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Technical Paper

Surface finish control by electrochemical polishing in stainless steel 316 pipes

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ABSTRACT

Electrochemical machining (ECM) is a non-conventional machining process which is based on the localised anodic dissolution of any conductive material. One of the main applications of ECM is the polishing of materials with enhanced characteristics, such as high strength, heat-resistance or corrosion-resistance, i.e. electrochemical polishing. The present work presents an evaluation of the parameters involved in the ECM of Stainless Steel 316 (SS316) with the objective of predicting the resulting surface finish on the sample. The interest of studying ECM on SS316 resides on the fact that a repeatable surface finish is not easily achieved. ECM experimental tests on SS316 pipes of 1.5″ (0.0381 m) diameter were conducted by varying machining parameters such as voltage, interelectrode gap, electrolyte inlet temperature, and electrolyte flow rate. The surface finish of the samples was then evaluated in order to find the significance of each of these parameters on the surface quality of the end product. Results showed that overvoltage, which is dependent on the interelectrode gap and the electrolyte temperature, is one of the main parameters affecting the surface finish; additionally there is a strong relationship between the resulting surface finish and the electrolyte flow. The interelectrode gap and inlet electrolyte temperature also affect the resulting surface finish but their influence was not so evident in this work. Finally, the variation of the electrolyte temperature during the process was found to have a great impact on the uniformity of the surface finish along the sample. We believe that this contribution enables the tailoring of the surface finish to specific applications while reducing manufacturing costs and duration of the ECM process.

1. Introduction

ECM of metals with special characteristics, such as enhanced strength, heat or corrosion resistance, is a manufacturing option to produce products that could be difficult or impossible to get with conventional manufacturing processes. ECM allows manufacturers to shape any conductive material without affecting the properties of the tool or the workpiece. In addition, ECM can generate a high quality surface finish at the workpiece.

ECM consists of an electric circuit formed by the tool and the workpiece connected to an external electrical source. The electrodes are submerged in an electrolyte bath that closes the circuit. When current passes through the circuit, a localised anodic dissolution occurs at the workpiece. This results more or less in the negative shape of the tool profile [1]. The electrolyte is pumped through the interelectrode gap dragging the dissolved material away and cooling down the electrodes. Unfortunately, the ECM process is difficult to predict due to the wide variety of physical phenomena involved and the lack of sufficient quantitative and qualitative data that can be used to develop of an accurate simulation model [2,3].

One of the main applications of ECM is the polishing of materials, i.e. electrochemical polishing. Several studies of electrochemical polishing can be found in the published research [4–10], and studies on applying electrochemical polishing for the manufacture of biomedical implants [11], solar cells [12] and electrodes for photoelectron guns [13], are still under development. However, electrochemical polishing is a process that regularly generates non-repeatable results, e.g. the application of the process on stainless steels (SS) typically generates widely variable surface finish. Therefore, in many of these studies, special attention has been given

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to ECM on steels with high chromium content. Iron-chromium alloys, such as stainless steels, have wide applications in industry due to their characteristic behaviour (oxidation resistance). The chromium in SS induces the formation of a protective film of oxide on the material surface that prevents further corrosion [8]. However, this oxide film also modifies the ECM at the surface of the material; it has low electrical conductivity and prevents the workpiece from making direct contact with the electrolyte. Hence, normal anodic dissolution cannot be implemented without the breakdown of the oxide film. Partial breakdown of this film often occurs, which causes pitting on the surface [4,8] or a non-uniform surface finish [6,7,14].

The surface finish of the samples results from the specular or non-specular reflection of light from the crystal faces that have been electrochemically dissolved at different rates during the ECM process [1,15]. An electrochemically polished surface is usually associated with the random removal of atoms from the anode (workpiece) [15]. Datta and Landolt [16] observed that an active dissolution of material at low current density leads to surface etching, and a transpassive dissolution at high current density leads to surface brightening. This was also noted by Lee [5] and McGeough [1]; in their studies when the current density was raised, the surface finish on the workpiece became smoother. Lozano-Morales [14] found the same behaviour with ECM in Niobium samples. Elsewhere, Wagner [17] and Wang et al. [18] gave a plausible explanation of the effect of the electrolyte flow rate on the surface finish on SS. They argue that during ECM, the electric current breaks the oxide film and local electrolyte flow turbulences would ideally remove the film particles (oxides, chromium carbides and reaction products). If the turbulence is not sufficient for removing these lose particles, Fe^{n+} - diffusion through the surface layer is possible, and the current density efficiency decreases drastically, thus affecting the surface finish.

In other works, Lee [5] found that when electropolishing stainless steel 316L, better electropolishing results were obtained at a temperature close to 68 °C than at 30 °C. Later on, Deconinck [2] demonstrated how the electrochemical reactions rates depend strongly on the electrolyte temperature, which in turn depends on the electrolyte flow rate, interelectrode gap and potential applied.

Mount et al. [6–8] built a segmented tool for the further analysis of the ECM process when applied on SS. Their results described a change in the surface finish of the samples along the electrolyte flow. It was found that this special behaviour is due to the change of the dissolution valence of the alloy. Their results showed that for high dissolution valences, $z = 3.5 \pm 0.1$, the resulting surface was reflective and bright. This surface fish is characteristic of iron and chromium dissolving in their high valence states (as Fe(III), $z_{Fe} = 3$, and Cr(VI), $z_{Cr} = 6$); however, if z was lower, 2.5 ± 0.1, the surface finish was passivated. This surface finish is also characteristic of iron and chromium dissolving but now in their low valence states (as Fe(II), $z_{Fe} = 2$, and Cr(III), $z_{Cr} = 3$) [8]. These results are in agreement with the study of Lohrengel et al. [3] and Murkherjee et al. [19].

From the above, we can conclude that it is essential to understand how the ECM parameters affect the surface finish. The effective removal of this film is governed by a combination of metal-electrolyte-machining parameters. Hence, in the present work, the ECM machining parameters, gap, voltage, flow rate and inlet electrolyte temperature, are modified in order to evaluate their role on the achievement of the expected surface finish and a homogeneous breakdown of the oxide film. To the best of our knowledge, this is the first time that the inner surface finish of stainless steel commercial pipes has been enhanced by electrochemical polishing to tailor it for industrial applications and large scale production.

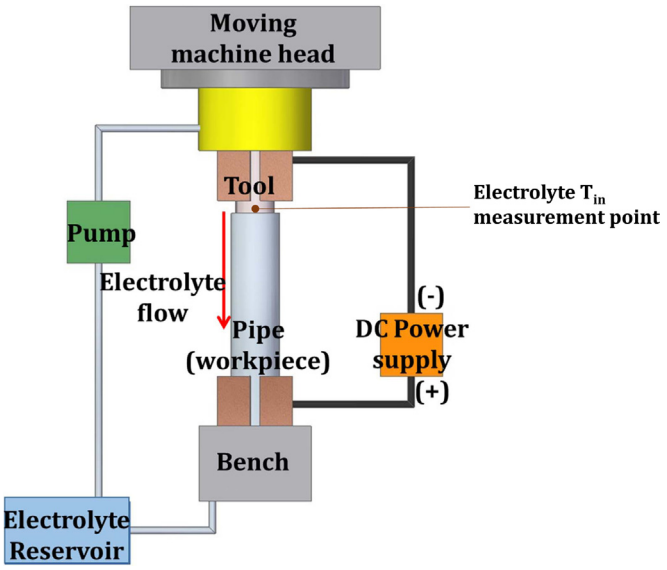

Fig. 1. Schematic of the electrochemical machining system.

2. Experimental method

2.1. Sample preparation

The pipes machined were commercial stainless steel 316 (SS316) pipes of 0.17 m length and 0.0381 m diameter, which were manufactured by rolling and welding. The surface finish of the pipe prior to processing was dark and opaque and its quality was uniform along the pipe. Welding left behind a weld-flash at the interior face of the pipe. The exterior of the pipe was not treated.

2.2. Electrochemical (ECM) setup

Fig. 1 shows the ECM array consisting of a cylindrical solid tool and a pipe (workpiece) placed vertically and concentric with each other on the bedplate of the ECM machine. The tool was held by the machine head and the workpiece was fixed to the bedplate by a non-conductive clamp. The electrolyte flowed from the top and between the pipe and the tool, and the setup was positioned in such a fashion that allows the electrolyte to exit the array. The temperature of the electrolyte was measured in situ at the entrance of the pipe using a digital thermometer.

2.3. Test parameters

The tool had the similar dimensions as the pipe. Its diameter offset from of the interior diameter of the pipe (workpiece) but undersized radially by 2, 4 or 8 mm. Electrical clips were connected to the tool-workpiece array providing a constant voltage of 18, 24 and 36 V (possible voltage losses in the system were not considered). The experimental parameters are summarised in Table 1.

The electrolyte used was Sodium Nitrate ($NaNO_3$) with specific gravity (S.G.) of 1.15. Electrolyte flow rate was recirculated and set

Table 1
Variables used for ECM on SS316 experimental tests.

	Name	Value
y	Interelectrode gap	2, 4, 8 mm
V_1	Voltage	18, 24, 36 V
Q	Electrolyte flow rate	1.7×10^{-4}, 4.2×10^{-4}, 6.7×10^{-4}, 10×10^{-4} m^3/s
T_e	Inlet electrolyte temperature	7, 15.3 °C