests were conducted to determine the pit potential (E_p) and repassivation potential (E_r), to quantify the effect of the surface treatments on pitting corrosion resistance (E_p) and crevice corrosion (E_r), compared to the as-ground reference sample.

The most improvement is seen from the wire brushing treatment ($E_p \sim 500$ mV/SCE compared to 100 mV/SCE for the as-ground reference state), which gives a pitting corrosion resistance equivalent to the electrolytically polished state. The sand blasting operation also produces an improvement of pitting corrosion resistance ($E_p \sim 350$ mV/SCE), albeit slightly less effective.

The only treatment that gives a significant change in the crevice corrosion resistance is electrolytic polishing, which raises E_r to 120 mV/SCE. The wire brushing and sand blasting treatments do give an increase relative to the condition after grinding (from ~ -200 to ~ -130mV/SCE), while the mechanical polishing shows virtually no change.

Stress Corrosion Cracking

Stress corrosion cracking is exacerbated by the presence of a tensile residual stress in the near-surface region of a component. The resistance to SCC was analyzed by immersing the prepared surfaces in $MgCl_2$ solution at 40 g/L heated at 140 °C, during 48 h. Resistance was quantified, for the purpose of this study, simply on whether surface cracking was observed in a scanning electron microscope after this treatment. The signs and the values of the residual stress express the gain provided by treatment improvement in terms of susceptibility to corrosion cracking. Table 2 summarizes the results of the microscopic observations made after surface immersion in $MgCl_2$ solution.

Near-surface layers in tension following the grinding operation were the site of crack initiation caused by a combination of the residual stress (500 MPa) and the Cl^- ions (Fig. 5).

When the brushing speed is below a threshold ($<$900 rpm),

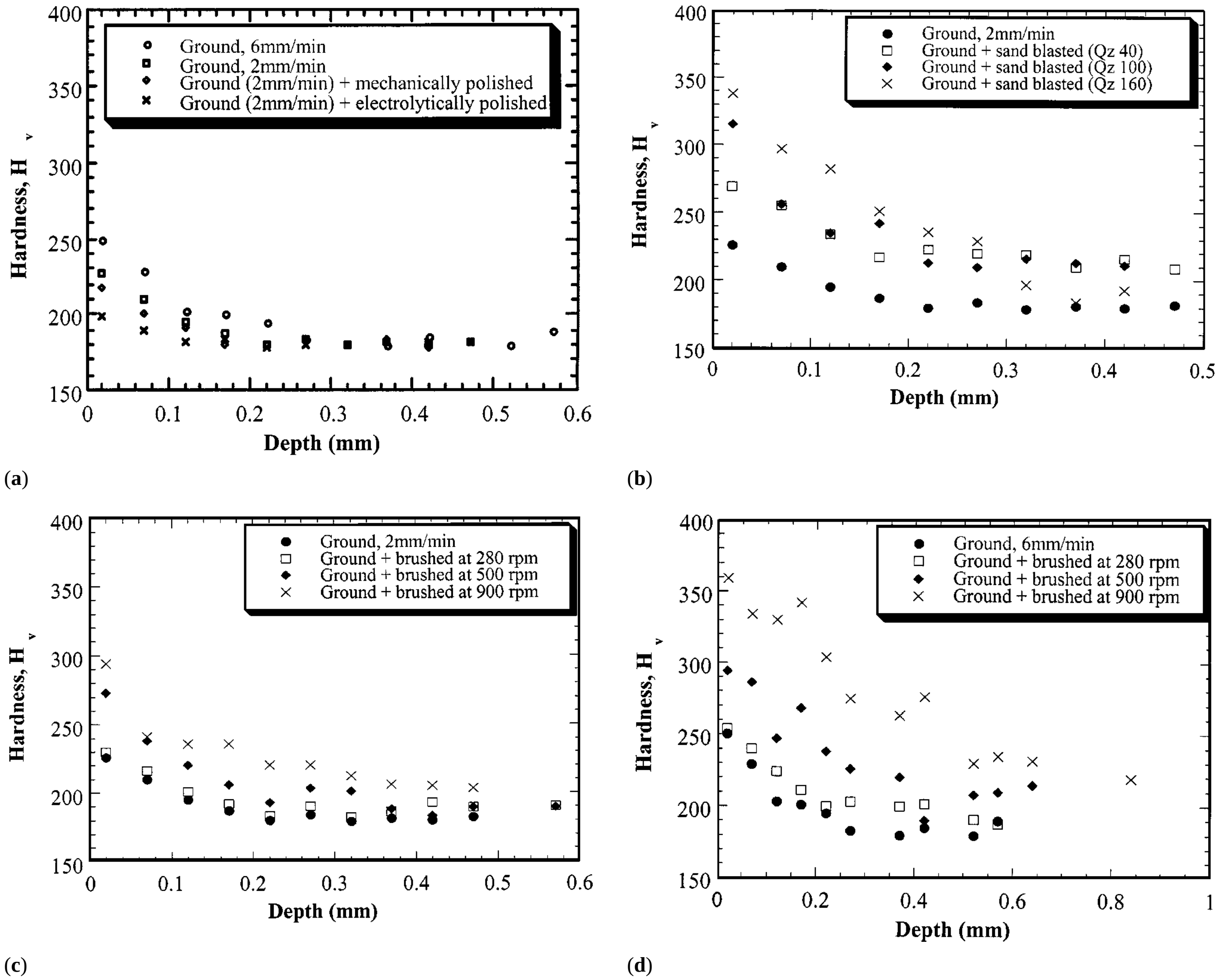

Fig. 3 Degree of cold work from the surface treatment, as measured by Vickers microhardness. (**a**) The two as-ground conditions, plus after electrolytic or mechanical polishing. (**b**) The effect of sand blasting on the hardness profile. (**c**) and (**d**) The effect of wire brushing on the hardness profile, for initial grinding at 2 and 6 m/min, respectively

Table 4 X-ray measurements of the surface stress after various grinding and finishing processes. The grinding direction is equivalent to $\phi = 0$

Initial grinding workpiece speed	Secondary treatment	Stress ($\phi = 0$) MPa	Stress ($\phi = 90$) MPa	Peak width (°) from a peak at $\phi = 0$; $\psi = 0$
2 m/min	…	400 ± 20	80 ± 25	2.30
2 m/min	Brushed 280 rpm	−335 ± 35	−515 ± 35	2.13
2 m/min	Brushed 500 rpm	−230 ± 35	−400 ± 20	2.16
2 m/min	Brushed 900 rpm	−300 ± 60	−425 ± 20	2.23
2 m/min	Sand blast QZ40	−630 ± 60	−595 ± 30	2.57
2 m/min	Sand blast QZ100	−580 ± 35	−515 ± 45	2.50
2 m/min	Sand blast QZ160	−670 ± 35	−720 ± 60	2.58
6 m/min	…	255 ± 35	−125 ± 65	2.31
6 m/min	Brushed 280 rpm	−275 ± 35	−330 ± 65	2.47
6 m/min	Brushed 500 rpm	−275 ± 65	−535 ± 25	2.23
6 m/min	Brushed 900 rpm	−505 ± 70	−555 ± 60	2.01
6 m/min	Sand blast QZ40	−685 ± 55	−675 ± 80	2.56
6 m/min	Sand blast QZ100	−580 ± 35	−620 ± 45	2.76
6 m/min	Sand blast QZ160	−640 ± 25	−560 ± 30	2.59

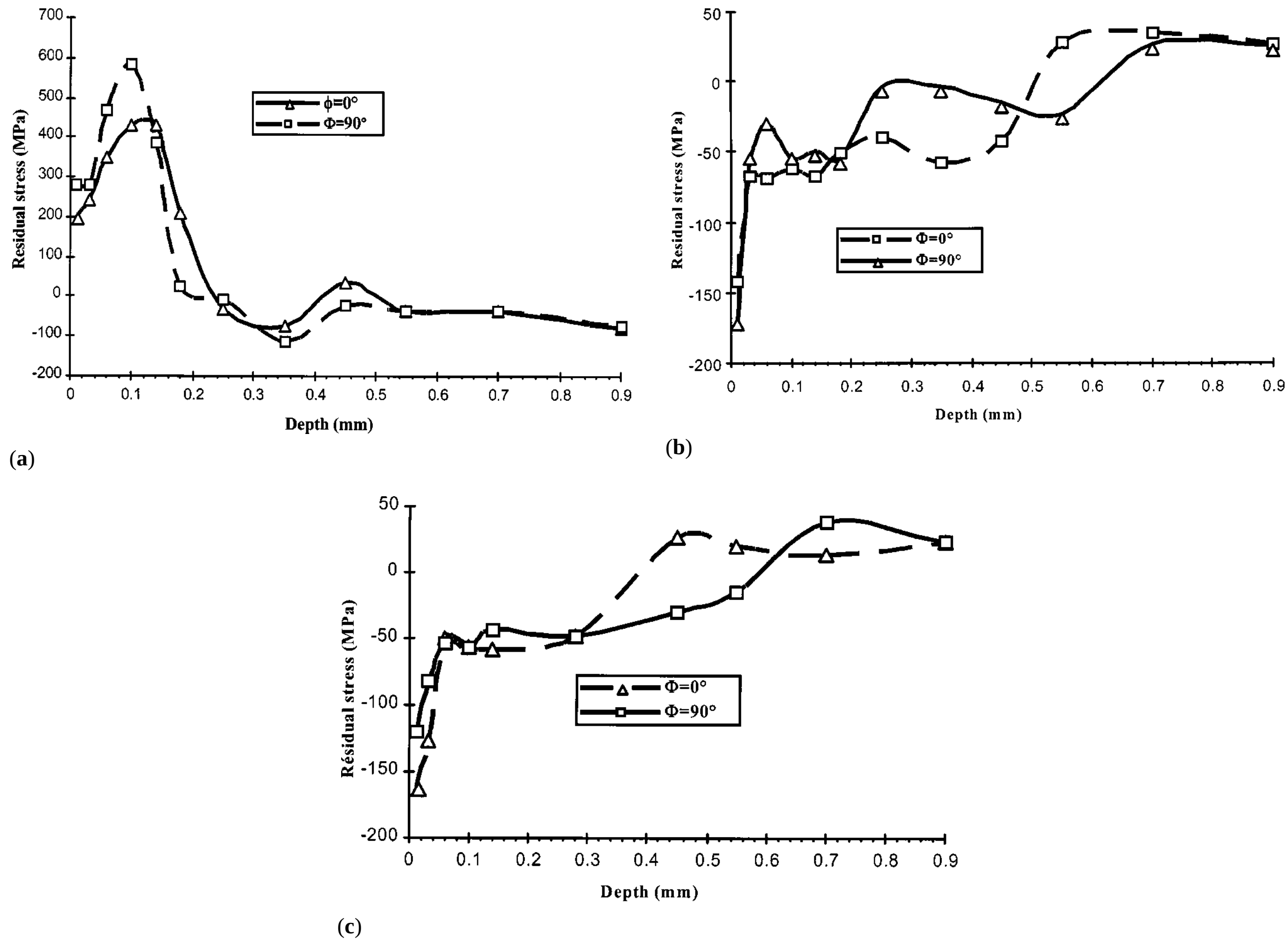

Fig. 4 Profiles of residual stress following surface treatment. (**a**) Grinding at workpiece speed = 2 m/min. (**b**) Sanding (Qz160) after grinding (workpiece speed = 2 m/min). (**c**) Brushing (900 rpm) after grinding (workpiece speed = 2 m/min)

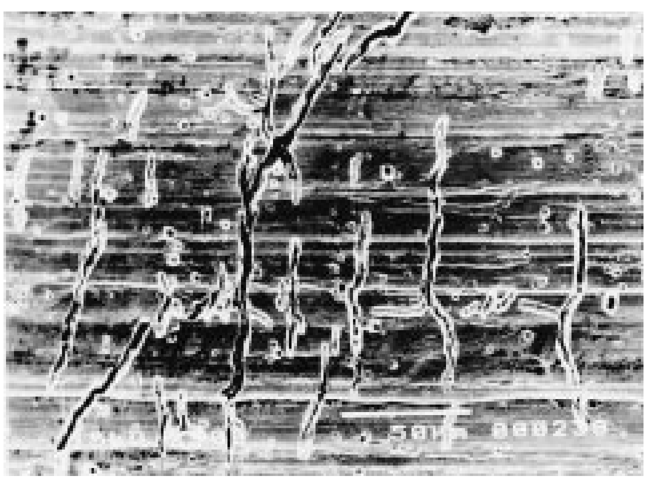

Fig. 5 SCC of ground state after immersion in $MgCl_2$ solution at 40 g/L heated at 140 °C

the surfaces ground at a work speed of 2 m/min followed by brushing have also been found to be sensitive to SCC phenomena (Fig. 6). On the other hand, layers under compression produced by sanding operation or brushing at higher speeds do not show any cracking that could be observed by scanning electronic microscopy.

Discussion

Finishing and improvement treatments such as sand blasting or wire brushing induce plastic deformation in the surface layers. This results in a surface hardening that depends on the precise surface preparation mode and the strain rate and deformation temperature at the surface.[2,10] In this way, the initial surface hardness is as important a parameter as the surface treatment speed (in the case of wire brushing) or the particle size (in the case of sand blasting): these parameters determine the amount of cold work as well as the depth of the hardened layers.

The surface state resulting from sand blasting is not affected as much as the similar treatment by shot peening, owing to the relative small projectiles size: 120 μm for Qz160 compared to shot peening where the diameter of balls varies between 300 and 800 μm, which results in greater surface deformation.[1,11]

The plastic deformation gradient, generated by finishing

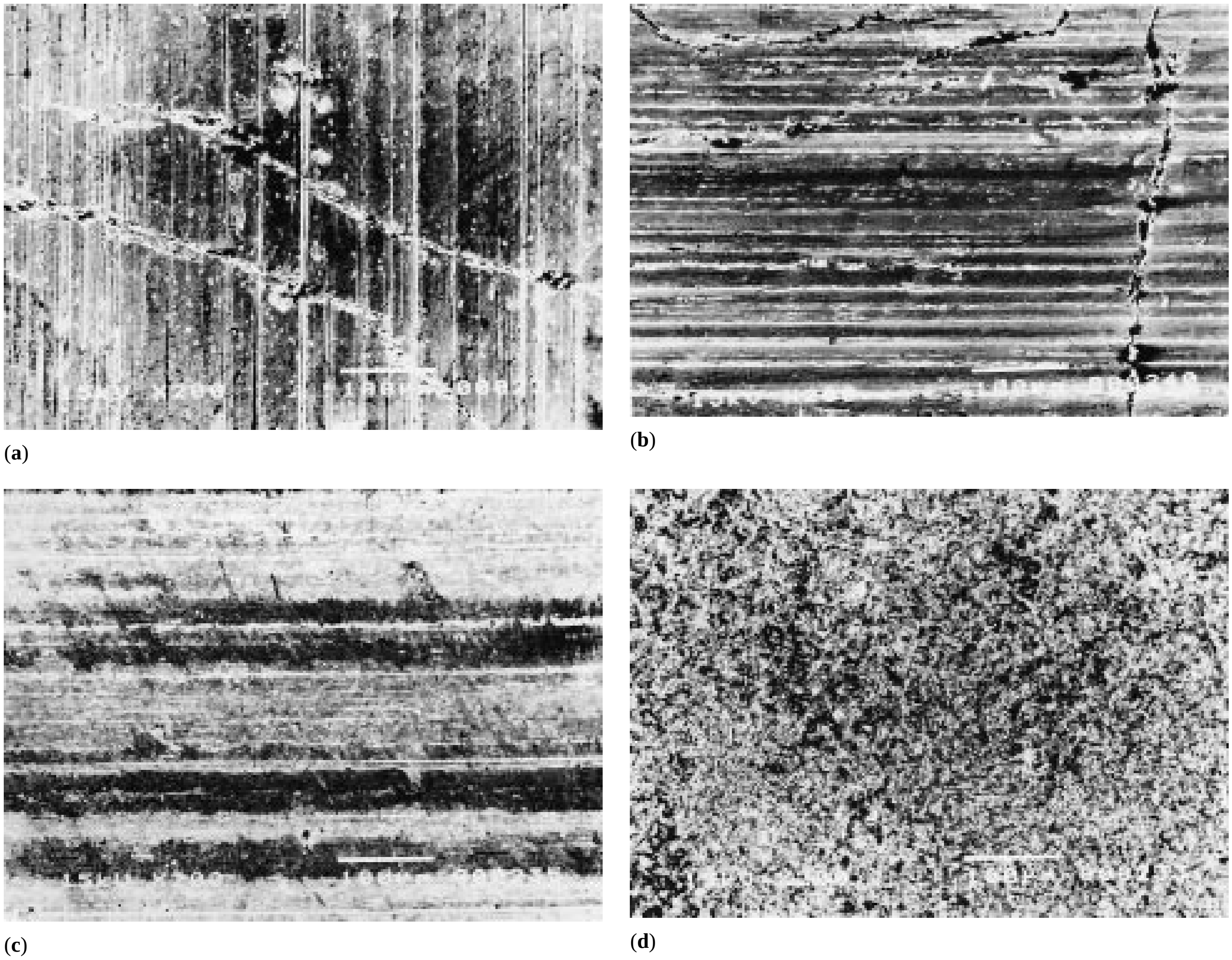

Fig. 6 Susceptibility to SCC. (**a**) Brushing (280 rpm) after grinding. (**b**) Brushing (500 rpm) after grinding. (**c**) Brushing (900 rpm) after grinding. (**d**) Sanding (Qz100) after grinding

operations or improvement treatments, creates an incompatibility of plastic deformation between the affected near-surface layers and the remaining base material. This incompatibility causes tensile residual stress in grinding and compressive residual stress in sand blasting and in brushing.[11–13] These stresses are in fact the result of superposition of two deformation fields (one created by the machining operations and the other by finishing treatments).

The tensile residual stress, measured in a direction parallel to the grinding streaks, was over the threshold of SCC of steel 316L in $MgCl_2$ solution. This explains the many cracks observed, particularly perpendicular to the machining direction.

Unpolished surfaces after sand blasting ($\sigma_r \sim -175$ MPa) or brushing ($\sigma_r \sim -125$ MPa) do not develop cracks after immersion in the $MgCl_2$ solution.

However, for lightly brushed surfaces, the level of residual tensile stress remains sufficiently high to develop cracks by stress corrosion.

It seems that pitting corrosion resistance improvements are due to the cold worked near-surface layers provided by the improvement treatment. Indeed, sand blasting, which does not give improvement of surface roughness, generates a better resistance to pit initiation in sea water than grinding.

Conclusions

Sanding and brushing could be retained as an improvement technique of machined or ground surfaces of stainless steel. When these techniques are used properly, they improve the resistance to pitting, crevice, and corrosion under stresses in a medium as aggressive as sea water.

The additional hardening by plastic deformation and compressive residual stress fields generated by these surface treatments are the origin of surface integrity improvement with respect to pitting corrosion and SCC resistance.

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