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Experimental study on parameter evaluation of thin metal sheets using photochemical machining

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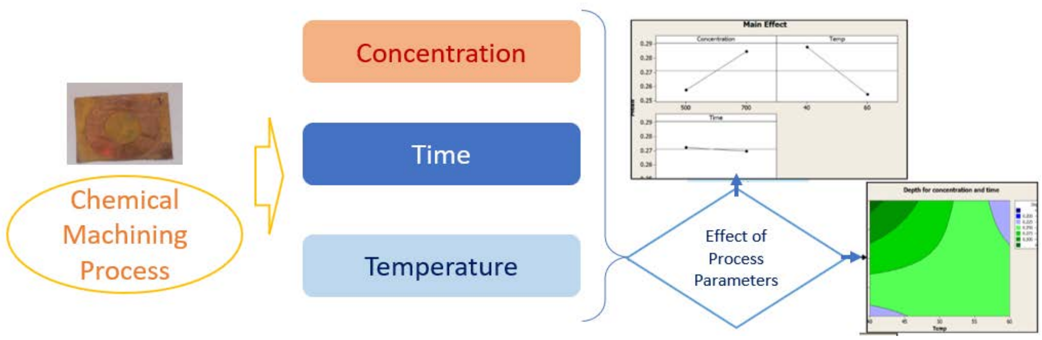
ABSTRACT



This study examines the impact of critical process parameters etchant concentration, etching duration, and temperature on the machining characteristics of thin copper sheets using PCM. Experiments were conducted on copper sheets of varying thicknesses, specifically 0.4 mm and 0.5 mm, to analyze the effects of these parameters on dimensional accuracy. The study systematically varied the concentration of ferric chloride ($FeCl_3$), a commonly used etchant, to assess its influence on etching depth and precision. The findings suggest that higher $FeCl_3$ concentrations enhance the etching rate, leading to deeper material removal. However, an excessive concentration may also contribute to surface roughness and undercutting, affecting the overall accuracy. While elevated temperatures generally accelerate chemical reactions and improve etching efficiency, excessive heat can lead to undesired effects, such as uncontrolled lateral etching and reduced precision. Similarly, the etching duration influences the final machining outcome. Overall, the study provides valuable insights into optimizing PCM parameters for precise and controlled micromachining of copper sheets, highlighting the need for a balanced approach to etchant concentration, temperature, and processing time.

Keywords: Photo Chemical Machining, DOE, Etchant Concentration, Time, Temperature, Sheet thickness

INTRODUCTION

Photochemical Machining (PCM) is a unique manufacturing process that produces precise, burr-free metal components without the need for mechanical cutting. By using a photolithographic mask to selectively etch material, PCM offers a cost-effective and efficient solution for creating intricate, 2D shapes from thin metal sheets. Unlike traditional machining methods, PCM's part complexity has minimal impact on cost or lead time. This makes it ideal for producing high-volume, intricate components in industries such as electronics, automotive, aerospace, and medical. Common applications include television shadow masks, integrated circuit lead frames, suspension head assemblies, and decorative elements for watches and jewelry. While most metals can be etched using PCM, copper, zinc, steels, magnesium, aluminum, nickel, and Kovar are particularly suitable due to their chemical reactivity.

Photochemical machining (PCM)[1] is a precision manufacturing technique that utilizes chemical etching to create intricate metal parts. This process involves a series of steps,

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beginning with selecting and preparing the metal substrate. Photochemical machining is a process of etching a very thin metal sheet through light, or it is a precise manufacturing technique that uses the method to mask patterns over the photo-etched metal sheet with given line widths and shapes. It can make different shapes with high precision and low tool wear. However, the process depends on some parameters, like light intensity and exposure, developer concentration, and the properties of the metal sheet.

Photochemical machining (PCM) offers high accuracy and flexibility in creating complex metal shapes. Yet, the feasibility of this process depends on the control of very sensitive process parameters such as surface roughness and undercut. The surface roughness is a quantitative measure of the surface texture. The functionality as well as the appearance of parts goes with surface roughness. High levels of roughness adversely affect the performance of the product, particularly when high-precision tolerances or fine finish are needed in an application. The undercut is the etching below the mask in the lateral direction. Although it helps in achieving a good aesthetic look for clearance, excess undercutting often creates dimensional inaccuracies and weakens structure. Some of these challenges can be reduced by optimizing process parameters, such as exposure time, etchant concentration, and developer strength, which affect surface roughness and undercut. By fine-tuning the above parameters, material removal, and part quality can be balanced to perfect the manufacturing requirements. Advanced masking techniques along with better resist materials also help in minimizing undercut and more stringent dimensional control.

Safety is another concern for PCM as it is done using dangerous chemicals in large percentages of ferric chloride etchant. Their vapors are corrosive to the point that ventilation and PPE are needed when using the equipment. The etching equipment has to be separated and isolated from accidental exposure or contamination.

LITERATURE REVIEW

Photochemical Machining is renowned for its precision and surface finish, utilizing chemical etching for material removal. By optimizing various parameters, it significantly improves efficiency and quality across a range of industrial applications [1-2]. The PCM process produces stress-free, burr-free micro components, particularly effective for materials like cartridge brass, which benefits electronics and microfabrication [3]. PCM leverages controlled etching parameters to achieve optimal surface quality and minimal undercut, enhancing precision in metal fabrication and addressing numerous manufacturing challenges [4]. Additionally, a study demonstrates how optimizing photochemical machining for aluminum reveals the substantial influence of etching temperature on material removal rate, surface roughness, and edge deviation using a Taguchi approach [5]. Moreover, PCM can create burr-free, stress-free components through selective etching, with process optimization significantly boosting material removal rates and surface quality for ASME 316 steel [6].

Optimization of parameters leads to massive improvement in efficiency and quality offered through a wide range of industrial applications [5-6]. The PCM process delivers stress-free, burr-free micro components that are especially useful for materials like cartridge brass, which are advantageous to electronics and microfabrication [7]. PCM exploits controlled etching conditions to ensure maximum surface quality and reduced undercutting ability for improved precision in metal fabrication and overcoming many manufacturing issues [8]. Further, the research shows optimization of photochemical machining of aluminum reveals the significant impact etching temperature has on the material removal rate, surface roughness, and edge deviation as applied in a Taguchi approach [9]. In addition, PCM can be used to produce parts without leaving behind burrs or any residual stresses if created through selective etching. The optimization of the process has been shown to increase the material removal rate and surface quality significantly in ASME 316 steel [10].

The PCM process parameters can be optimized for the maximum efficiency and desired machining results. Numerous articles have focused on various optimization techniques and the parameters that are considerably influencing the performance of PCM. Concentration of Etchant: The maximum optimum concentration of etchant was reported ranging from 400 g/L to 850 g/L, depending on the results obtained [11]. Etching Time and Temperature: The preferred etching time ranges from 6 to 60 minutes and the most effective etching temperature is observed to lie between 40°C to 70°C [12]. Etching temperature is considered one of the primary parameters that affect MRR and surface roughness [12-13]. Taguchi's approach has been successfully used to study in detail some of the parameters that also result in enhanced machining conditions [13]. In recent years, MCDM techniques like TOPSIS and ANOVA have been applied to evaluate and optimize multiple performance metrics such as MRR and surface roughness [14].

Etching depth and surface roughness increase with the increased temperature as well as etching duration. [15] The most favorable etching concentration of aluminum is about 400 g/L as it gives the highest material removal rate. [12, 15] More concentrated solutions ensure more efficient etching but may also lead to a poor-quality surface. The concentration of etchant and etching time is in proportion to the rate at which the material is removed and surface roughness and at optimized conditions 55°C of temperature and 15 minutes of etching time with 800 gm/liter concentration. [16-17].

Over the years, researchers have delved deep into understanding and optimizing the process, uncovering how various parameters influence the outcome. For instance, Allen [18] pointed out that while increasing etchant temperature speeds up material removal, it can also compromise the sharpness of edges—a classic case of balancing speed with precision. Cakir et al. [19] added to this by showing how the etching time and the quality of the masking material play a pivotal role in maintaining dimensional accuracy. Too much time, and you risk undercutting; too little, and the job remains incomplete.

Wang et al. [20] brought fluid dynamics into the picture, demonstrating how controlled agitation of the etchant can lead to more uniform results. Meanwhile, Jain et al. [21] shifted the focus to sustainability, comparing traditional etchants like ferric chloride with greener alternatives. Their work reminds us that while eco-friendly options are kinder to the planet, they often demand more time and patience. Kumar et al. [22] took a closer look at the material itself, revealing that metals with finer grain structures etch more consistently, making them ideal for high-precision applications.

Innovation has also played a key role in advancing PCM. Zhang et al. [23] introduced a laser-based system to monitor etching depth in real-time, reducing the risk of over-etching and improving control. Patel et al. [24] explored how the thickness of the photoresist layer affects the sharpness of features, while Li et al. [25] pushed the boundaries by using PCM to create intricate microfluidic devices for biomedical applications. More recently, Singh et al. [26] harnessed the power of machine learning to predict optimal parameters, saving time and resources. Finally, Gupta et al. [4] highlighted the importance of post-etching treatments like electro-polishing to enhance surface quality without compromising precision.

The goal of this work of experimental research is to study in detail the impact of these parameters on the quality of etched patterns in thin metal sheets. The controlled experiments and analysis would aid in optimizing the PCM process for certain applications and materials. Understanding relationships between process parameters and etching outcomes will allow manufacturers to consistently and often at high quality carry out their PCM operations.

METHODOLOGY

PCM starts with a design (drawing or sketch). A CAD system creates a photo tool, which is used to transfer the design onto a photosensitive metal sheet. The sheet is etched, removing metal not protected by the photoresist, resulting in the desired part.

Preparation of Masters

Photo tool preparation for photochemical machining begins with generating oversized artwork on paper, polyester drafting film, or glass scribing film. The design is created using software like AutoCAD, with areas to be etched in black. This artwork is printed onto the transparency using a plotter. Multiple images are prepared to maximize efficiency. The photo film, carefully handled to avoid exposure, is cut to size and exposed to UV light for 3-4 minutes. This transfers the artwork onto the photo film. The film is then developed using a developer and catalyst solution to create a permanent image. Finally, the photo film is cleaned with water to complete the process, readying it for etching.

Masking with Photoresists

Masking with photoresists creates a photosensitive surface that resists etching by providing a tightly adhering protective coating. Photoresists can be applied as thin liquids or laminated as thicker, solid films. Liquid resists offer better resolution. Positive resists washing away exposed areas, while negative resists hardening. The final result is a metal panel with bare areas for etching and acid-resistant coatings elsewhere. Photoresists are applied by dipping, whirl coating, or spraying and must dry properly. UV exposure transfers patterns from the phototool onto the resist. For etching both sides, specimens are exposed for 6-7 minutes, enhancing resistance.

Etching

In photochemical machining (PCM), etching occurs when an acid reacts with exposed metal, oxidizing it to form a soluble product. Etching can be performed by immersing the metal in a chemically agitated bath or by spraying it with heated acid. The spray method helps remove reaction products, such as carbon content, to ensure fresh metal is always exposed to the etchant. When dipping, the specimen should be placed in a wire-net bag to prevent damage from the etching machine's sidewalls. As etching progresses, it penetrates the metal until it reaches halfway, causing a breakthrough. The etchant then flows through the opening, smoothing the edges and producing vertical sidewalls. Etching causes undercutting of the photoresist, which increases with metal thickness. Key parameters affecting etching include etchant concentration, temperature, and time. The etchant concentration is managed by adjusting the water and ferric chloride mix, while a stirrer ensures consistency. Temperatures must stay below 70°C to prevent damage to plastic components. Etching machines generally have a sump for etchants, with a titanium heating element and cooling coil to maintain temperature. For uniform etching on both sides, the specimen is positioned vertically. Proper safety measures are essential to handle the hazardous chemicals involved in etching.

EXPERIMENTATION WORK

During experimentation, temperature, time of etching, and concentration of etchant must be changed. For this heating bath is used which varies temperature from 20° C to125°C. In the heating bath heater is used to change the temperature of water which the sensor can sense. In the heated water, four beakers can be placed for experimentation. This instrument is used in the placing of the etching machine as shown in Figures1-3 given below.

Figure 1. Work part preparing setup [8]

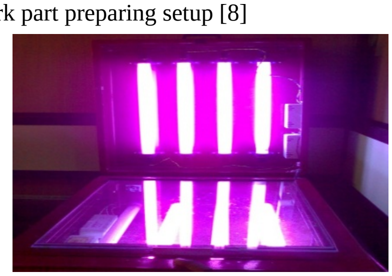

Figure 2 Ultra-violet (UV) set up for sample preparation [8]

There are other factors, which can be expected to affect the measures of performance. To minimize their effects, other factors as mentioned in Table 1 were held constant. The other fixed parameters are shown in table 4. The experiment was designed using different parameters. Three different levels are considered to determine the performance of these parameters on the output of the process. The following table 2 elaborates on the parameters and their level.

Figure 3 Etching Machine for etching purposes [8]

Table 1 Different controlling factors and details

Sr. No.	Parameter	Details
1	Etchant	Ferric Chloride
2	Base Material	Copper
3	Workpiece thickness	0.4 and 0.5 mm
4	Size of workpiece	45mm X 45 mm

Table 2 Different process parameters and their levels

Sr. No.	Parameter	Level of parameters	
		Low	High
1	Concentration (gm/lit)	500	600
2	Temperature (° Celsius)	40	60
3	Time (minute)	30	50

RESULT AND DISCUSSION

Experimental Work

The readings shown in Table 3 give the exact idea of the etching rate that took place on the plates at different concentrations, temperature, and times. Along with this, the photos of plates help in easily understanding the etching. The design of the experiment and the subsequent ANOVA analysis are closely interconnected. ANOVA decomposes the total variation in the data into its constituent components, identifying the sources of variation that contribute to the observed differences. The P-value approach is commonly used to assess the significance of the findings. The P-value represents the probability of observing a test statistic as extreme or more extreme than the one obtained, assuming that the null hypothesis (Ho) is true.

A smaller P-value indicates stronger evidence against Ho, allowing for a more confident conclusion at a given significance level. The accompanying graph, generated using MINITAB software, illustrates the main effect diagram. A visual representation of the effects of different factors on the response variables. The provided graphs offer valuable insights into the complex relationship between concentration, temperature, and time in the Etching depth of copper sheets using ferric chloride (FeCl3).

The Figure 4 illustrates the direct correlation between concentration and etching depth. As the concentration of FeCl3 increases from 500 to 700 grams per liter, the depth of the etched copper sheet also increases. This suggests that a higher concentration of FeCl3 leads to a more aggressive etching process.

The Figure 4b explores the impact of temperature on the etching rate. While the initial etching rate is high at 40 degrees Celsius, increasing the temperature further leads to a gradual decrease in the etching rate. This could be attributed to factors such as changes in the chemical reaction kinetics or the solubility of $FeCl_3$ at higher temperatures.

The details of the process parameters and their corresponding outcomes are visually represented in Table 3 in the form of a pictorial view. Each process parameter is considered at two distinct levels, ensuring a comprehensive analysis of variations. Based on these levels, a Design of Experiments (DoE) was carefully structured to systematically explore the effects of different parameter combinations. Following the designed framework, a series of experiments were conducted to observe and analyze the results, providing valuable insights into the process behavior.

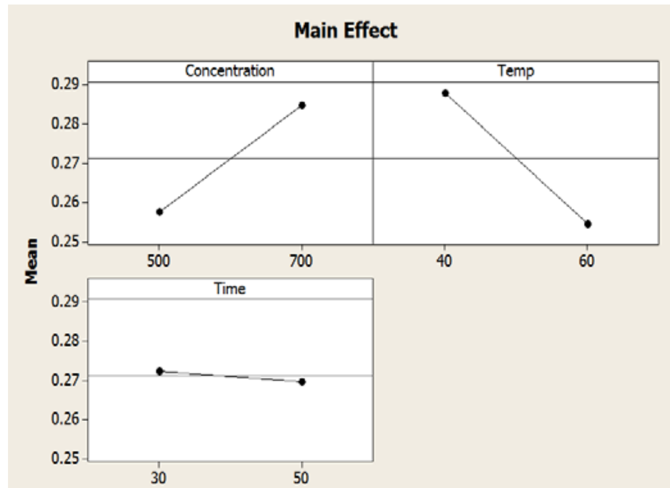

Figure 4 Effects of Concentration, Temperature, and Time on Etching Depth

Table 3 Readings taken in the form of ideal metric

Sr No	Concentration (gm/liter)	Temperature (^{0}C)	Time (minute)	Photograph
1	500	40	30	
2	500	40	50	
3	500	60	30	
4	500	60	50	
5	700	40	30	
6	700	40	50	

7	700	60	30	
8	700	60	50	

Figure 4c examines the relationship between time and etching depth. In this case, the graph indicates that increasing etching time does not result in a significant increase in depth. This suggests that the etching process reaches a plateau after a certain duration, and further time may not lead to substantial improvements in depth.

Figure 5 provide a more comprehensive understanding of how these three parameters influence etching depth. By varying concentration, temperature, and time, it is possible to identify the optimal conditions for achieving the desired etching depth.

Table 4 Percentage deviation in actual and calculated depth

SR. NO	Concentration (gm/liter)	Temperature (^{0}C)	Time (minute)	Calculated Depth (mm)	Actual Depth (mm)	Deviation (%)
1	500	40	30	0.2754	0.294	6.33
2	500	40	50	0.2726	0.246	-10.81
3	500	60	30	0.2458	0.248	0.887
4	500	60	50	0.2394	0.265	9.66
5	700	40	30	0.3026	0.328	7.74
6	700	40	50	0.2998	0.341	12.08
7	700	60	30	0.2694	0.245	-9.96
8	700	60	50	0.2666	0.250	-6.64

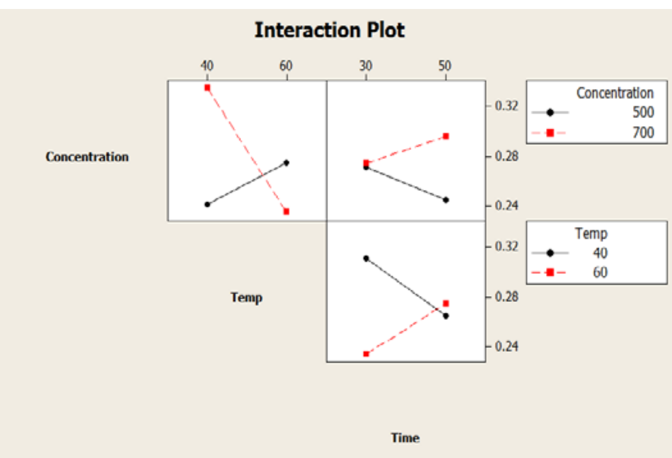

Figure 5 Interaction Plot for concentration, time, and temperature with its level

Figure 5 illustrates the complex relationship between concentrations, temperature, and etch depth. Figure 5a, showing the effect of concentration and temperature, reveals a non-linear interaction. At a concentration of 500 g/l, increasing temperature leads to a gradual increase in depth. However, at a concentration of 700 g/l, the relationship is reversed, with increasing temperature causing a significant decrease in depth. This suggests that the influence of temperature on etch depth is highly dependent on the concentration used. The second plot, examining the relationship between concentration and time, also demonstrates a non-linear effect. At a concentration of 500 g/l, increasing time leads to a decrease in depth. Conversely, at a concentration of 700 g/l, increasing time results in an increase in depth. This indicates that the optimal etching time varies with concentration.

Figure 5c, exploring the interaction between temperature and time, highlights the importance of temperature in the etching process. At a temperature of 40°C, increasing time results in a slow reduction in depth. However, at a temperature of 60°C, the etch depth increases rapidly with time. This suggests that a higher temperature can significantly enhance the etching rate. Overall, these interaction plots demonstrate the intricate interplay between concentration, temperature, and time in determining the final etch depth. Understanding these relationships is crucial for optimizing the photochemical machining process and achieving desired etching results.

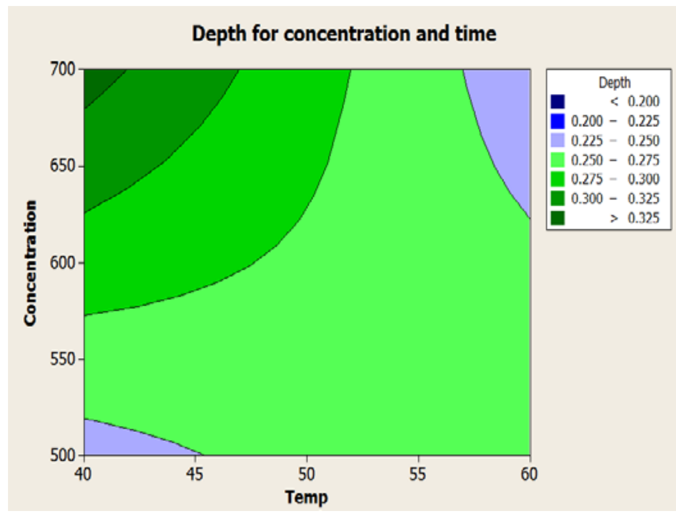

Figure 6 Surface plot of Depth VS Concentration and time.

The 3D surface plot offers a fascinating glimpse into the intricate relationship between concentration, time, and etch depth as shown in Figure 6, revealing how these variables interact to shape the outcome of the photochemical machining (PCM) process. On the X-axis, concentration takes center stage, while time stretches along the Y-axis, and etch depth rises along the Z-axis. The plot shows a good correlation with the concentration and time work in harmony to achieve maximum etch depth. When concentration is high and time is kept relatively short, the etching process hits its peak efficiency, suggesting a synergistic relationship between these two factors. It is as though the etchant is working at its best when its strong and fast, delivering precise and deep results [28-29].

However, the plot also uncovers a more nuanced narrative. Beyond a certain threshold—when the concentration exceeds 625 g/l and time stretches past 57 minutes the etch depth begins to decline. This unexpected twist hints at underlying complexities, such as saturation effects or limitations in mass transfer. It is a reminder that more isn't always better; pushing the process too far can lead to diminishing returns. On the flip side, when concentration drops below 520 g/l and time falls under 46 minutes, the etch rate slows significantly. This suggests that there is a minimum threshold for both variables to keep the process effective like a delicate balance that must be maintained.

Figure 7 also explores the interplay between temperature, concentration, and depth, painting another layer. Here, concentration is plotted on the x-axis, temperature on the y-axis, and depth on the z-axis. The graph reveals a direct correlation as concentration increases and temperature decreases, etch depth grows. The slightly curved shape of the plot hints at a nonlinear relationship, emphasizing that concentration and temperature don't act in isolation. Instead, their combined effects create a dynamic interplay determining the final depth same results are obtained in earlier researchers [29]. It is a reminder that PCM is a complex process, where even small changes in one variable can ripple through the entire system.

Together, these insights highlight the delicate balance required to optimize PCM. The 3D surface plots as shown in Figure 7 serve as a visual guide, helping navigate the intricate relationships between concentration, time, temperature, and depth. It reminds that while there is an optimal zone for achieving the best results, straying too far in any direction can lead to inefficiencies or unexpected outcomes. For researchers and engineers, these plots are more than just graphs they are a roadmap to unlocking the full potential of PCM, offering clues to refine the process and push the possible boundaries.

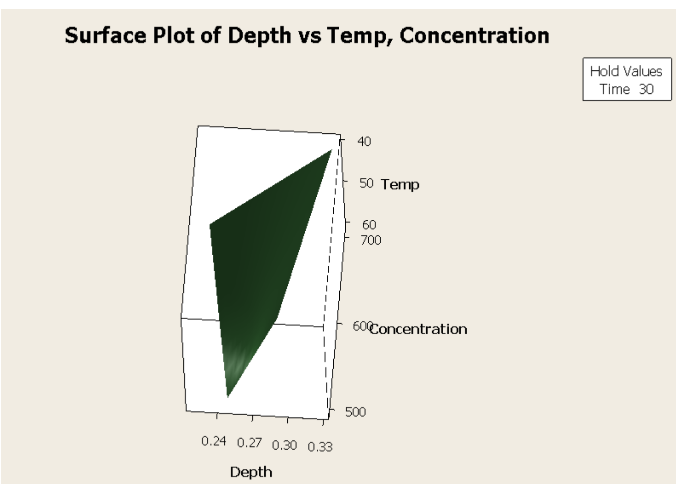

Figure 7 A surface plot of the relationship between Depth Vs temperature and Concentration holding time for 30 minutes.

The future of photochemical machining (PCM) is brimming with possibilities, driven by the need for precision, sustainability, and innovation. By integrating advanced technologies like AI and IoT, we can optimize parameters in real time, making the process smarter and more efficient. Sustainability will play a key role, with research focusing on eco-friendly etchants and waste management to reduce environmental impact. As new materials like composites and smart alloys emerge, PCM can adapt to meet the demands of industries like aerospace, automotive, and electronics. The potential for micro- and nano-fabrication opens doors for applications in biomedical devices and renewable energy, while hybrid techniques could push the boundaries of precision. Challenges like edge quality and material compatibility remain, but with automation, cost-effective solutions, and standardized protocols, PCM is poised to become a cornerstone of modern manufacturing.

Conclusion

The experiments conducted on photochemical machining (PCM) reveal that the concentration of ferric chloride ($FeCl_3$) plays a crucial role in determining the etch depth. A higher $FeCl_3$ concentration tends to produce a deeper etch, making it a key factor in controlling material removal. Additionally, while an increase in etching temperature generally enhances the etching rate, exceeding a certain threshold may adversely affect the process, potentially leading to a slower etching reaction. This indicates the presence of an optimal temperature range beyond which the efficiency of etching diminishes.

Furthermore, etching time has a significant impact, but beyond a certain duration, the increase in etch depth becomes negligible. This suggests that excessively long etching times do not necessarily contribute to improved results and may only lead to unwanted side effects, such as undercutting or surface roughness. For achieving the desired etch depth with minimal defects, it is essential to consider all three parameters $FeCl_3$ concentration, temperature, and etching time—in a balanced manner. By carefully optimizing these factors, an efficient and precise etching process can be achieved, ensuring high-quality outcomes in photochemical machining.

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Conflict of Interest Statement

Authors do not have any conflict of interest for this work

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