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PRECISION EQUIPMENTS

Performance Enhancement of Heat Exchanger Tubes by Electropolishing

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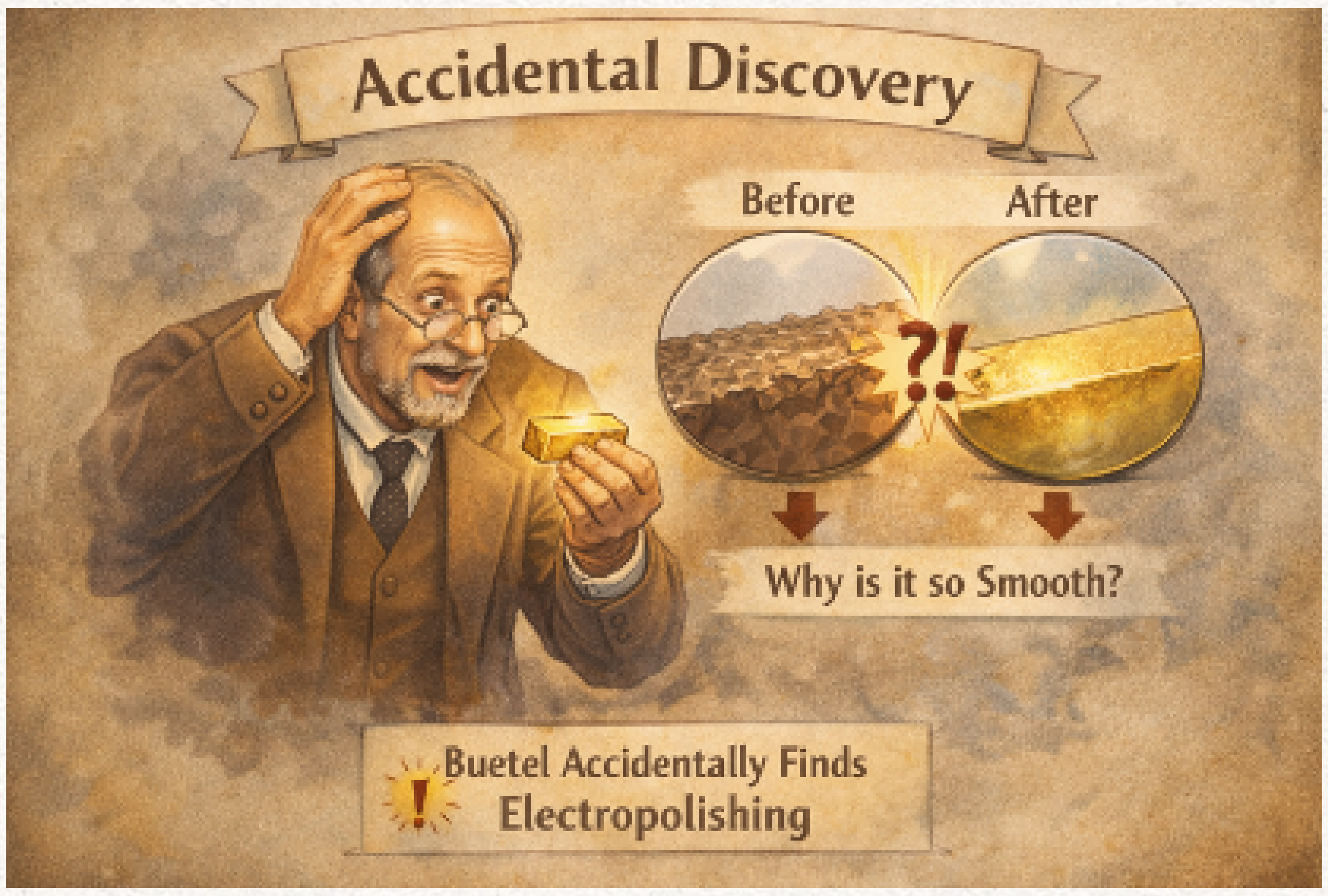
ABSTRACT

Heat exchangers are critical components in large-scale industrial plants, where even minor improvements in surface condition can lead to measurable gains in thermal performance, reliability, and service life. In response to specific operational requirements at one of India's largest PVC manufacturing facilities, Precision Equipments Chennai Pvt. Ltd. (PECPL) conducted focused engineering studies and followed by Mock-up on electropolishing. Among the available surface finishing methods, electropolishing was selected due to its ability to produce ultra-smooth, contamination-free internal surfaces. This paper presents the process involved in electropolishing of tubes and tube sheets.

1. INTRODUCTION

One of our recent clients required a vertical heat exchanger equipped with electropolishing on the internal surface of tubes and on the channel side including tube sheets to satisfy specific process performance requirements. To address this need, PECPL conducted a Mock-up study to evaluate the technical feasibility and ensure successful implementation. Duplex stainless steel (DSS) seamless tubes were manufactured by tube vendor and supplied in electropolished condition and channel along with the tube sheets were electropolished with in-house developed procedures, strictly adhering to the client's technical criteria. Although electropolishing is a specialized surface finishing process with a relatively higher cost compared to conventional polishing methods, it offers substantial functional benefits. In this application, the heat exchanger operates in a PVC plant, where the process fluid exhibits high viscous tendency to adhere to rough internal tube surfaces, leading to stickiness, deposit formation, and flow restrictions. The inherent surface roughness of untreated tubes & channel significantly accelerates such fouling behaviour. Electropolishing of the internal surfaces markedly reduces surface roughness and promotes the formation of a smooth, passive layer, thereby minimizing PVC adhesion and deposit buildup. As a result, free and stable fluid flow is achieved, heat transfer efficiency is improved, maintenance frequency is reduced, and the overall reliability and service life of the heat exchanger are enhanced. This paper presents the electropolishing process, its methodology, key applications, and the benefits achieved through its implementation in heat exchanger systems.

Do You Know? Accidental Discovery



In 1907, Buetel was not intentionally developing electropolishing. He observed a smooth, satin-like surface on gold while it was immersed in an acid bath during electrochemical experiments. The surface improvement was an unexpected side effect, which was later recognized and developed into the controlled process now known as electropolishing.

Stainless Steel (SS) & Duplex stainless steels (DSS) have gained significant attention in advanced engineering applications due to their combination of high mechanical strength and excellent corrosion resistance. Among SS and DSS materials, DSS exhibits a balanced duplex microstructure, consisting of approximately equal proportions of austenite (γ) and ferrite (α). This unique phase balance makes DSS particularly suitable for demanding environments such as chemical processing, marine structures, and transport pipelines. In such aggressive service conditions, both microstructural stability and surface condition play a critical role in governing corrosion behaviour and long-term service performance.

1.1 TYPES OF POLISHING

Chemical Polishing (CP)

Chemical polishing is a straightforward and widely used surface treatment that relies on a buffered acid mixture to remove material from the inner surface of the cavity. The process offers a relatively fast removal rate and provides fairly uniform polishing over most regions, although it tends to etch more deeply near the iris due to the vertical orientation of the cavity during processing. While CP is efficient for bulk material removal, excessive polishing can lead to grain boundary etching, which may limit surface quality for high-performance applications. The resulting surface finish is moderately smooth, and thorough water rinsing is essential afterward to eliminate residual chemicals and particles.

Barrel Polishing (BP)

Barrel polishing is a mechanical technique designed to eliminate surface imperfections such as scratches, weld defects, and irregularities left from fabrication. By rotating the cavity with abrasive media inside, this method slowly but effectively smooths the surface, especially around the equator where defects are most critical. BP is particularly valuable because it can simultaneously refine weld seams and improve overall surface consistency, reducing preparation steps and cost. However, abrasive particles can become embedded in the surface, making a light chemical or electro-polishing step necessary afterward to remove contamination. When completed properly, BP achieves a very fine surface texture.

Mechanical Polishing (MP)

Mechanical polishing is a direct, surface-refinement technique that uses abrasive wheels, belts, or pads to remove imperfections such as scratches, tool marks, weld irregularities, thermal discoloration, and fabrication defects. Unlike mass-finishing methods, mechanical polishing applies controlled abrasive action directly to the targeted area, enabling precise correction of local defects and uniform blending across the entire surface.

Electropolishing (EP)

Electropolishing is a high-precision electrochemical finishing technique that produces exceptionally smooth, clean, and corrosion-resistant metal surfaces by selectively dissolving microscopic surface asperities and impurities at the ionic level. Unlike mechanical finishing, it removes material without physical contact, thereby avoiding surface deformation, minimizing grain boundary damage, and significantly reducing micro- and nano-scale roughness, particularly when higher material removal is required. The process promotes the formation of a uniform, stable passive film, resulting in superior surface homogeneity, enhanced corrosion resistance, improved cleanability, increased fatigue life, and reduced sites for contamination or bacterial adhesion. Although hydrogen uptake can occur and may lead to performance degradation such as Q-disease, this risk is effectively mitigated through appropriate post-polishing heat treatment. When properly controlled, electropolishing delivers unmatched surface quality, smoothness, and long-term reliability, making it ideal for high-performance and hygiene-critical applications such as advanced cavities and heat exchanger components.

Owing to these advantages, electropolishing is widely applied across industries such as biomedical, aerospace, petrochemical, food processing, semiconductor manufacturing, and thermal engineering systems.

In heat exchanger applications, electropolishing is especially important for improving performance, durability, and operational reliability. Electrochemically smoothing the internal tube surfaces minimizes surface roughness, embedded contaminants, and micro-defects that typically act as initiation sites for corrosion and fouling. The resulting ultra-smooth and uniformly passive surface enhances resistance to pitting, crevice corrosion, and stress corrosion cracking under aggressive fluids and elevated temperatures. Furthermore, reduced surface roughness lowers fouling and scale deposition, improves heat transfer efficiency, and decreases pressure drop by promoting smoother fluid flow. Electropolished heat exchanger tubes are also easier to clean and maintain, while the removal of stress concentration points enhances fatigue resistance and extends service life under thermal cycling and vibration. Consequently, electropolishing plays a vital role in achieving high efficiency, long-term performance, and compliance with stringent hygienic and quality requirements in heat exchanger systems.

2 MATERIAL AND METHODS

2.1 ELECTROPOLISHING IN TUBES

Electropolishing is typically performed within the limiting current density region of the anodic polarization curve, where metal removal is governed by mass-transfer-controlled dissolution rather than charge-transfer kinetics. In this regime, the amount of material removed follows Faraday’s law of electrolysis, establishing a direct relationship between dissolved metal, applied current, and processing time. The identity of the species controlling mass transport is strongly influenced by both alloy composition and electrolyte chemistry. In duplex stainless steels (DSS) & (SS), the presence of ferritic and austenitic phases introduces micro-galvanic effects that can modify local anodic dissolution behaviour. Additionally, microstructural characteristics such as phase morphology, grain orientation, and crystallographic defects contribute to spatial variations in dissolution rate, which, under optimized conditions, facilitate surface levelling and brightening.

2.1.1 FARADAY'S LAW OF ELECTROLYSIS

Faraday's law of electrolysis states that the amount of material dissolved or deposited at an electrode during an electrochemical reaction is directly proportional to the quantity of electric charge passed through the electrolyte.

During electropolishing (EP), material removal follows Faraday's law, meaning metal dissolution is controlled by the electric charge passed through the electrolyte. The process mainly involves anodic dissolution of metal elements from the DSS surface in an acidic electrolyte (commonly phosphoric–sulfuric acid based). As both DSS and SS have shown good performance during electropolishing, we have provided a detailed evaluation of DSS tubes below. Table 1 shows the Typical Chemical Composition of Duplex Stainless-Steel Alloys and Table 2 shows the Typical Physical Properties of Duplex Stainless-Steel Alloys

Element	2205	UR52N+
C	0.00 – 0.03	≤ 0.03
Mn	≤ 2.0	≤ 1.5
Si	≤ 1.0	≤ 0.8
P	≤ 0.03	≤ 0.035
S	≤ 0.02	≤ 0.02
Cr	21.0 – 23.0	24.0 – 26.0
Mo	2.5 – 3.5	3.0 – 5.0
Ni	4.5 – 6.5	5.5 – 8.0
N	0.08 – 0.20	0.20 – 0.35
Cu	—	0.5 – 3.0

Table 1. Typical Chemical Composition of Duplex Stainless-Steel Alloys (wt.%)

Property	2205	UR52N+
Density (g/cm³)	7.805	7.81
Modulus of Elasticity (GPa)	200	205
Electrical Resistivity (Ω·m)	0.85×10^{-6}	0.85×10^{-6}
Thermal Conductivity (W/m·K)	19 (at 100 °C)	17 (at 100 °C)
Thermal Expansion (m/m·K)	13.7×10^{-6} (to 100 °C)	13.5×10^{-6} (to 200 °C)

Table 2. Typical Physical Properties of Duplex Stainless-Steel Alloys

2.2 ELECTRODE REACTIONS IN ELECTROPOLISHING OF DSS TUBES

1. Anodic reactions (at DSS tube – material removal side):

The DSS tube acts as the anode, where controlled dissolution of alloying elements occurs:

a. Iron dissolution:

$Fe \rightarrow Fe^{2+} + 2e^{-}$

b. Chromium dissolution:

$Cr \rightarrow Cr^{3+} + 3e^{-}$

c. Nickel dissolution:

$Ni \rightarrow Ni^{2+} + 2e^{-}$

These reactions remove microscopic peaks faster than valleys, leading to surface levelling and smoothing.

2. Formation of viscous surface film (key EP mechanism):

A thin, viscous salt layer forms on the metal surface due to metal ions reacting with the electrolyte. This layer:

- Limits mass transport
- Enhances preferential removal of surface asperities
- Produces a bright, smooth finish

3. Cathodic reaction (at cathode):

At the cathode, hydrogen evolution occurs:

- $2H^{+} + 2e^{-} \rightarrow H_2 \uparrow$

This reaction balances the charge flow in the system.

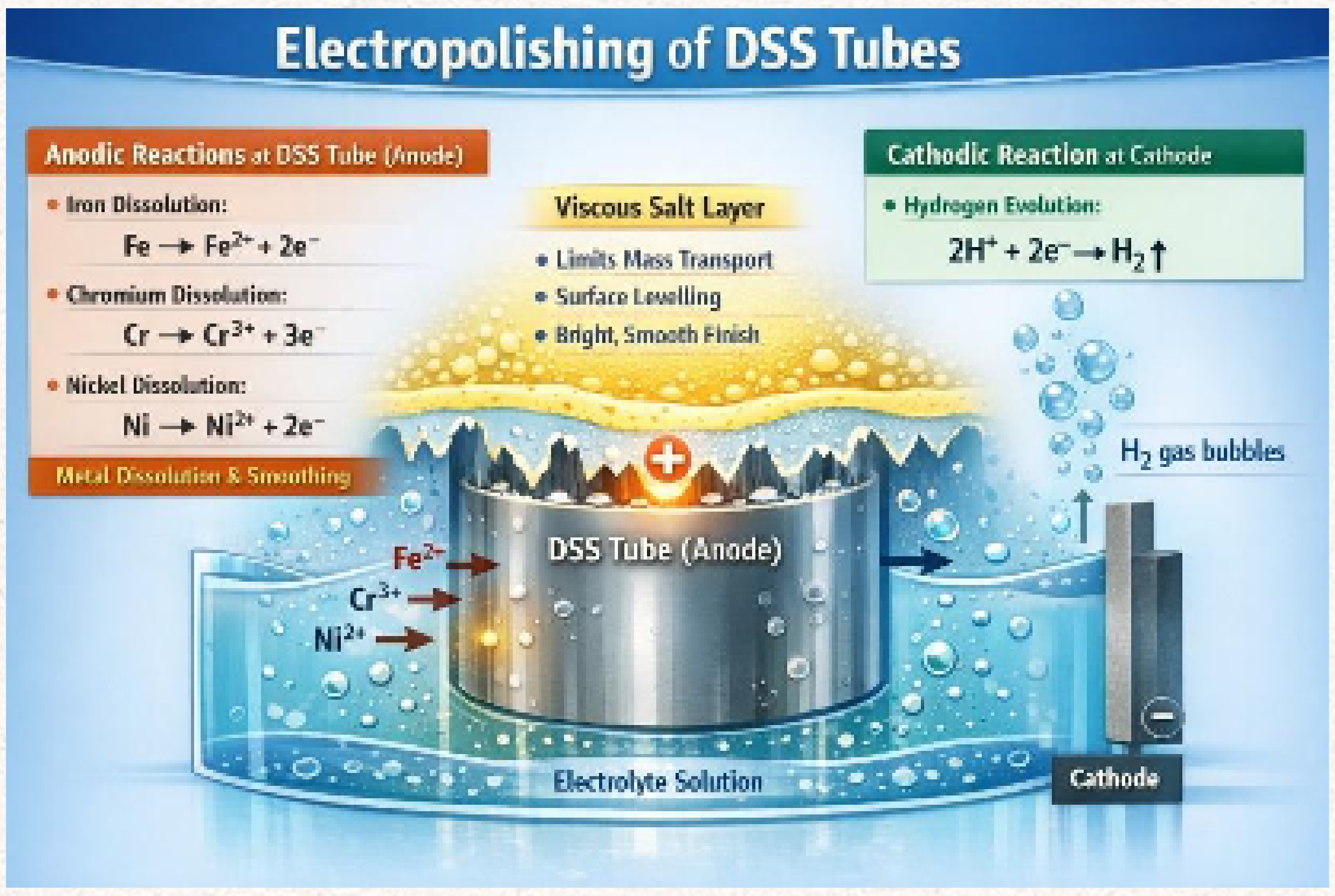


Fig 2. Electropolishing reaction process in tubes

The choice of electrolyte is a critical factor in achieving effective electropolishing. Concentrated, high-viscosity acidic electrolytes - particularly phosphoric, sulfuric acid mixtures are widely used due to their ability to sustain stable limiting current conditions and promote uniform material removal. During electropolishing, the workpiece functions as the anode, undergoing controlled oxidation and dissolution, while hydrogen evolution occurs at the cathode. The electrolyte must therefore provide adequate ionic conductivity and maintain a stable dissolution environment. Although strong acids remain the most common electrolytes, increasing attention is being directed toward environmentally benign alternatives to reduce safety risks and environmental impact.

At the metal–electrolyte interface, electropolishing behaviour is governed by classical electrochemical principles, including the formation of an electrical double layer that influences ionic transport and surface reactions. The final surface quality is determined by key operational parameters such as current density, applied voltage, temperature, electrolyte composition, and polishing duration. Preferential dissolution occurs at surface protrusions where current density is locally higher, leading to progressive reduction in surface roughness. Maintaining the process within the limiting current plateau is essential to ensure controlled, uniform material removal and to avoid surface damage associated with over-etching or gas evolution.

The electrolyte composition of stainless steels, specifically the volume ratio of sulphuric to phosphoric acid, is crucial for surface finish and polishing effectiveness. According to earlier research, volume ratios between 1:1 and 3:1 have a major impact on surface levelling and brightness; the ideal ratio varies depending on the alloy.

Nevertheless, there are still few thorough and methodical studies that concentrate on the electropolishing behaviour of duplex stainless steels under different electrolyte volume ratios. In this work, phosphoric–sulfuric acid mixtures with volume ratios of 1:1, 2:1, and 3:1 was used to electropolish DSS specimens under various pretreatment conditions. The impact of electrolyte composition on polishing behaviour and surface characteristics is examined.

Reference Standards

- **ASTM B912:** Standard Specification for Passivation of Stainless-Steel Using Electropolishing
- **ISO 15730:** Metallic and Other Inorganic Coatings — Electropolishing as a Means of Smoothing and Passivating Stainless Steel

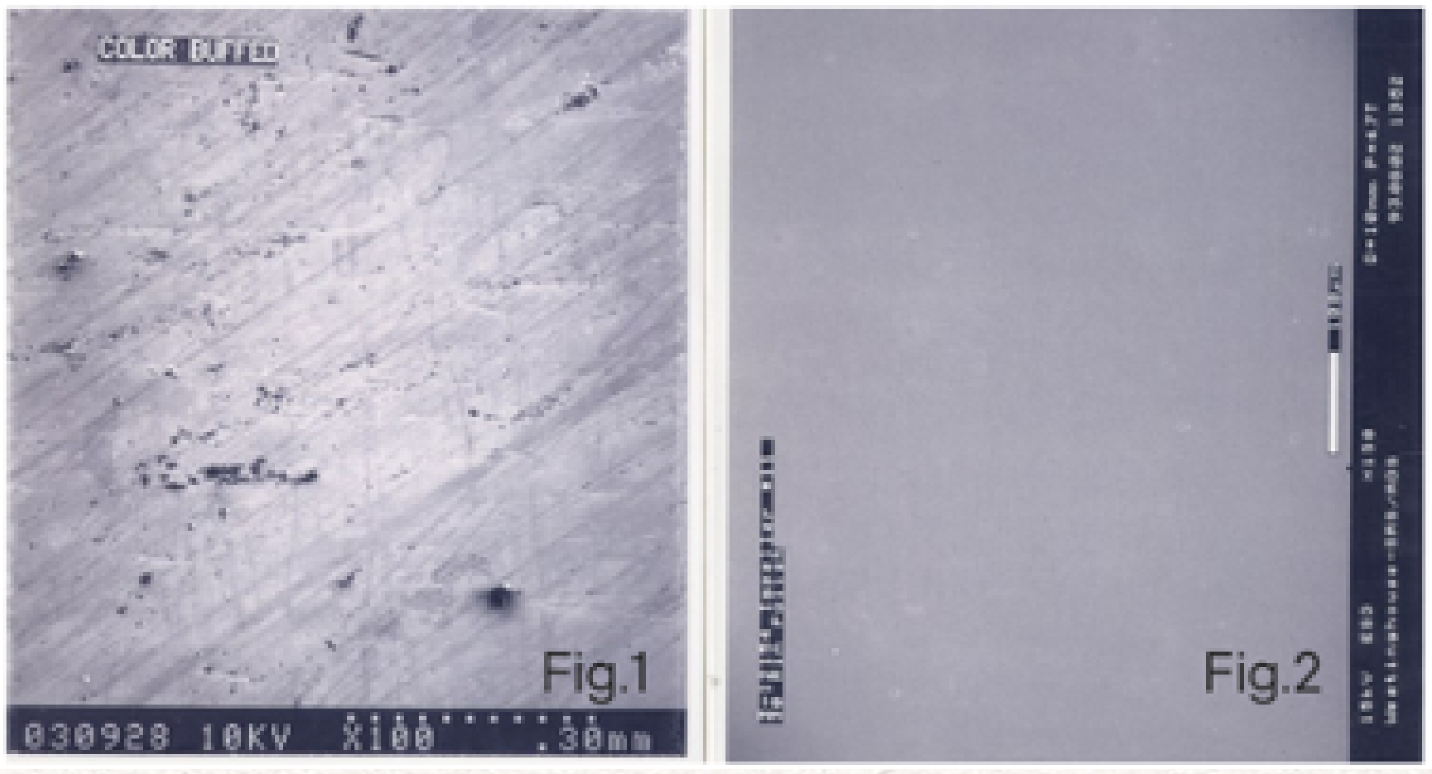


Fig 1. Microscopic image of the Duplex stainless-steel surface before electropolishing, showing pronounced surface irregularities, grinding marks, scratches, and localized defects resulting from mechanical processing. These features contribute to higher surface roughness and potential sites for fouling and corrosion initiation.

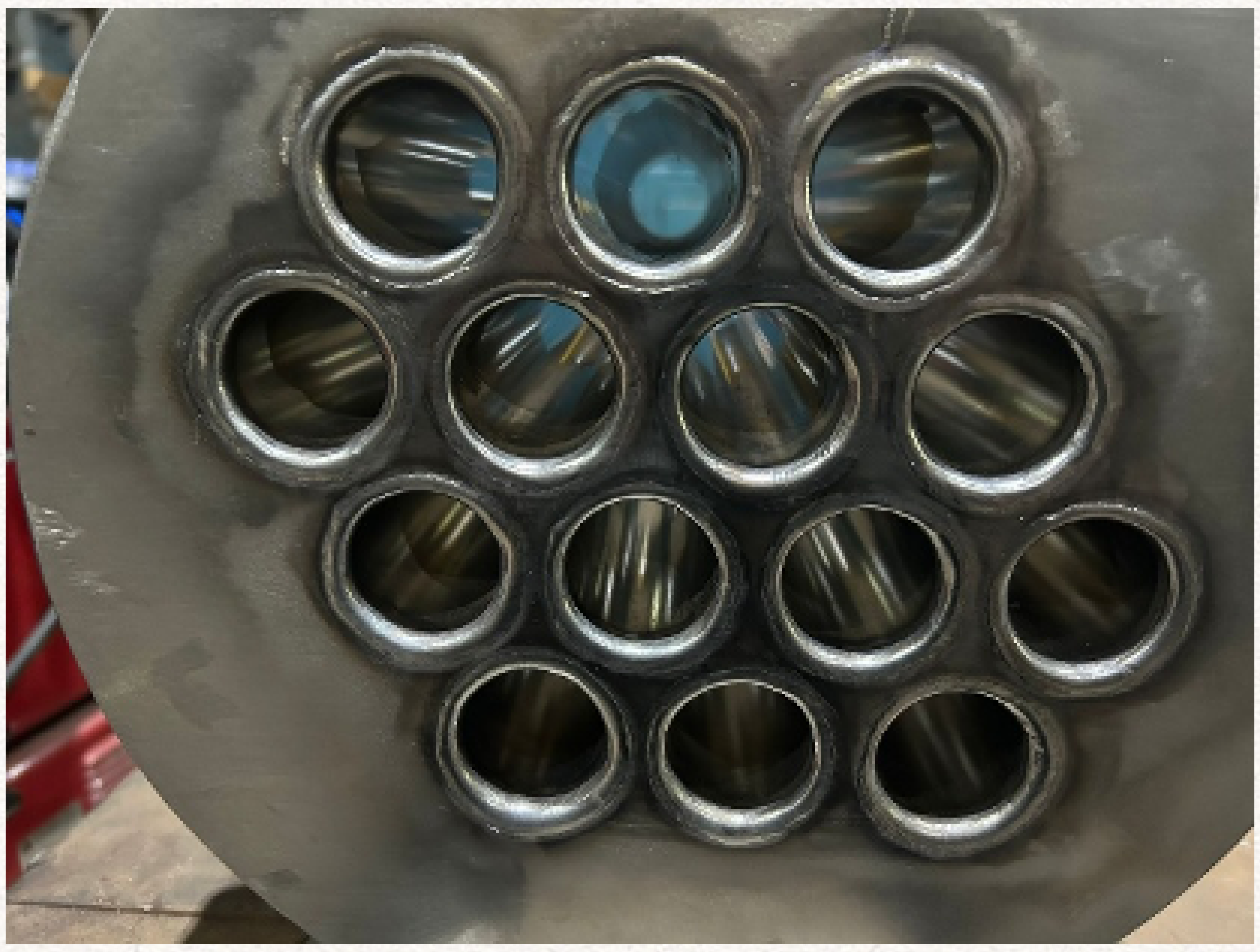


Fig 3. Before Electropolishing

Fig 4. After Electropolishing

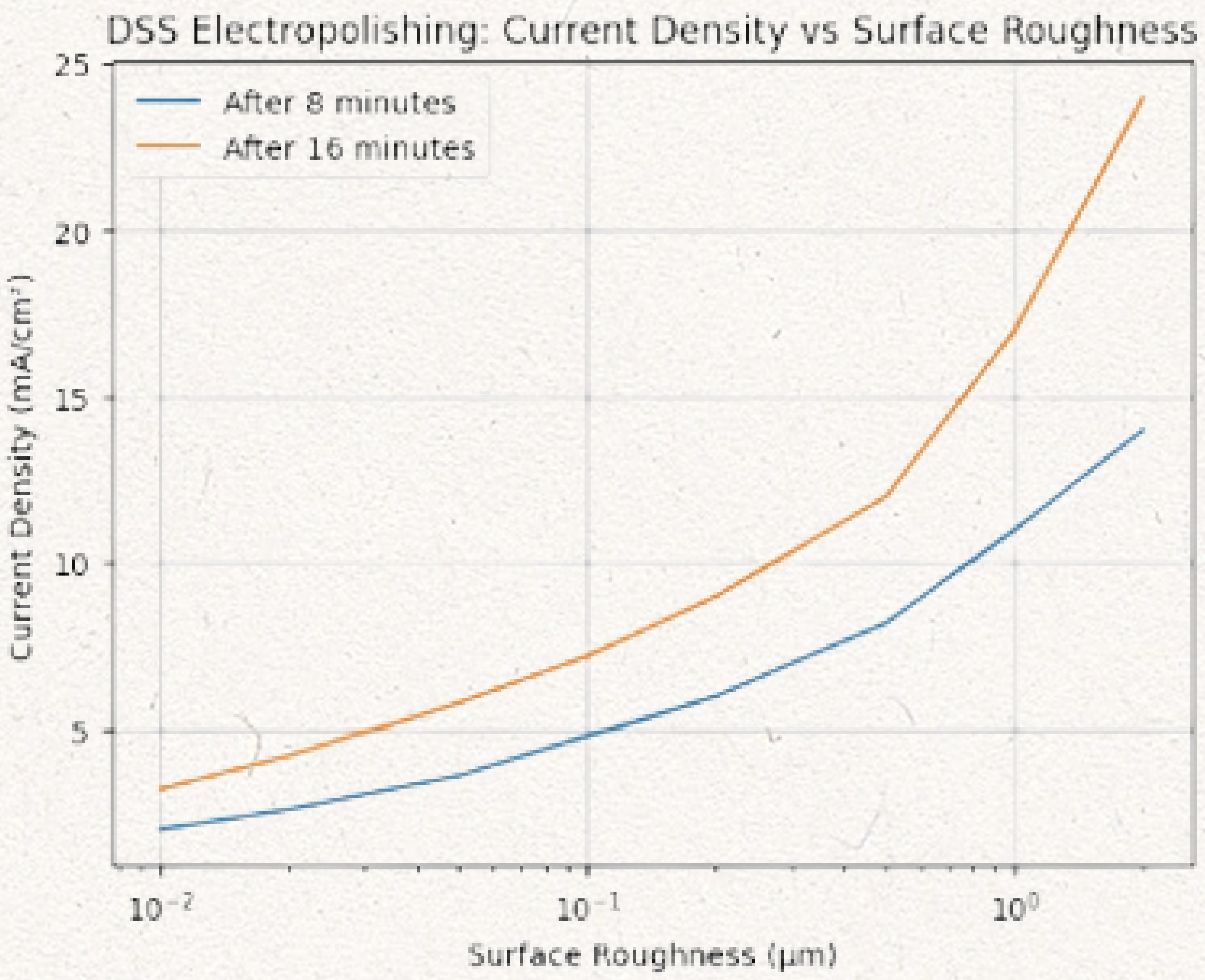


Fig 5. Effect of surface roughness on current density during electropolishing of duplex stainless steel. At a surface roughness of approximately 0.02 µm, stable current density behaviour is observed, indicating effective surface levelling within the limiting current region.

Fig 6. The surface roughness of mock-up is 0.026 is achieved after electropolishing.

3. RESULT

The implementation of electropolished tubes in the heat exchanger for the PVC plant demonstrated significant improvements in surface quality, operational efficiency, and reliability. Microscopic examination revealed that the untreated tubes exhibited pronounced surface irregularities, scratches, and defects, which promoted fouling, deposit formation, and reduced flow efficiency. Following electropolishing, the internal surfaces became smooth, uniform, and mirror-like, with Ra values reduced to ≤ 0.02 µm, confirming effective removal of surface asperities and formation of a stable chromium-rich passive layer. Electropolishing was carried out using phosphoric–sulfuric acid mixtures within the limiting current density regime, ensuring uniform material removal and controlled surface levelling. Key parameters such as electrolyte composition, temperature (75–85 °C), current density (140–250 A/ft^2), and exposure time were optimized based on DSS alloy properties. Maintenance requirements decreased, and the service life and reliability of the heat exchanger increased. Overall, electropolishing proved to be a highly effective surface finishing technique, delivering superior performance and long-term operational benefits in industrial plant applications.

4. CONCLUSION

The use of electropolished tubes in heat exchanger applications demonstrates clear operational and performance benefits. Electropolishing not only produces a highly smooth, mirror-like surface but also creates a chemically passive layer that resists fouling, scaling, and corrosion under aggressive process conditions. For any future requirements or needs, please contact Kesavan (kesavan@pecpl.com) and Dhakshna Moorthy (dhakshnamoorthy@pecpl.com).

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