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Investigation on Electrochemical Mechanical Polishing: Review

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Abstract*:* The complex process of electropolishing involves both electrical and chemical reaction, and it is impacted by a number of process variables, including workpiece rotation, temperature, electrolyte types, and current densi-ty. The electropolishing process remains largely unexplained by any existing theory, particularly in light of recent improvements that have made the material removal mechanism increasingly difficult to comprehend. In order to provide readers with a brief understanding of the material removal mechanism, this paper reviews the fundamental theories and aspects of electricity and chemical reaction. A variety of process factors, including current density, temperature, and electrolyte types reviewed by different researchers, influence the mechanism. Lastly, an overview of the electropolishing technique's development is given as a resource for further study.

Keywords: *ECMP-Electrochemical mechanical polishing, EP-Electro polishing, IEG-Inter electrode gap, ECF-Electrochemical finishing, MNM-Micro nano machining.*

1. Introduction

The technique of improving a part's surface polishing and performance by making it more corrosion resistant is known as electrochemical mechanical polishing. Process is widely used to finish parts in a variety of sectors, including complicated surfaces, die and mold manufacture, and small components utilized in a wide range of applications.

Metal components undergo electro polishing procedures when they are immersed in a chemical bath. This chemical bath is powered by a power supply that changes the AC voltages to DC after the pieces are submerged. The counter electrode is a very smooth tool electrode, and the metal or alloy work piece is biased at a positive potential. In order to remove metal ions from the bath, a viscous acid is utilized as the electrolyte in this process.

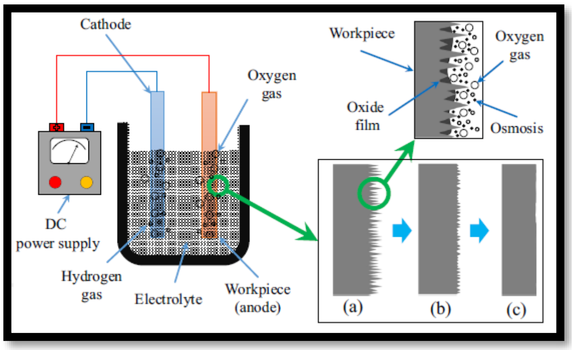

Fig.1 the basic principles of ECP: (a) original surface, (b) after polishing starts and (c) final surface [14]

The metal ions are driven to dissolve from the anode (work piece) surface by the electrical charge generated when the DC power source is turned on. The anode's surfaces are covered with a thin, passive layer of a high-specific-gravity metallic oxide throughout the operation. As seen in Figure 1, this film has different thicknesses throughout its surface, with the thickest areas over micro-depressions and valleys and the thinnest areas over micro-projections and peaks.

2. Mechanical Forces for Finishing In Electrochemical Process

Due to the low material removal rate associated with electropolishing, some surface roughness and scratches are visible, and the material removal process leaves surface pits. The compound method of electrochemical mechanical polishing can be used to get around these flaws. The mechanical action speeds up the anodic smoothing process and raises the removal rate in the anode surface's high spot region. While mechanical abrasion is kept to a minimum,

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electrochemical action removes a significant portion of the material.

Because less material will be removed mechanically, the process tool will last longer than a traditional machine tool. The abrasives in Figure 2(a) are combined with an electrolyte instead of being bound to the polishing instrument. The workpiece in Figure 2(b) functions as an anode when it is linked to the positive side of a DC power supply. Connected to the negative side of the power supply, a conductive tool with bonded (non-conductive) abrasives serves as a cathode. The workpiece in Figure 2(c) is rotated while being connected by brush to the positive side of a DC power supply (anode). The workpiece is subjected to the burnishing force using a non-conductive tool. The power supply's negative side is linked to a cathode. These three configurations represent potential means of applying mechanical forces to the electrochemical process for completion.

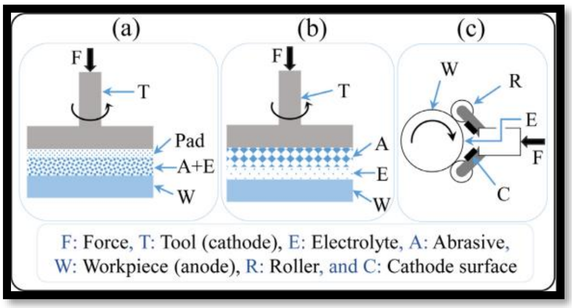

Fig. 2 Different hybridization types between electrochemical and mechanical polishing actions: (a) Free abrasives type, (b) Bonded abrasives type and (c) Burnishing force type [14]

3. Literature Survey

As an alternative to chemical mechanical polishing (CMP) for the integration of low-k dielectrics in microelectronic devices, J. Huo, R. Solanki, and J. McAndrew [1] investigated electrochemical polishing (ECP) of copper using hydroxyethylidene diphosphonic acid (HEDP). As an alternative to CMP, ECP of copper utilizing HEDP has been utilized to integrate low-k dialectrics in microelectronic devices. The maximum current density of 20–40% of HEDP solutions is 80 A/cm2. An 80 percent reduction in mean roughness was observed along with a metal removal rate of 1.8 µm/min. All HEDP can produce the ECP effect with a decent smoothing effect when using an H3PO4 solution; however, this solution was found to have a lower metal removal rate.

Based on uniform and localized intergranular corrosion (IGC) assessments, Shuo-Jen Lee and Jian-Jang Lai [2] processed on improving the corrosion resistance of a work piece of SS 316L stainless steel by electro polishing. Sulfuric acid, phosphoric acid, glycerin, and DI water made up the electrolyte. Between the electrodes and the process time, there is a gap in the EP process parameters. The thickness of the passive film and its metallurgical composition were analyzed using Auger electron spectroscopy (AES) and X-ray photoelectron spectroscopy (XPS). It was discovered that a 5 mm electrolyte gap and a 5 minute polishing time were ideal. There was a more than 60% improvement in uniform corrosion. The IGC resistance increased by about 85% using EPR analysis.

Jong C., Yuan-Long Chen, Shu-Min Zhu, and Shuo-Jen Lee [3] In this study, Wang introduces the mechanism, processing regulation, and application of ECMP. When using NaNO3 + Na2SO4 solution, additives such glycerine, glycol, and sodium tartrate are added .Additionally, the electrolyte's temperature will be between 20 and 40 degrees Celsius because variations in temperature have the potential to affect passivation and current density. Especially for hardened steel and hard alloy, ECMP offers superior quality and efficiency.

A surface contact temperature model was created by Jeng-Haur Horng and Chun-Liang Chen [4] for the polishing process. It deals with the interaction between the work piece and abrasive, as well as the roughness of the pad. They investigate how the temperature rises in relation to particle size, density, pad hardness, and pad roughness value. They concluded that the contact temperature rise of the pad work piece is independent of the hardness of the work piece and that the contact temperature between the work piece and the particle is typically higher than the contact temperature between the polishing pad and the work piece.

The effects of electrochemical parameters, such as the electrolyte, pH levels, and operating potential, on the metal removal rate of polishing AISI 316L stainless steel (SS316L) are investigated by Shuo-Jen Lee, Yu-Ming Lee, and Ming-Yu Chung [5]. Concluded that an addition may also aid to increase the MRR and that a stronger acidic electrolyte solution will be advantageous to the MRR.

Chang Yong An and Nadiia Kulyk [6] investigated how the materials used in polishing pads affected the polishing procedure. Polishing parameters such additive quantity, electrolyte content, and pad rotation speed were all tuned. Lastly, displays the outcomes that enhance the uniformity of the Cu layer's planarization on PCBs. Additionally, the "dishing effect" could be avoided by adding chemicals and use a firm polyurethane cushion.

Using basic geometry, J. L. Ebert and S. Ghosal [7] created a COSMOL model of the ECMP and validated the data with experimental findings. A two-dimensional model of a parallel plate with a wafer at the bottom and a polishing pad at the top is created. Ultimately, they suggested utilizing a scaled-down version of the verified physical model to create multivariable feedback control for the ECMP.

Fundamental principles and governing parameters of the ECF/ECP processes are reviewed by Piyushkumar B. Tailor, Amit Agrawal, and Suhas S. Joshi [8] using mathematical and empirical methodologies for the modeling with formulations. The majority of ECF process variations are nanofinishing procedures. The electrolyte and work/tool characteristics parameters bear equal responsibility for the surface quality produced by the ECF/ECP operations.

In contrast, aqueous electrolytes used in pulse or pulse reverse processes don't require specialist maintenance techniques or aggressive chemicals for surface de-passivation, according to research by E. J. Taylor and M. Inman [9]. As a result, the pulse or pulse reverse surface finishing method has less safety risks, requires less handling of chemicals, and has better robustness at a reduced cost.

A self-developed process setup for machining AISI-304 stainless steel W/P was carried out by K. B. Judal and Vinod Yadava [10]. It was based on the response surface methodology's central composite rotat-able design technique. Investigations were conducted into the effects of W/P rotational speed, electromagnet current, electrolytic current, and vibration frequency on the output, or surface roughness (Ra) and metal removal. The best results were obtained by optimizing for maximum MR and minimal Ra. The ideal input variables were W/P rotational speed of 1200 RPM, electromagnet current of 2.4 A, electrolytic current of 2.5 A, and vibration frequency of 6 Hz.

The electrolyte composition concentration, pressure, applied voltage, feed rate, and electrolyte composition of the unique special purpose S-03 stainless steel were examined by Lin Tang and Yong-Feng Guo [11] using NaNO3 and NaClO3. Investigations were conducted on the side gap between the cathode and anode work pieces, machining efficiency, and surface roughness of the work piece. The ideal specifications for S-03 material are 20V and 0.8Mpa with a composition of 178 g/l NaNO3 and 41 g/l NaClO3. Ra dropped by 41%, the side gap shrank from 0.32 mm to 0.25 mm, and MRR increased by 95%.

The cutting edge preparation of tungsten carbide (WC) ball nose end mills can be done without the need for mechanical polishing by using the method developed by Ramesh Kuppuswamy and Kapui Mubita [12]. The electro-polishing method produced high-quality cutting edge surfaces with a roughness of magnitude 0.3–0.35 mm. The growth of flank wear on the electro-polished ball nose end mills of Ti6Al4V alloy was investigated using surface texture analyses and machining tests. The electro-polished ball nose end mill reached a 0.15 mm flank wear after 550 m of cutting, according to the data. For the same amount of flank wear, this was substantially greater than the cutting distance of the typical ball nose end mill, which is approximately 350 m. This indicated a longer tool life of over 50%.

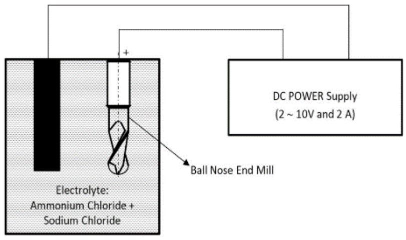

Fig.3 Basic set-up of an electro-polishing arrangement for the ball nose end mill. [12]

In order to forecast the sample's final surface finish, A.A. Gomez-Gallegos, F. Mill, and A.R. Mount [13] assessed the parameters involved in the ECM of stainless steel 316 (SS316). Experimental tests of ECM were carried out on SS316 pipes with a diameter of 1.5 (0.0381 m) by adjusting variables including voltage, inter electrode gap, electrolyte inlet temperature, and electrolyte flow rate. A voltage of 9 to 15 V, an inter electrode spacing of 8 mm, and a current density of 4.5 A/cm2 are required to achieve the desired bright and reflective surface finish.

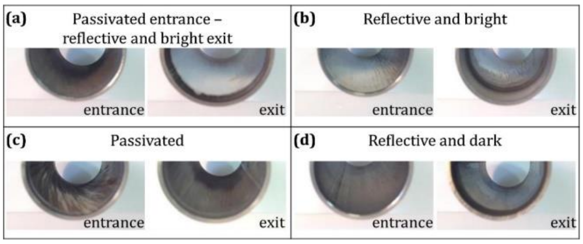

Fig.4 Effect of passivation for SS316pipesmachinedbyECM. [13]

Abd El Khalick Mohammad and Danwei Wang [14] revisited the ECMP, its advancements, and upcoming industrial research requirements. They re-examined and concluded that surfaces with simple geometry and planarization processes are the only applications for the ECM technique. Therefore, ECMP implementation may result in the exploration of novel geometries. Additionally, suggest a number of robotic ECM polishing system setups and combinations.

The goal of the review by G. Yang, B. Wang, K. Tawfiq, H. Wei, S. Zhou, and G. Chen [15] was to give readers a comprehensive grasp of the electropolishing process from both the fundamental and applied perspectives. We went over the definition, the basic setup, the principles involved, and the techniques for assessing the electro polishing finishes, in addition to the general characteristics of the process. Numerous hypotheses of electro polishing, both quantitative and qualitative, were presented. Important parameters that emerged during the electro polishing process are listed based on those beliefs. The electronic polishing surface finishes are assessed using a variety of microscopic technologies.

The corrosion resistance of the most often used Cr-Ni-Mo austenitic biomaterial, AISI 316L stainless steel, was studied by V. Zatkalikova, L. Markovicova, and M. Skorvanova [16]. The assessment of the corrosion behaviour of five different surfaces—three that have undergone combined treatment and three that have been electropolished—is based on cyclic photodynamic polarization experiments conducted in physiological solution at a temperature of 3 7 ± 0.5 °C. It does not appear that a single polishing without a pre-treatment would provide a uniformly thick passive coating that is robust enough.

The state-of-the-art in EC-MNM techniques for direct writing, surface planarization, polishing, and 3D-MNS fabrications is presented in a review on electrochemical micro/nano-machining conducted by Dongping Zhan, Lianhuan Han, Jie Zhang, Quanfeng He, Zhao-Wu Tian, and Zhong-Qun Tian [17]. It was discovered that the immediate solution is to contain the reactions inside 3D templates made using nano- imprinting, photolithography, and other unconventional machining techniques like EFAB and LIGA. Future studies on EC-MNM fundamentals, with a focus on reaction kinetics in particular, are possible. Inducing mechanical motion is an alternate means of improving mass transfer and mass balance in EC-MNM with the introduction of hydrodynamic and microfluidic methods.

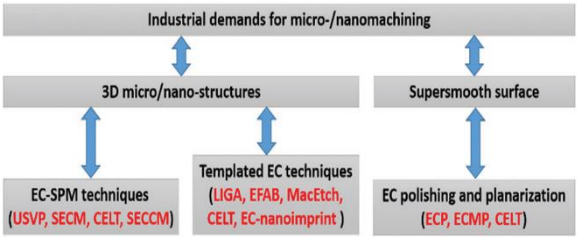

Fig. 5 The industrial demands for micro/nanomachining and the ECMNM techniques [17]

The electro-polishing procedure was studied by Mubita Kapui and Ramesh Kuppuswamy [18] with the goal of increasing the surface texture of stainless steel 304. At a volume ratio of 2:3:5, the electrolyte was a mixture of H2O, H2SO4 (98%) and H3PO4 (85%). The materials were analyzed using stylus profilometry and grav-imetric analysis. The needle insertion forces at various insertion depths were modeled theoretically. The optimal surface texture was discovered at 2.11A and 10 minutes, showing a 65% improvement.

A robotic-based ECMP procedure has been proposed as a replacement for the traditional ECMP process by Abd El Khalick Mohammad, Jie Hong, Danwei Wang, and Yisheng Guan [19]. An integrated macro-mini robot polishing cell houses the end-effector. The micro robot manages the polishing force, while the macro robot positions the mini robot in accordance with the W/P profile. Ra is decreased for unmilled and milled surfaces (with initial MP) from 0.073 and 0.069 to 0.047 and 0.038, and for unmilled and milled surfaces (without initial MP) from 0.549 and 0.368 to 0.111 and 0.083.

Impact analysis was conducted by Guodong Liua, Yong Lia, Quancun Konga, and Liqiu Yua [20] on the shape precision of micro holes in ECM using hollow electrodes. COMSOL Multiphysics software was utilized to build the multi-physics models that included electric current field, electrolyte movement, gas diffusion, and heat transfer. The area of the vortex zone in the machining gap grows and the side wall's material removal rate varies as pressure rises. As a result, the precision of the shape degrades. A changing rule of ideal electrolyte pressure for improved form accuracy and machining stability of micro reverse tapered holes is produced based on the analysis of simulation and experimental results.

The polishing work piece with inner corner feature was researched by Hongping Luo, Dahai Mi, and Wataru Natsu [21] using the electrochemical machining (ECM) technique. The surfaces of the upstream and downstream areas differ significantly, and the surface quality at the corner area is significantly lower than that at other locations. Investigations were conducted into the features of this corner area phenomena. Understanding the current density distribution on the work piece surface aids in the analysis of the corner area phenomenon and clarifies process features, as the current density has a significant impact on surface roughness in the ECM process. One of the reasons that are thought to contribute to a rougher surface at downstream surface areas is a decreased current density.

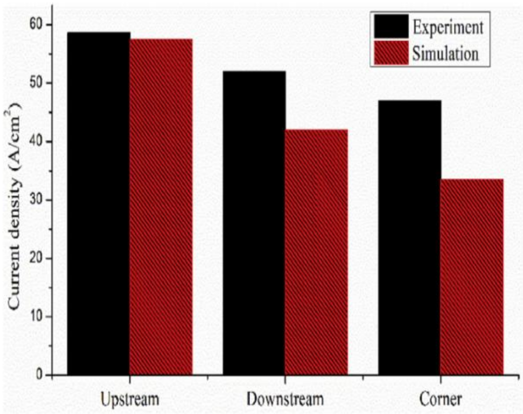

Fig. 6 Measured and simulated current densities of different area [21]

In their experimentation, Xu Yang, Yuji Ohkubo, Katsuyoshi Endo, and Kazuya Yamamura [22] used single-crystal SiC (4H-SiC) Since the surface of SiC is softened by anodic oxidation and then removed by soft abrasives, the realization of a scratch-free and subsurface damage (SSD)-free surface is anticipated using the ECMP process. Additionally, the mechanism of the first anodic oxidation was explored, as was the production process of the oxide layer in the anodic oxidation of 4H-SiC (0001) by atomic force microscopy (AFM) observation. The oxidation began on the surface of the terrace edges and spread to the terrace bottoms, according to the results. After the oxides were removed, the oxide protrusions caused the pits, which greatly increased the surface roughness.

Investigating the electropolishing of aluminum in ethaline, a eutectic mixture of choline chloride and ethylene glycol at varying electrode potentials, were A.A. Kityka, V.S. Protsenkoa, F.I. Danilova, O.V. Kuna, and S.A. Korniya [23]. I discovered that aluminum had not been anodized. Surface appearance (the surface gets significantly brighter) and the roughness coefficient decrease with an increase in the electrode potential at which the anodic treatment was carried out. Consequently, it was proposed that a deep eutectic solvent would be a good choice for electropolishing aluminium. Different alloying elements (Cu, Mg, Mn, Si, Zn, etc.) found in commercial alloys of aluminium can have a noticeable impact on the qualities of the treated surfaces as well as the electrochemical polishing process utilizing DES-based electrolyte.

In an experiment utilizing ECMP for copper, Di Wu, Renke Kang, Jiang Guo, Zuotao Liu, Ce Wan, and Zhuji Jin [24] found that hydroxyethylidene diphosphonic acid (HEDP) can be used in conjunction with other water treatment agents to reduce electrolysis and smooth the metal surface. Experiments on potentiostatic and potentiodynamic corrosion as well as ECMP were carried out at greater potentials to examine the process' viability. More investigation can be done into the connection between the mechanical characteristics of the barrier layer, planarization, and the optimization of variables including operating voltage, flow velocity, and process time.

An extensive investigation of the anodic behaviors of tungsten during ECP under various applied potentials was conducted by Fang Wang, Xinquan Zhang, and Hui Den [25]. ECP was used for 10 minutes to produce a mirror surface with a Sa roughness of 3.73 nm, demonstrating its efficacy. The ECP of tungsten was split into three stages based on changes in surface morphology and current density. These stages were the etch-ing stage, during which crystallographic etching produced rough etching marks, the brightening stage, which produced ultra-smooth surfaces with distinct boundaries, and the pitting stage, which saw the formation of crystal-lographic pitting.

The goal of Wei Han and Fengzhou Fang [26] was to analyze the foundational elements and most current advancements in the electro polishing process. In the copper electro polishing process, the viscous layer is thought to be the primary obstacle preventing copper ions from diffusing from the anode to the electrolyte. The minimum material removal thickness is currently in the order of only micrometers, indicating that the method of dissolving materials at the nano or atomic scale is still challenging and promising. This is due to the limiting effect of the formation of a salt film or viscous layer in the limiting current plateau region and removal of the material ion by ion. Further research is needed to determine how the microstructure of the work piece affects the electro polishing process, and some new electrolytes are still required.

Xu Yang, Xiaozhe Yang, Kentaro Kawai, Kenta Ari-ma, and Kazuya Yamamura [27] investigated slurry-less electro-chemical mechanical polishing as a method of planarizing sliced 4H-SiC (0001) wafer. The SiC surface's Sq roughness decreased from 286 to 1.352 nm, and a scratch-free mirror surface was achieved using a ceria vitrified grinding stone. With a material removal rate of roughly 23μm/h, the sliced surface's surface damage and saw marks were entirely eliminated. The ECMP-processed surface showed no underlying damage or residual oxide, and its quality was far superior to that of conventional lapping.

Using track point density distribution, Zuotao Liu, Zhuji Jin, Di Wu, and Jiang Guo [28] provide a new model to examine non-uniformity of material removal in ECMP. Two different kinds of polishing pads were produced for this work: (a) concentric arrangement and (b) phyllotactic arrangement. To reflect the uniformity of electrochemical action across substrate, the density distribution and coefficient of variation of track point density of two polishing pads at different speed ratios were simulated, and experiments were designed to validate the simulation results. The findings demonstrate that the phyllotactic arrangement polishing pad's non-uniformity outperforms that of the concentric arrangement pad, suggesting that the density distribution of the track point on the sub-strate can be used to reflect the uniformity of the ECMP material removal. Further investigation can be conducted into material removal non-uniformity in ECMP when the electric field strength of each hole varies.

Abrasive-free electrochemical mechanical polishing (AF-ECMP) for a SiC surface utilizing Ce film placed on a polishing pad is reported by Junji Murata and Daiki Nagatom [29]. Continuous electrolysis on the SiC surface results in a rough surface due to the excess oxide. On SiC, the abrasive ECMP with CeO2 particles broadens the original scratches, while the AF-ECMP shows no broadening of scratches at all. The AF-ECMP reduced the amount of material removed with less polishing time, even if its material removal rate (MRR) was lower than that of the abrasive ECMP.

More research can be done on the wear of the Ce film on the polishing pad.

Wei Han and Feng-Zhou Fang [30] conducted research on electropolishing tungsten using an environmentally safe electrolyte, and they used an electrochemical etching approach to find the minimal material removal depth on the electropolished tungsten surface. Because of the higher current density when employing the NaOH electrolyte, the surface roughness decreases with the inter electrode gap width. With a much smaller gap, the electropolishing effect is less pronounced because the produced bubbles cannot escape the small working gap in time. On the tungsten surface, a 300 µm diameter region shows a material removal depth of less than 10 nm.

To shed light on the SiC surface anodic oxidation mechanism, Xincheng Yin, Shujuan Li, and Peng Chai [31] combined anodic oxidation and mechanical polishing (AOMP), which is based on the inner-outer double-directional diffusion theory. The Deal-Grove model was used to characterize the link between the thickness of the oxide layer and the oxidation time. Following chemical mechanical polishing (CMP), the surface roughness for various oxidation and polishing times was measured. Findings reveal that when the anodic plasma oxidation rate equals the CMP rate, a just-polished surface with acceptable surface quality can be achieved. This is evidenced by the surface roughness following CMP.

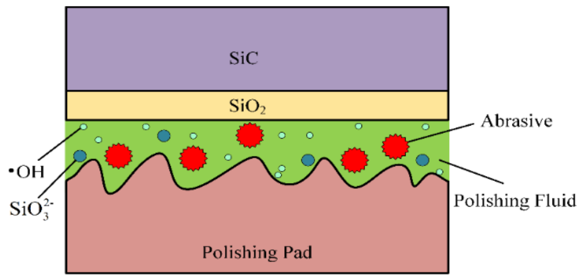

Fig. 7 Model showing the modified layer [31]

4. Conclusion

According to a survey of the literature, the majority of ECMP investigation is conducted on flat surfaces. Initial work has been identified for the completion of micro-nano jobs and components. Additionally, not much work is done on the ECMP's thermal features.

5. Future Enhancement

Corrosion is a significant component for any material, and its impact on corrosion resistance when surface finish is taken into consideration can be studied while accounting for ECMP regulating parameters.

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