PHOTOCHEMICAL ETCHING OF HEAT EXCHANGER PLATES

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1. Introduction

Photochemical etching is used to produce 2D and 3D metal components. The most commonly etched metals are stainless steel and copper alloys. However, recently there has been a growing interest in other metal alloys such as aluminium, titanium, nitinol, and nickel super alloys.

Photochemical etching is a highly versatile process; it can be used to manufacture metal components for a broad range of applications, including automotive, aerospace, medical, defence, electronic, renewable energy, and other applications. The process is also highly flexible, allowing design changes to be implemented quickly and easily. Other advantages include short turnaround times and inexpensive tooling.

One of the most promising applications of photochemical etching is the fabrication of heat exchanger plates. Fluid flow channels can be created on flat metal sheets using this technique. Indeed, some intensive development work has been conducted at Advanced Chemical Etching Ltd. to investigate the feasibility of manufacturing heat exchanger plates using photochemical etching.

This report presents an overview of the process of photochemical etching and describes how this process can be used in the manufacture of heat exchanger plates.

2. Process description

The etching process is divided into seven stages: metal preparation, photo-tool production, lamination, printing and exposure, developing, etching, and stripping, as shown in Figure 1. While these steps are independent of the type of metal to be etched, the composition of the etching solution generally varies from one metal to another.

The stages of photochemical etching are described below. A more in-depth description of the process can be found in [1].
2.1. Metal preparation

The metal type and thickness are specified by the end user. The raw metal is prepared by (i) cutting it into the required sheet size and (ii) cleaning the metal surface. The cleaning process removes grease, particulate matter, and any other contamination from the surface. The cleaning step is critical because any surface contamination can lead to serious problems during lamination and etching. Cleaning is achieved using chemical agents (degreasing and dilute acid or alkali solutions), as well as by mechanically brushing the surface in an automated machine.

2.2. Tool production

The pattern to be etched on the metal surface is produced as a digital drawing using CAD software and is then printed on a transparent polymeric film to produce the photo-tool. To produce the required dimensions of the etched features on the final metal component, the CAD drawing must take into account what is known as the ‘undercut’. Undercut can be defined as lateral or horizontal etching that takes place under the edge of the photoresist, and is caused by the fact that the etching solution etches the metal surface in all direction. This is known as
isotropic etching. The metal underneath the photoresist at the edge of the etched areas is exposed to the etching solution and is therefore etched (as can be seen in Figure 1). The design of the CAD drawing must compensate for this phenomenon by including an etch allowance or compensation applied to all the dimensions that are affected by undercut. The compensation is calculated based mainly on the required etch depth. The deeper the etched feature, the larger the undercut and the bigger the compensation needed.

2.3. Lamination

In this step, a photoresist layer is applied to the whole surface of the metal. The photoresist is a polymeric film containing binder polymers, acrylate monomers and photo-initiators. It is applied to protect the surface of the metal from the action of the etching reagent except in the areas that need to be etched. The photoresist is applied to the metal under heat and pressure to ensure good adhesion to the metal surface.

2.4. Printing and exposure

Here, the image from the photo-tool is transferred to or superimposed on the laminated (i.e. photoresist-coated) metal sheet. This step specifies the exact areas where the photoresist must be dissolved or removed in order to allow the metal in these areas to be etched.

It should be noted that there are two types of photoresists. If the opaque lines on the photo-tool specify the areas that need to be etched, the photoresist is described as a positive-working photoresist. On the other hand, if the photo-tool specifies the areas that need to be protected from the etchant, we have a negative-working photoresist. This is illustrated in Figure 1 above.

In the process described in this report, a negative-working photoresist is assumed. First, the laminated metal sheet is sandwiched between the two layers of the photo-tool (one layer per side). The sheet is then exposed to UV radiation from a UV lamp. The areas of the photoresist that are protected from the radiation by the opaque lines on the photo-tool remain unaffected, while the areas exposed to the radiation through the transparent areas of the photo-tool undergo a polymerisation reaction that causes the photoresist in these areas to harden. The photo-initiators in the photoresist initiate the reaction in which the acrylate monomers are converted into a polymer under the influence of UV radiation. This transfers the image from the photo-tool to the photoresist.

2.5. Developing

The non-polymerised regions of the photoresist are removed by exposing the laminated sheet to a mild alkaline solution that dissolves these regions. The polymerised (hardened) regions of the photoresist, on the other hand, remain unaffected by the developing solution. As a result, there are now two different regions on the surface of the metal: (i) exposed (i.e. bare) areas formed by selectively dissolving the photoresist to produce the desired pattern, and (ii) protected areas where the photoresist is present and intact.
2.6. Etching

The etching step dissolves the exposed metal, while the protected areas of the surface under the photoresist remain largely unaffected (except for the effect of undercut as explained above). The sheet is fed into the etching machine via a conveyor that moves the sheet horizontally through the etching chamber. In the etching chamber, a set of oscillating spray nozzles deliver the etching solution to the surface of the metal where the etching reaction takes place. The etching reaction is a reduction-oxidation (redox) reaction in which the metal is oxidised by the etching reagent, while the etching reagent is reduced. The oxidised metal dissolves into the solution.

The depth of the etched features produced by the reaction depends largely on the reaction time, which in turn is controlled by setting the speed of the conveyor. Longer etch times (slower conveyor speeds) lead to a deeper etch. Also, longer etching times lead to increased undercut, thus requiring a larger undercut allowance when designing the photo-tool (section 2.2 above).

2.7. Stripping

After etching, the photoresist is removed by exposing the sheet to a proprietary alkaline solution which weakens the adhesion of the photoresist to the metal surface, thus allowing the photoresist to be removed. This is done in a stripping machine in which the stripping solution is sprayed on the sheets.

3. Fabrication of heat exchanger plates

In recent years, there has been a drive to develop more compact and efficient heat exchangers for a wide range of applications where heat management is required. For example, lithium-ion batteries are widely used as a source of energy in electric and hybrid electric cars [2]. The battery is cooled using a plate-to-plate heat exchanger which transfers heat from the battery coolant loop to the refrigerant loop. Plate heat exchangers use metal plates with features that allow the flow of two fluids and the transfer of heat between these fluids.

Fluid flow and heat transfer can be achieved using flow channels of different shapes. Heat transfer can be enhanced by providing a large surface area between the two fluids and by using a metal of high thermal conductivity in the construction of the exchanger plates.

Due to an interesting combination of properties, aluminium alloys are widely used in the construction of heat exchangers in the automotive industry. These properties include low density (2.7 g cm\(^{-3}\)), good thermal conductivity (237 W m\(^{-1}\) K\(^{-1}\)), relatively good corrosion resistance, and satisfactory mechanical properties [3]. Titanium is also attractive due to its excellent corrosion resistance.

Photochemical etching can be used to produce flow channels on metal plates. The geometry and dimensions of these channels have a large influence on the characteristics of heat transfer between the two fluids. Larger surface areas lead to better heat transfer rates.
To fabricate a heat exchanger unit, photochemical etching can be used to produce the desired flow channels on the metal plates. Figures 2 & 3 show examples of heat exchanger plates manufactured using photochemical etching. One of the major advantages of photochemical etching is the ease with which design changes can be implemented. For example, different flow geometries can be tested to determine the optimum channel shape and dimensions. Plates of different metals and thicknesses can be produced quickly in order to compare their performance and to determine the best metal and thickness for the construction of the heat exchanger.

Figure 2: Etched heat exchanger plate (RenewX project)

Figure 3: A cross section of an etched heat exchanger plate
The etched plates can be diffusion bonded, diffusion brazed or brazed together to make the heat exchanger stack (Figure 4). The resulting heat exchanger stacks can be much smaller than conventional shell-and-tube heat exchangers, thus delivering major space and weight benefits. Moreover, more than two process streams can be incorporated into a single unit thus reducing the requirement for piping and valves. Reaction and mixing features can also be incorporated into the plate heat exchanger design.

Figure 4: A section of a heat exchanger (RenewX project)

4. Conclusions

Photochemical etching is a versatile process that can be used to produce flow channels on heat exchanger plates. The process consists of seven stages, (i) metal preparation, (ii) photo-tool production, (iii) lamination, (iv) printing and UV exposure, (v) developing, (vi) etching, and (vii) stripping. The process uses inexpensive digital tooling and offers several advantages. Different designs of heat exchanger plates can be produced quickly using this technique in order to determine the optimum channel shape and dimensions. Moreover, different metals of varying thicknesses can be etched. The rate of heat transfer within the heat exchanger is determined mainly by the shape and dimensions of the flow channels, type of metal alloy used in the construction of the heat exchanger plates and the plate thickness.
5. References

