

Investigating the Influence of Process Parameters on Photochemical Machining of Phosphor Bronze Alloy Microchannels

Pradnya Krishna Bhuse^{1*}, Sandeep Sitaram Wangikar²

Abstract

Microchannels are widely employed in microfluidic devices, biomedical systems, and compact heat exchangers, where their functional efficiency depends strongly on surface finish, dimensional control, and edge quality. Traditional machining techniques often face limitations in producing such features with the required precision, prompting the use of advanced micromachining methods. In the present work, photochemical machining (PCM) has been applied to fabricate serpentine-shaped microchannels in phosphor bronze. The study systematically investigates the effect of three process parameters—etchant concentration, etching duration, and solution temperature—on machining performance. Ferric chloride was employed as the etchant, and a full factorial design of experiments was used to develop the experimental framework. The fabricated samples were examined through optical microscopy to evaluate edge sharpness and surface smoothness. Statistical validation was carried out using analysis of variance (ANOVA) to quantify the influence of process variables. Results confirm that etchant concentration and temperature are the most significant contributors to etch rate and machining quality, while etching duration plays a secondary role. The study revealed that surface roughness (R_a) increased with higher etchant concentration, temperature, and etching time, whereas edge sharpness (ES) improved with concentration and temperature but declined with prolonged etching. Optimal conditions for the minimum R_a were achieved at a concentration of 250 g/L, 35 °C, and 5 minutes, while the lowest ES occurred at the same concentration and temperature, with 21 minutes of etching. Overall, the study demonstrates that careful optimization of PCM parameters can produce precise and reliable microchannels, making the process highly relevant for engineering and biomedical applications.

Keywords: Photochemical machining, surface roughness, microchannel, phosphorus bronze alloy, edge sharpness

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Received Date: September 06, 2025

Accepted Date: September 30, 2025

Published Date: April 16, 2026

Citation: Pradnya Krishna Bhuse, Sandeep Sitaram Wangikar. Investigating the Influence of Process Parameters on Photochemical Machining of Phosphor Bronze Alloy Microchannels. Journal of Polymer & Composites. 2026; 14(Special Issue 2): S837–S846p.

INTRODUCTION

Photochemical machining (PCM) is a mask-based subtractive manufacturing process leveraging controlled chemical dissolution to create intricate geometries, especially suitable for materials that are normally hard to machine [1]. PCM offers a non-contact and high-precision method for processing complex geometries, especially in advanced metallic alloys.

While PCM has been widely studied for steels, copper, and nickel alloys [2-3]. Its application to bronzes—especially phosphor bronzes—remains less explored. These bronzes are essential in various artistic, marine, aerospace, and biomedical

applications due to their enhanced integrity and robustness against corrosion [4]. This work aims to bridge the knowledge gap by investigating the significance of key etching measures on machining alloy performance characteristics. Unconventional machining techniques have been explored, highlighting photochemical machining (PCM) as one of the least investigated methods [1]. The etching of oxygen-free high-conductivity (OFHC) copper demonstrated that temperature and time significantly impact undercut formation [2]. PCM of copper analyzed using a factorial method determined optimal etching conditions to minimize surface roughness and undercut [3]. The impact of workpiece positioning on PCM efficiency was studied, with improvements proposed for better accuracy [4]. A simulation model for two-dimensional etching was developed, considering various factors affecting micro-geometry [5]. Photolithography and etching processes were optimized for carbon steel in PCM to enhance texture profiles [6]. Copper etching using cupric chloride was investigated, analyzing parameters such as temperature, concentration, and additives, while also exploring environmentally friendly waste regeneration techniques [7].

PCM of Muntz metal showed that temperature has a greater influence on surface roughness (Ra) and material removal rate (MRR) than etching time [8]. A comparison of cupric chloride and ferric chloride etchants for stainless steel assessed surface roughness and engraving depth [9]. PCM settings for SS-304 stainless steel were calibrated using grey relational analysis, analyzing material removal, undercut, and surface roughness [10]. Microfeature fabrication on copper and brass was investigated, with conditions optimized for microfluidic applications [11]. An artificial neural network (ANN) model was developed to predict PCM outcomes for SS-304, validating improvements in machining performance [12]. Fabrication errors in brass microchannels were examined, with recommendations to adjust photo-tool size for enhancing dimensional accuracy [13]. A predictive mathematical model for PCM was created using the Taguchi method and confirmed through experimental validation [14].

Etching of SS-430 demonstrated that temperature significantly affects material removal and undercut, while time influences surface roughness [15]. Etching of aluminum 6068 using ferric chloride was analyzed, optimizing control factors for better accuracy [16]. A new etchant mixture for St304 achieved high machining rates with minimal pitting and improved surface quality [17]. The integrity of cobalt chromium alloy (L605) surfaces after PCM processing was examined, highlighting the impact of manufacturing techniques on metallurgical properties [18]. PCM conditions were enhanced for precise micro-mold fabrication used in engineering and biomedical applications [19]. Three-dimensional PCM was successfully performed on copper, achieving variable depths on complex surfaces [20].

A grey-based Taguchi method was applied to PCM for Inconel 601, reducing undercut and improving material removal rates [21]. Further investigations on Inconel 718 focused on surface finish parameters using EDAX and SEM analysis [22]. Microchannels in Monel 400 were fabricated, showing that rolling direction affects etching depth and surface quality [23]. A comparison between FeCl_3 and CuCl_2 etchants for Monel 400 revealed that FeCl_3 provided superior overall etching, while CuCl_2 improved geometrical accuracy [24]. The etch rate of AISI 316L stainless steel during PCM was significantly enhanced when a magnetic field was applied [25]. PCM-based surface texturing of Monel 400 was also explored for advanced manufacturing applications [26].

The effects of temperature, rolling direction, and etching time on Monel 400 microchannel fabrication were analyzed, optimizing machining efficiency [27]. PCM for german silver and brass was refined, concluding that brass exhibited lower roughness and a higher removal rate, whereas german silver had less edge deviation [28]. Optimization of PCM using grey relational analysis for ASME 316 steel identified etching time and concentration as critical factors [29]. PCM of SS316L steel was optimized using response surface methodology, determining parameters to enhance material removal while minimizing undercut [30].

Photochemical machining (PCM) has been widely explored for its ability to fabricate precise micro-

features on various engineering alloys. Studies on high-strength and high-conductivity copper alloys have shown that etchant type and processing state significantly affect the etched surface characteristics, influencing both quality and performance [31]. Comparative investigations on Monel 400 using FeCl_3 and CuCl_2 revealed notable differences in surface roughness, etch depth, undercut, and geometry retention, underlining the importance of selecting suitable etchants and process parameters [32]. Similar experimental work on stainless steel highlighted the role of etchant chemistry in determining machining response and surface finish [33].

Beyond experimental evaluations, comprehensive reviews have emphasized the principles, mechanisms, and broad application potential of PCM in precision manufacturing [34]. Advancements in etchant formulation, such as those tested on Co–Cr L605 alloy, demonstrated improved surface topography with promising implications for biomedical applications like cell growth[35]. Investigations on thin metal sheets further established the parameter–response relationship, aiding in optimization for accuracy and quality enhancement [36].

Recent innovations include the use of maskless digital projection techniques in micro-PCM, enabling highly precise machining on 100Cr6 steel by eliminating the need for traditional photoresist masks [37]. Complementary to these process advancements, error analysis studies on brass microchannel fabrication have identified key sources of dimensional deviations, providing guidelines for improving machining precision and reliability [38].

This research outlines a comprehensive parametric analysis and optimization of PCM for phosphor bronze. A full factorial DOE array was employed to assess the impact of three key factors—etchant concentration, etching time, and temperature—on Ra and etching depth.

METHODOLOGY

Material

The component chosen for the fabrication of microchannels through PCM is phosphor bronze, selected for its excellent heat-related properties. This material finds widespread applications in various domains, including electrical and electronic applications. Test specimens of size 20 mm × 20 mm × 1 mm were prepared.

Photolithography Procedure

The photolithography procedure began with applying a negative photoresist onto the phosphor bronze substrate. The coated substrates were then soft-baked at 90 °C for 10 minutes to remove any remaining solvent. Following this, the samples were exposed to UV light. To enhance adhesion and ensure accurate pattern formation, a post-exposure bake was conducted at 110 °C for 5 minutes, after which the samples were developed in an aqueous alkaline solution for 90 seconds to reveal the desired patterns. Etching was performed using ferric chloride (FeCl_3) at mentioned concentrations. Constant agitation was applied to ensure uniform etchant distribution. After the etching process, the samples were rinsed thoroughly with deionized water, the photoresist was removed using acetone, and the substrates were dried.

Full Factorial Design of Experiments (DoE)

Previous studies indicate that control factors like etchant concentration, etching time, etching temperature and significantly influence the output measure. Both the identified fixed and variable process parameters are presented in Table 1.

Table 1. Levels of constant and adjustable process settings.

Constant parameters	Description	Adjustable parameters	Level	Values
Etchant	FeCl_3 (Ferric Chloride)	Concentration in g/l	3	250,350,450
Specimen Thickness	1 mm	Temperature in °C	3	35,43,51
Size of Specimen	30 millimetres x 20 millimetres	Time in Minutes	3	5,10,15

A full fractional factorial approach was utilized for experimentation planning. A total of 27 experiments were required to analyze the combination of the selected parameters. The photochemical machining experiments were conducted on phosphor bronze with two replications, yielding a total of 81 trials. The preliminary trials resulted in the fabrication of serpentine microchannels devoid of internal obstructions, whereas microchannels integrated with triangular obstacles were manufactured based on the optimized process parameters. The output parameters of this study included Edge Sharpness (ES) and Surface Roughness (Ra).

Experimentation

The experimental apparatus (as depicted in Figure 1) which involves use of a Mitutoyo surface roughness tester to measure average surface (Ra), and a RAPID I Vision 5 microscope to evaluate edge sharpness (ES). The study utilized the full factorial DOE to structure the experimental trials. Control parameters included concentration of etchant, etching time & temperature. The values of these factors, along with the corresponding Ra & ES measurements, are detailed in Table 2. Figure 2 presents the fabricated photo tool used for machining.

Post-machining, the surface roughness parameter (Ra) was quantitatively characterized using a Surface Roughness Tester (Mitutoyo), whereas edge sharpness (ES) was analyzed through high-resolution imaging facilitated by a microscope. Table 2 presents the values of the process parameters and measured surface roughness and edge sharpness. Representative images of the fabricated photo tool are provided in Figure 2.



Figure 1. Configuration of the experimental apparatus.

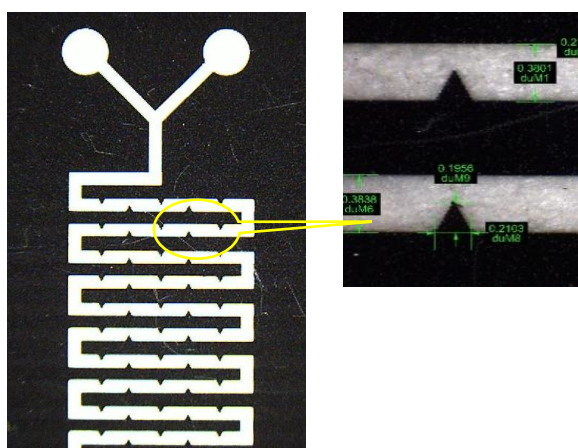


Figure 2. Photo tool.

Table 2. Full Factorial DOE with experimental parameters and resulting surface quality metrics.

Concentration. (g/l.)	Temperature. (°C)	Time (min.)	Surface roughness	Edge sharpness
			<i>Ra</i> (μm)	<i>ES</i> (μm)
250	35	5	0.1079	32.25
250	35	10	0.1421	32.54
250	35	15	0.1958	32.95
250	43	5	0.2354	32.61
250	43	10	0.2752	33.13
250	43	15	0.3025	33.87
250	51	5	0.3347	32.97
250	51	10	0.3582	33.75
250	51	15	0.3892	34.23
350	35	5	0.1689	33.1
350	35	10	0.1959	33.88
350	35	15	0.2312	34.85
350	43	5	0.2629	34.11
350	43	10	0.2903	35.05
350	43	15	0.3243	35.48
350	51	5	0.3387	34.98
350	51	10	0.3647	35.44
350	51	15	0.3913	38.17
450	35	5	0.2577	34.85
450	35	10	0.2954	35.15
450	35	15	0.3491	35.87
450	43	5	0.379	35.16
450	43	10	0.4287	35.95
450	43	15	0.4656	36.46
450	51	5	0.4789	35.88
450	51	10	0.5381	36.7
450	51	15	0.5921	37.83

RESULTS AND DISCUSSION

ANOVA

Table 3. demonstrates the effect of process parameters for Ra and ES was statistically examined using ANOVA, as summarized in Table 3. The results reveal that both etchant concentration and temperature significantly affect the machined microchannels' surface roughness and edge sharpness. On the other hand, etching time had a relatively lower influence on surface roughness. This underscores the need to carefully control concentration and temperature to optimize surface integrity. The experimental results were examined to assess the influence of selected process parameters on the response measures and depicted in Figure 3(a) and 3(b), respectively.

PARAMETRIC EFFECT STUDY

Influence of Concentration

A higher concentration corresponds to greater molarity of the solution of the etchant. At a concentration of 250 g/L, the solution exhibits lower specific gravity, indicating better flow characteristics. This enhanced flow facilitates more effective interaction between the etchant and the metal surface, resulting in improved surface finish (i.e., lower Ra) and more uniform edges, which correspond to lower edge sharpness (ES). However, as the specific gravity increases—observed in this study beyond a concentration of 350 g/L—the solution becomes more viscous, reducing its flowability.

Continued metal dissolution within a constant volume of etchant, coupled with evaporation, further increases the specific gravity, leading to a denser solution. This hampers the removal of dissolved metal ions from the surface and may promote sludge formation, both of which contribute to increased surface roughness (Ra) and edge sharpness (ES)

Table 3. ANOVA for surface roughness and edge sharpness.

Source	Degree of freedom	Seq SS	F ratio	P value
<i>Ra (Surface roughness)</i>				
Concentration	2	0.098363	33.06	0.026
Temperature	2	0.089631	33.77	0.029
Time	2	0.010312	3.89	0.205
Error	2	0.002654		
<i>ES (Edge sharpness)</i>				
Concentration	2	26.4202	70.70	0.014
Temperature	2	17.4572	46.72	0.021
Time	2	5.6572	15.14	0.062
Error	2	0.3737		

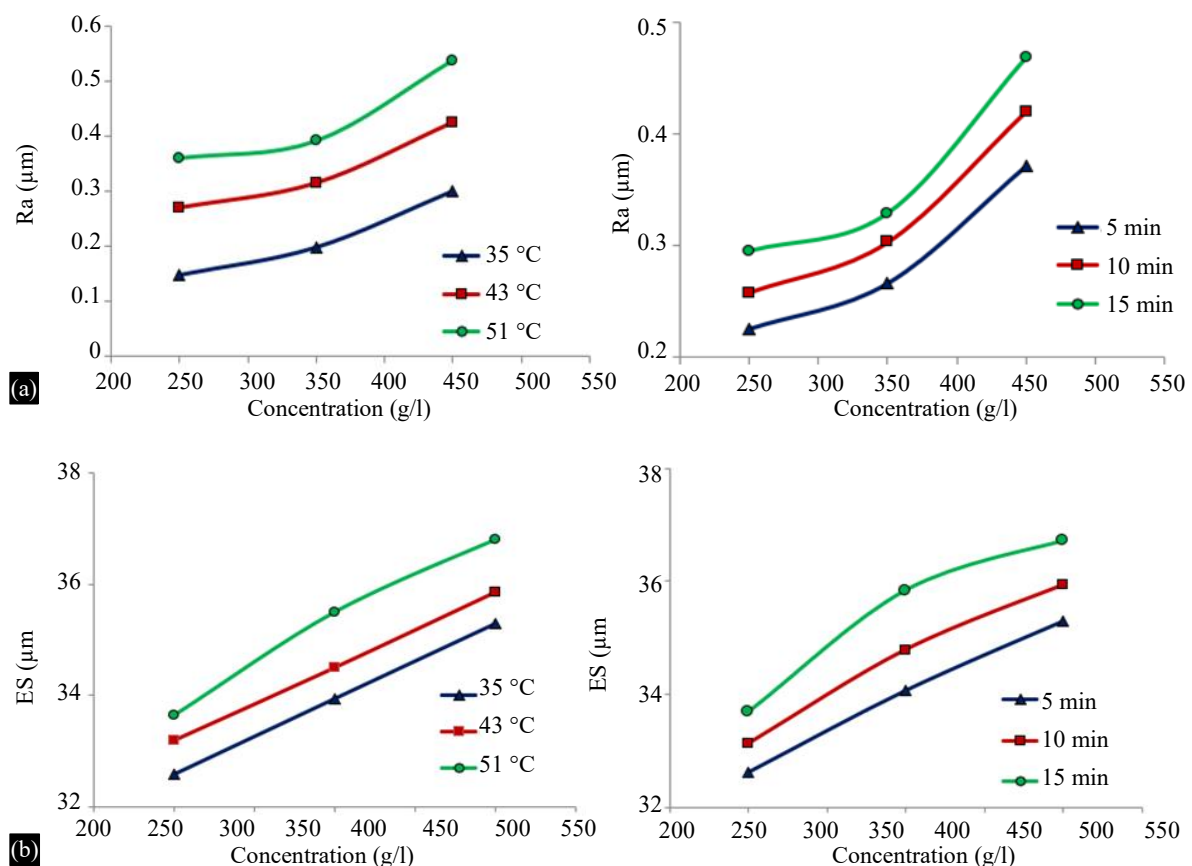


Figure 3. Investigation into the average influence of key process variables on (a) Ra and (b) (ES).

Influence of Temperature (T)

As the temperature rises, ion mobility also rises. At 35°C, the relatively lower ion mobility results in reduced etchant activity on the component surface, leading to an improved surface quality (lower Ra) & more even edge formation (lower ES). In contrast, at elevated temperatures such as 43°C and 51°C, the increased ion mobility enhances the etchant's aggressiveness, which results in a rougher surface (higher Ra) and irregular edges, reflected in a higher ES.

Influence of Etching Time

Shorter etching durations result in less material being removed from the metal surface, yielding a smoother finish (lower Ra). As etching time increases, more material is dissolved, causing the surface to become rougher. At 5 minutes, minimal material is removed from the edges, producing uneven edges and thus a higher ES. However, with longer etching times, more material is removed uniformly from the edge, resulting in smoother edges and subsequently lower ES values, as observed at 15 minutes.

Confirmation Experimentation

Figure 3 shows that the lowest surface roughness (Ra) was achieved at 250 g/L etchant concentration, 35 °C, and 5 minutes of etching, while the minimum edge sharpness (ES) occurred at the same concentration and temperature but with an etching time of 15 minutes.

Validation experiments were performed using the optimized parameters identified for minimizing surface roughness (Ra) and maximizing edge sharpness (ES). The measured Ra has 0.13 μm , and the average edge sharpness recorded was 30.51 μm . A surface roughness (Ra) of 0.13 μm and an average edge sharpness of 30.51 μm were recorded. Fig 4 shows the image used for ES measurement, and Figure 5 displays the SEM image of the machined component. The surface exhibited a smooth, defect-free finish, confirming the effectiveness of PCM

Micro channels with Triangular Obstacles

Serpentine microchannels, featuring triangular obstacles, were fabricated on a phosphor bronze plate using the photochemical machining (PCM) process. The machining was performed using the parameters from Experiment No. 1. Figure 6(a) presents the full view of the fabricated microchannels, while Figure 6(b) provides an enlarged view highlighting the triangular obstacle features.



Figure 4: Evaluation of ES.

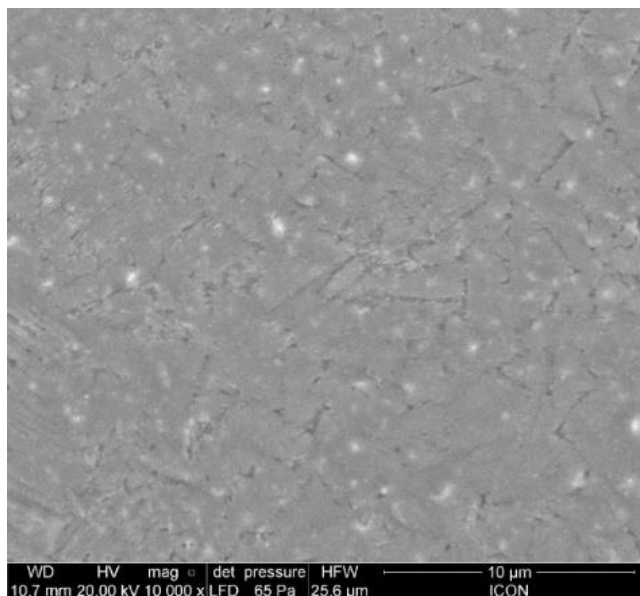


Figure 5. SEM Image of the photochemically machined surface.

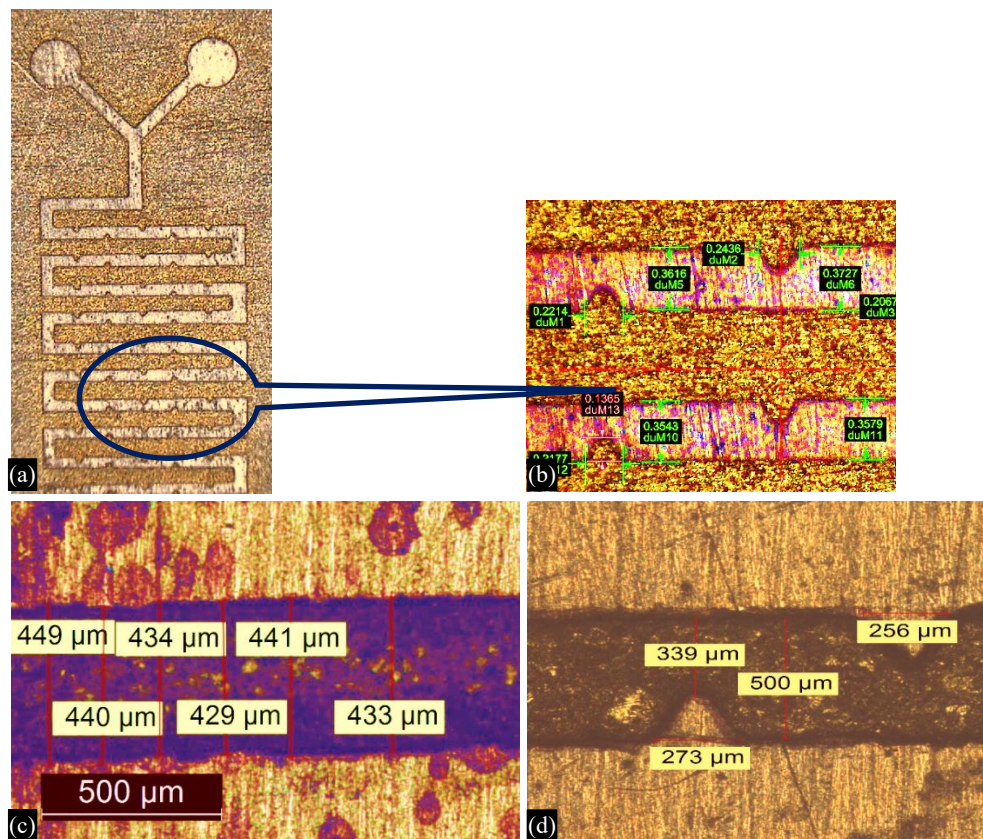


Figure 6. Visualization of serpentine micro channel configurations: (a) Complete layout with triangular obstacles, (b) Magnified section, (c) Micro channel without obstacles, and (d) Geometrical dimensions of triangular obstacles.

CONCLUSION

Photochemical machining (PCM) was employed to fabricate serpentine microchannels on phosphor bronze substrates, using FeCl_3 as the etchant. This research initially aimed to investigate how key process parameters, such as the concentration and temperature of the etchant and the etching duration, affect surface roughness (R_a) and edge sharpness (ES). ANOVA was conducted to identify the most significant factors affecting R_a and ES. Confirmation experiments were then carried out under the identified optimal conditions for minimizing both R_a and ES. Subsequently, serpentine microchannels with triangular obstacles were successfully fabricated using these optimized parameters.

An increase in etchant concentration, etching time, and temperature led to a corresponding rise in surface roughness (R_a) within the investigated ranges. Edge sharpness (ES), on the other hand, showed an increasing trend with higher concentration of etchant and temperature but decreased with longer durations of etching. The reduced R_a was achieved at a 250 g/L concentration, 35°C temperature, and 5 minutes etching time. At the same temperature and concentration, the lowest ES value was obtained when the etching time was extended to 21 minutes.

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