Surface and Mechanical Properties of Steel Processed By Electro-Plasma Technology

by P. Gupta[*] *& G. Tenhundfeld*

The present study involves removal of the oxide scale from A36 steel strip by Electro-Plasma Technology (EPT). The surface morphology and roughness of the cleaned strip were analyzed and compared with a grit-blasted surface. The microhardness and microstructure of the EPT-cleaned strip were compared with the parent strip. EPT efficiently cleaned the steel and created a desirable anchor surface profile along with uniform microroughness. The microhardness and microstructure of the basis metal were not affected by EPT. EPT presents a commercially viable solution as a "Green Technology" to pickle steel, enhancing the surface characteristics and maintaining the desired properties of the processed material.

Surface preparation (removal of oxide scale, lubricants, oil, dirt, etc.) is a crucial step prior to most metal finishing processes. The industrial technology most used for the removal of scale is acid pickling. Problems of health hazards, acid storage and disposal, and increasing restrictions posed by governments worldwide have created a need to find an alternative environmentally-friendly technology. Mechanical descaling methods (grit blasting, wire brushing, etc.) provide an alternative solution, but the maintenance cost is high. Additionally, mechanically descaled material is generally cleaned by acid pickling prior to drawing or coating.

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Nuts & Bolts: What This Paper Means to You

The technology most commonly used for the removal of oxide scale from steel is acid pickling. This work presents an alternative, commercially viable "green technology" to pickle steel, which enhances the surface characteristics and maintains the properties of the steel. Called Electro-Plasma Technology (EPT), this method, as you will see, is a hybrid of electrolytic (aqueous) and atmospheric plasma processes. The results are intriguing.

The electroplasma process has shown immense potential in providing an acid-free cleaning solution for conductive materials.[1-3] Previous studies have shown that this cathodic atmospheric plasma process improves the corrosion and adhesion characteristics of the surface.[1,2] The present study focuses on the second generation of electroplasma technology (EPT) that uses "foam contained in a reactor" as compared to the liquid medium used by the first generation "flow through" process.[1] Foam provides better control, increases efficiency and makes the process industrially economical.[4] In the current investigation, steel strip was cleaned by EPT. This paper addresses issues of the effects of EPT on the microstructure and hardness of steel, a major industrial concern that has not been reported earlier, even for the first generation of technology. This paper also verifies whether EPT maintains and/or improves the surface conditions reported for the first generation of technology.

Experimental

A laboratory unit was designed to clean scale from low carbon (A36) steel strip. The electrolyte used was a $NaHCO_3$ solution with some additives, at a temperature of 70 to 80°C (158 to 176°F). The pH and conductivity of freshly prepared electrolyte were 8.5 and 140 mS/cm (milli-Siemens/cm) at 70°C (158°F), respectively. Metallographic cross sections were prepared to study the microstructure and hardness of EPT-processed steel strip. Microhardness profiles were measured along the thickness cross-section using a Knoop indenter with a 500 g load. Knoop microhardness values were converted into Rockwell hardness values as per ASTM E140. The microstructure and microhardness of the parent material were also analyzed for comparison. The morphology and composition of the surface were analyzed by SEM and EDAX,[**] respectively. The surface roughness and profile of the cleaned strip were measured by using an optical profilometer.[***] The surface morphology and roughness of the grit-blasted steel strip were also analyzed for comparison. The corrosion resistance of the EPT-processed surface was studied by exposing the cleaned material in a laboratory environment at a relative humidity of about 75% for six months. The results for a grit-blasted surface exposed under similar conditions are also provided for comparison.

[**] *Hitachi S-4500II Field Emission SEM, Hitachi Ltd., Tokyo, Japan.*
[***] *Wyko NT-3300 Optical Profiler, Veeco Instruments, Woodbury, NY.*

Results

Characteristics of the cleaned surface

Figure 1 shows the microstructures of the parent and EPT-cleaned steel strip. The thickness of the scale in the parent strip varied from 5 to 11 μm (197 to 433 μ-in.) [Fig. 1(a)]. The thickness is close to the typical mill scale thickness range of 7 to 14 μm (276 to 551 μ-in.). The parent material exhibited a microstructure typical of low carbon steel, characterized mostly by the presence of ferrite grains [Fig. 1(a)]. The EPT-cleaned steel specimen exhibited no significant change in microstructure and grain size from surface to bulk [Fig. 1(b)]. Also, it can be seen that the scale was completely removed from the surface after cleaning. EDAX spectra also support the cleaning of scale by the reduction of oxygen content at surface after EPT treatment, [Figs. 1(c) and 1(d)].

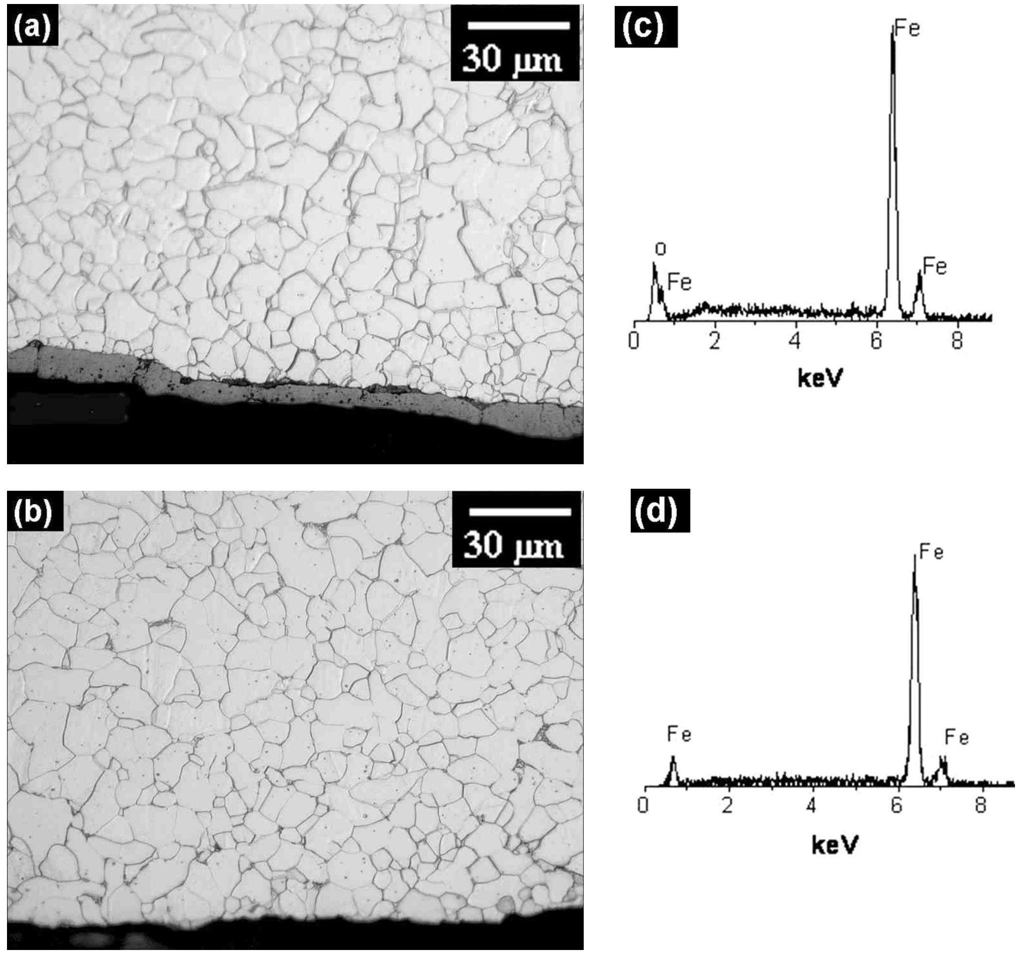

Figure 1—Microstructure (a) parent and (b) EPT cleaned and EDS of (c) parent and (d) EPT cleaned steel strip.

Surface morphology and profile

Figure 2 shows morphology of the EPT-cleaned surface. The morphology of the grit-blasted surface is also shown for comparison. The EPT-cleaned surface exhibited typical electroplasma processed morphology, characterized by microcraters and spheroid like features [Fig. 2(a)]. On the contrary, the grit-blasted surface was characterized by the presence of deep pits [Fig. 2(c)]. It is interesting to note that the pits do not seem to be uniformly distributed over the treated surface in contrast to the uniform distribution of microcraters in EPT samples. Furthermore, the region between the pits in the grit-blasted surface was relatively smooth, as shown by comparing the high magnification micrographs [Fig. 2(b) and (d)].

Figure 3 shows the depth profiles of the surfaces after EPT treatment and grit blasting. A summary of surface roughness results is presented in Table 1. The grit-blasted surface had a higher surface roughness than the EPT-treated surface. The contrast is visually evident when comparing the depth profile of the two surfaces [Figs. 3 (a) and (c)]. It is

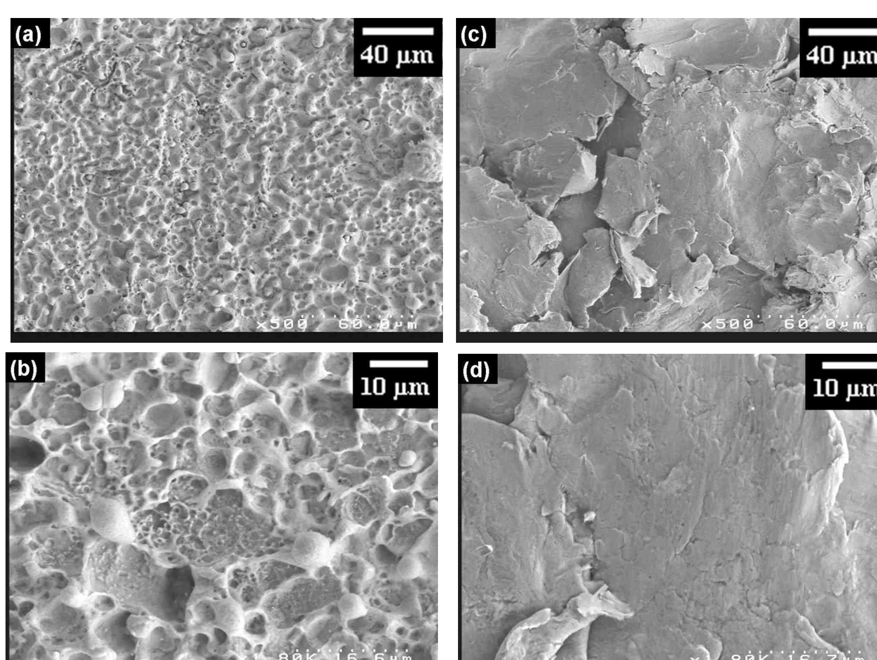

Figure 2—Surface morphology of strip after cleaning with (a) EPT and (c) grit blasting. (b) and (d) are high magnifications of (a) and (c), respectively.

interesting to note that depth profile measured at different positions along the X-axis [*i.e.*, the Y-axis profiles in Figs. 3(b) and (d)] also shows that an EPT-treated surface had a uniformly rough surface when compared to that of the grit-blasted surface. Furthermore, the wavelength between consecutive valleys or peaks is much longer in a grit-blasted surface versus an EPT surface. This distinction can clearly be seen in the 3D photos of the surface profiles. The surface roughness results are in agreement with the SEM study. The uniform distribution of microcrater morphology led to the creation of uniform microroughness in EPT-treated surfaces.

Table1
Roughness of EPT and Grit Blasted Steel Surfaces

	Grit Blasted	Plasma Cleaned
R_a (μm)	9.4	2.2
R_q (μm)	13.3	2.3

R_a = Average surface roughness; R_q = RMS surface roughness.

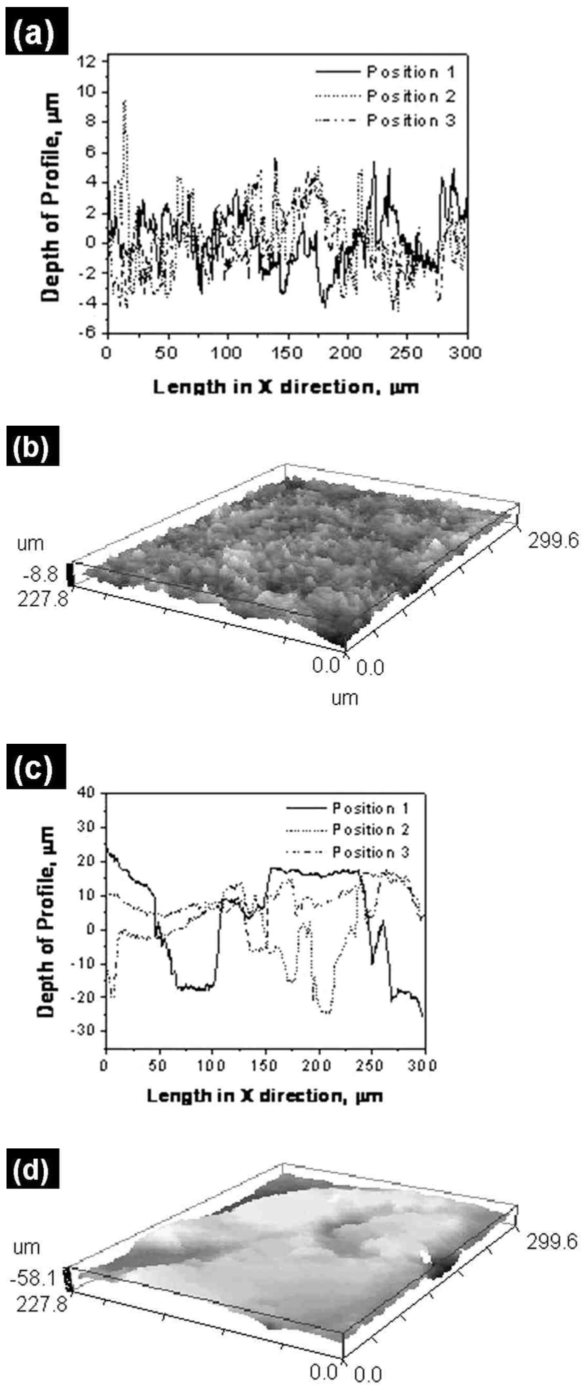

Figure 3—(a) and (c) depth profile of EPT and grit blasted surfaces, respectively. (b) and (d) are 3-D photos of the respective surface profiles.

Microhardness testing

Figure 4 shows the microhardness profile along the thickness of the EPT-cleaned steel specimen. The results for parent material are also presented for comparison. The parent material showed higher hardness at the edges when compared to the center. This behavior is typical for rolled material. The EPT-cleaned strip exhibited no significant change in hardness with an average hardness of 125 HK_{500} (63 R_B) versus 124 HK_{500} (62 R_B) for the parent material. It is interesting to note that the EPT-processed material exhibited a microhardness profile along the strip thickness which was similar to that of the parent material. The microhardness results were compatible with the results of the microstructure study.

Surface passivation

Figure 5 shows the level of rusting observed on the EPT-cleaned and grit-blasted strip steel samples after exposure for six months in a laboratory environment at a relative humidity of 75%. The EPT-cleaned material exhibited little rusting when compared to the grit-blasted material. Some rust could be seen at the edge of EPT-cleaned strip [Fig. 5(a)]. The strip was cut for different analyses after EPT processing, exposing the fresh metal at the edges to the atmosphere, and subsequently leading to rusting.

Discussion

Electroplasma technology (EPT) is a hybrid of electrolytic (aqueous) and atmospheric plasma processes. Hydrogen, in the bubbles produced at or in the vicinity of the cathode surface, is ionized and converted to plasma with the application of high voltage (>70 V_{DC}). This is unlike conventional electrolytic processes that oper-

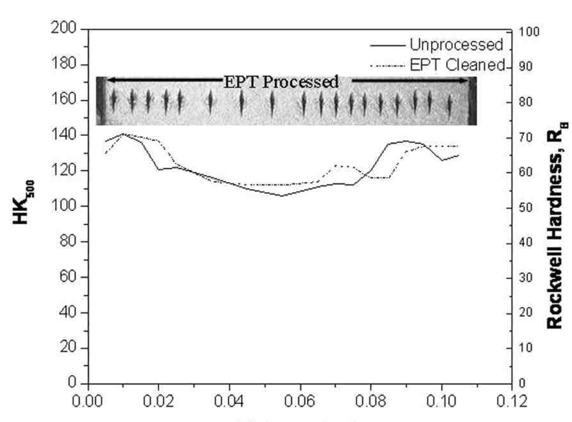

Figure 4—Microhardness profile along the thickness of the strip (HK_{500}).

ate at low voltages. The temperature in the plasma bubbles can reach a level, locally, of 2000°C (3632°F) or higher. This results in melting of the specimen surface that is limited to microzones, most likely due to the small size of the plasma bubbles. Furthermore, shock waves produced by the implosion of bubbles (*i.e.*, cavitation) in combination with the quenching of the melted microzones by the electrolyte leads to the formation of the spheroidal and microcrater type of morphology, as reported earlier.[1,4] By contrast, the grit-blasted surface was cleaned by angular steel shot to provide maximum roughness. The plate-like abrasion exhibited by the grit-blasted surface was more than likely due to the machining effect produced by the angular shot.

Despite the fact that the grit-blasted surface exhibited higher roughness, the EPT-treated surface had higher tendency to provide a mechanical anchor for coatings and adhesives because of its morphology and uniform microroughness. Previous studies on the first generation of the technology showed that electroplasma provided a better anchor surface for coating adhesion when compared to grit blasting in tensile adhesion tests.[2] The size of plasma bubbles was an important factor in determining the size of the microcraters produced. EPT provided improved control of the plasma bubble size by constraining it in a limited reactor space when compared to first generation technology. The size of the microcraters affected the microroughness of the treated surface. Thus, the containment afforded by the foam medium in EPT provided much better microroughness control. The process control afforded by EPT has resulted in excellent adhesion of copper-cladded steel, after a beta industrial cleaning test on a 5.5-mm (0.22-in.) diameter steel rod at a line speed of 61 m/min (200 ft/min).[4]

Prior work has shown that the surface roughness of the workpiece is an important parameter in increasing the lubricant transport rate during the drawing process.[5,6] Some studies indicate that surface morphology plays a significant role in improving the lubricant holding capacity of a surface.[7] Recently, a study conducted on electrolytic phosphate observed that porosity, its size and distribution was important in retaining soap-based lubricants for wire drawing.[8] Furthermore, the study showed that the small crystallite size produced by electrolytic phosphate performed better during wire drawing when compared to conventional zinc phosphate. It is interesting to note that the surface morphology created by EPT [Fig. 2(a)] is similar to that produced by electrolytic phosphate.[4,8] All the above facts and the present results suggest that the microcrater morphology and microroughness provide favorable conditions for lubricant pickup and entrapment during drawing or rolling. This also suggests that EPT possesses great potential to reduce if not eliminate the use of phosphate coatings prior to metal drawing processes.

As discussed earlier, the high plasma temperatures are limited to the microzones in the surface layer, thereby maintaining the bulk temperature of the material at about 100°C (212°F), *i.e.*, the boiling point of the electrolyte, or lower. Recently, some microdischarges were observed by digital imaging, for an anodic electrolytic process, plasma electrolytic oxidation (PEO).[9] The plasma was reported to consist primarily of small microdischarges (cross-section area approximately 0.02 mm^2) with their fraction 96% at the beginning and 67 to 77% in the final stages of treatment. EPT, a cathodic process, may exhibit the same or smaller size discharge throughout the process, thereby causing no significant change in the microstructure or hardness of the bulk material after EPT processing.

Previous corrosion studies conducted by open circuit potential measurements in tap water[1] and linear polarization tests[2] have shown superior corrosion resistance for electroplasma-cleaned steel surfaces. Furthermore, it was reported that a 150 to 250 nm-thick layer of pure iron, having a grain size of 10 to 20 nm, formed

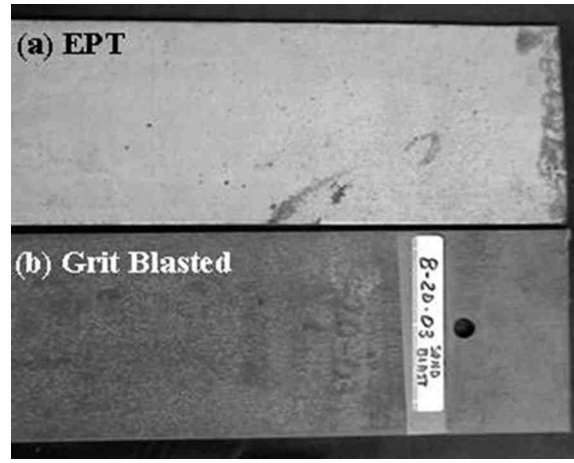

Figure 5—Level of rusting on steel strip, cleaned by (a) EPT and (b) grit blasting, after exposure for 6 months in the laboratory under a relative humidity of about 75%.

on the steel surface.[1] This may be causing the passivation behavior exhibited by an EPT-cleaned surface. Superior localized corrosion resistance, because of fine grain structure, has been reported for nanocrystalline 304 stainless steel, when compared to conventional 304 stainless steel.[10] The passivation phenomenon occurring after EPT treatment is not fully understood at present, and more detailed analysis is required. The passivated surface of EPT-treated steel provides the potential capability of processing such material (like drawing or coating), after storage on the order of a few days after cleaning as shown in the previous study.[4]

Conclusions

Electroplasma technology (EPT) cleaned scale from steel strip with the creation of a microcratered surface morphology and uniform microroughness. The microstructure and microhardness of the parent material was not affected after cleaning by EPT. The passivated surface obtained after cleaning resisted corrosion for a few weeks in closed humid conditions. EPT shows great potential in providing an environmentally friendly solution to the cleaning needs of industry.

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