Chemical Machining for Stainless Steel, Aluminum and Copper Sheets at Different Etchant Conditions

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Received: 10/4/2015 Accepted: 15/10/2015

ABSTRACT

Chemical etching is employed as a micromachining process to produce micron-size components. The method is widely applied to machine geometrically complex parts of thin and flat materials. The effect of etchants (namely, FeCl₃ and FeCl₃+HNO₃), its initial concentration and temperature on Metal Removal Rate (MRR) of stainless steel, copper and aluminum sheets were examined. The results showed that the highest values of MRR were achieved at 33% concentration of FeCl₃ with 50±2°C for all metals, which were 0.738 mm³/min for aluminum, 0.287 mm³/min for copper and 0.224 mm³/min for stainless steel. The value of MRR increased approximately 10, 8 and 3 times with added HNO₃ to FeCl₃ for aluminum, stainless steel and copper machining at room temperature respectively.

Key Words: Nontraditional machining, Chemical machining, Metal removal rate, Etchants

INTRODUCTION

Machining process is divided into traditional and non-traditional machining. Traditional machining is the group of machining operations that use single- or multi-point tools to remove material in the form of chips (1). On the other hand, nontraditional machining processes are extensively employed to produce geometrically complex and precision parts from engineering materials in industries as diverse aerospace, electronics and automotive manufacturing (1-2). There are many multiple geometrically designed precision parts, such as deep internal cavities, miniaturized microelectronics and fine quality components can only be manufactured by nontraditional machining processes (3-4). Moreover, the chemical machining method is widely used to produce micro-components for various industrial applications such as micro-electromechanical systems (MEMS) and semiconductor industries (5-6). Chemical machining is the controlled chemical dissolution of the machined workpiece material by contact with a strong acidic or alkaline chemical reagent. Special coatings called maskants protect areas where the metal is not to be removed. The process is used to produce pockets and contours and to remove materials from parts having a high strength-to-weight ratio.

Chemical etching is a process in which material removal is carried out using strong chemical solution called “etchant”. This is simply the “accelerated and controlled corrosion” process. The method is recently employed as micromachining process in the production. The process has advantages over traditional machining processes (1-5). Copper, as one of the major commercial engineering materials, is extensively used in various industries such as electronics, automotive and chemical industries because of its excellent electrical and thermal conductivities, good strength and fatigue resistance, high corrosion resistance and ease of fabrication (6-8). Various copper etching studies are conducted with FeCl₃ (4, 9-12). The etching process was or efficient and produced better etching properties also for Al and Stainless Steel.
Maskants are used to protect the work piece surface to be machined from chemical etchant. It can be a polymer material or rubber. The effective chemical etchant would produce a higher etching rate and smooth surface finish. So, the selection of efficient etchant is probably the most important parameter. \( \text{FeCl}_3 \) is the most attractive chemical etchant for most of the engineering materials such as metal and alloys of steels, aluminum and copper etc. It is cheap and easy to control during the etching process, and like various etchant regeneration systems, \( \text{FeCl}_3 \) solution can be accessible from the industrial point of view. The best possible etchant should have high etching rate, good surface finish, compatibility with commonly used maskants, high dissolved-material capacity, economic regeneration, easy control of process and personal safety maintenance (12-16).

In this work chemical machining of Al, Cu and Stainless steel will be studied. It aims at studying the effect of chemical etching for aluminum, copper and stainless steel using \( \text{FeCl}_3 \) at different concentrations and with the addition of \( \text{HNO}_3 \) at different etching temperatures.

**EXPERIMENTAL PROCEDURE**

**Materials**

\( \text{FeCl}_3 \) and \( \text{HNO}_3 \) were obtained from Sigma-Aldrich. silicon rubber, acetone and alcohol are commercial grade and were used without any further purification.

**Experimental Set Up**

The set up of chemical machining processes consists of a glass flask used as a reactor equipped with low pressure air pump (electric air pump SH-202) for mixing to accomplish a homogenous reaction medium, Fig. (1). The temperature of the reaction was controlled using a water bath (Sanford SF500HPT, China). The effects of etching parameters on the depth of etch and metal removal rate of machining were studied.

![Fig. (1) Schematic diagram and photograph of chemical etching setup.](image)

**Workpiece and Etchant Preparation**

The workpiece material has to be cleaned at the beginning of chemical machining process. The cleaning operation is carried out to remove oil, grease, dust, rust or any substance. The surfaces of workpiece material were cleaned using fine polishing paper and washing with acetone and alcohol followed by ultrasonic cleaning before masking. A good cleaning process produces a good adhesion of the masking material. The most widely used cleaning process is the chemical method due to less damages occurred comparing to mechanical one.
Etchants with three different concentrations were prepared by dissolving 500, 400 and 300 gram FeCl\textsubscript{3} in one liter of distilled water to produce solutions with concentrations of 33\%, 28.5\% and 23\%, respectively. Concentrated HNO\textsubscript{3} was added in some experiments.

**Etching Processes**

The cleaned workpiece material is coated with a masking material, (Fig. 2,3). The selected masking material should be a readily strippable mask, which is chemically impregnable and adherent enough to stand chemical abrasion during etching. Silk-screen masks are preferred for shallow cuts requiring close dimensional tolerances. The masking material was removed from the exposed areas that receive chemical machining process. The selection of mask depends on the size of the workpiece material, the number of parts to be produced, and the desired detail geometry. In this work the masked material was commercial silicon rubber.

![Fig.(2) a) Sample full masking, b) Sample after demasking for machining c) After machining](image)

The most important stage to produce the required component from the sheet material is etching, which was carried out by immersing the workpiece material into selected etchant in etching set up as shown in Fig. (1). This process is generally carried out at elevated temperatures, which depend on the solution type, the concentration and etching period. The air pump is added to increase the inflow of the active agent to the surface of the workpiece during etching. The workpiece will react with the solution and release hydrogen ions. This reaction stops only when etch product blocks the chemical flow and causes an invisible wall between ions and workpiece\textsuperscript{16}. Then; the etched workpiece was rinsed to clean etchant from machined surface. The final step is to remove masking material from workpiece. The inspections of the dimensions and surface quality are completed before packaging the finished part. Fig.(3) shows chemical machining for some samples for industrial applications masking, demasking and after etching process.

![Fig.(3) Samples before and after chemical etching machining of different metals for industrial applications](image)
RESULTS AND DISCUSSION

The masked materials for all samples were removed from one side according to geometry of shape machining. In this work the shape is square dimension. The MRR was estimated depending on the etched area, 20x20 mm$^2$. The MRR was calculated from the change in the volume of materials per time of machining part according to the following equation.

$$\text{MRR} = \frac{\text{Volume of Metal Removed}}{\text{time}} \text{ mm}^3/\text{min} \quad (1)$$

Effect of Etchant Concentration

The MRR were calculated for Al, stainless steel and Cu at different FeCl$_3$ etchant concentrations (Fig. 4). From this figure there is an increasing of the MRR for Al, St. steel and Cu with the increasing of the solution concentration and this was due to increasing of the electron acceptor concentration ions (Fe$^{3+}$), which enhances the rate of surface reactions, known as oxidation-reduction reactions. The increase in Fe$^{3+}$ concentration is compatible with the fact which states that the chemical potential of ions increases with increasing its concentrations. The oxidation-reduction reactions of the three metals are indicated in the following equations:-

$$\text{FeCl}_3 + \text{Cu} \rightarrow \text{FeCl}_2 + \text{CuCl} \quad (2)$$
$$\text{FeCl}_3 + \text{CuCl} \rightarrow \text{FeCl}_2 + \text{CuCl}_2 \quad (3)$$
$$3\text{FeCl}_3 + \text{Al} \rightarrow 3\text{FeCl}_2 + \text{AlCl}_3 \quad (4)$$
$$2\text{FeCl}_3 + \text{Fe} \rightarrow 3\text{FeCl}_2 \quad (5)$$

Also, it was observed that the MRR for Al was higher than that of Cu and Fe and this is because the chemical activity difference between Al and Fe$^{3+}$ ions is higher compared to that for the other two elements. MRR at 33% concentration with 50±2 $^\circ$C was 0.738, 0.287 and 0.224 mm$^3$/min for Al, Cu and Stainless Steel, respectively.

![Fig. (4)](image-url) MRR of the three metals at 50$^\circ$C with different concentrations of FeCl$_3$.  

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**Fig. (4)** MRR of the three metals at 50$^\circ$C with different concentrations of FeCl$_3$. 

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Effect of Etchant Types

The second etchant was the mixture of FeCl\(_3\) and HNO\(_3\), which has high activity in reduction of the three metals compared to that of FeCl\(_3\). Nitric acid is a strong oxidizing agent, which can be ionized, dissociated, in water producing H\(^+\) ions, (equation 6). H\(^+\) ions are electron acceptors and increase the reduction rate of the three metals. Also, equation 7 indicates another dissociation reaction of HNO\(_3\) where, the nitronium ion, NO\(_2^+\), is the active reagent and plays as electron acceptor.

\[
\text{HNO}_3 \rightleftharpoons \text{H}^+ + \text{NO}_3^- \quad (6)
\]

Or

\[
2\text{HNO}_3 \rightleftharpoons 2\text{NO}_2^+ + \text{NO}_3^- + \text{H}_2\text{O} \quad (7)
\]

The reduction reaction of Cu is shown in equations 8 and 9, where the rate of reduction of Cu metal is very high compared to that for FeCl\(_3\) and this is the same mechanism for the other two metals.

\[
\text{Cu} + 4\text{H}^+ + 2\text{NO}_3^- \rightarrow \text{Cu}^{2+} + 2\text{NO}_2 + 2\text{H}_2\text{O} \quad (8)
\]

\[
3\text{Cu} + 8\text{HNO}_3 \rightarrow 3\text{Cu}^{2+} + 2\text{NO} + 4\text{H}_2\text{O} + 6\text{NO}_3^- \quad (9)
\]

The stability of etchant is critical. The etching process is a closed-loop system and needs high investment. These etchants can be regenerated and etched copper can be recovered. These etchants are only economical if the copper etching is as mass production process.

Figure (5) presents the influence of etchant type on the metal removal rate for Al, stainless Steel and Cu at room temperature. It can be noted that, the addition of HNO\(_3\) to FeCl\(_3\) increases MRR significantly. The MRRs were 2.4, 1.86 and 0.32 mm\(^3\)/min for aluminum, stainless steel, and copper respectively. Comparing between the results obtained from FeCl\(_3\) and FeCl\(_3\)+HNO\(_3\) etching solutions, it can be noticed that the values of the MRR for FeCl\(_3\)+HNO\(_3\) etching solutions increased approximately 12, ~20 and 8 times for Al, St. steel and Cu, respectively.

![Fig. (5) Influence of etchant type on the MRR of the three metals at room temperature.](image-url)
Effect of Etchant Temperature

The MRR of Al, Cu and stainless Steel has high values by increasing the temperature of etching, and this is due to chemical activation of the etchant which becomes more active with the increasing of temperature (Fig. 6, Fig. 7 and Fig. 8). The evaporation rate of the solution increases at high temperature, so the temperature of etching should not be more than 60°C. The etching time is important; longer etching periods produced a constant etching process in case of aluminum etching, because chemical etching was not properly controlled in the first part of etching process (first 5 min etching). After this period, the etching of aluminum was more stable.

Fig. (6) MRR of Al at different temperatures with different concentrations of FeCl₃

Fig. (7) MRR of Cu at different temperatures with different concentrations of FeCl₃
CONCLUSION

Chemical machining for Al, Cu, and stainless steel were investigated using FeCl₃ solution with different concentrations as an etchant and in another case with the addition of HNO₃ at different temperatures. According to parameters studies it can be concluded that:

1. FeCl₃ is a very suitable etchant for Stainless steel and Aluminum and Copper. The etching reaction is simple, that makes the process easy to control. This is important in case of weight reduction of the workpiece material.
2. Addition of HNO₃ to the FeCl₃ etchant increases MRR approximately by 12, 8 and 20 times for Al, Cu and stainless steel, respectively.
3. Raising etching temperature increases the MRR and reduces the machining time.
4. Aluminum has the highest MRR comparing with Copper and Stainless steel.

REFERENCES


