BEST: International Journal of Management, Information Technology and Engineering (BEST: IJMITE)
ISSN 2348-0513
Vol. 2, Issue 3, Mar 2014, 77-86

ANALYSIS OF CHEMICAL MACHINING FOR PRACTICAL APPLICATIONS

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ABSTRACT

Chemical machining (CHM) is the stock removal process for the production of desired shapes and dimensions through selective or overall removal of material by controlled chemical attack with acids or alkalis. This is one of the oldest non-traditional machining process and have some drawbacks also. The main issue faced by chemical machining is the reduced material removal rate when compared to other non-traditional machining techniques. Accuracy of machining should also paid attention. Apart from that, since we are using chemical etchants for the process, it also have got some environmental issues. The machining quality of chemical machining is comparatively less. So it is necessary to think of an idea to improve the quality of machining. Laser-chemical machining is a method which can be adopted for improving the quality of machining. Improving the surface roughness should also paid attention. This study is an investigation to find the ways to solve the above specified issues.

KEYWORDS: Chemical Machining, Photochemical Blanking,

INTRODUCTION

Chemical machining is a well-known nontraditional machining process and is the controlled chemical dissolution of the machined work piece material by contact with a strong acidic or alkaline chemical reagent. It is also called as chemical etching. Nearly all the materials from metals to ceramics, can be chemically machined. CHM process is employed where blanking or metal removal is difficult or impractical by the conventional machining processes because of material hardness, brittleness, size of part, complexity of shape or thinness of the part.

Chemical milling, photochemical blanking and milling, chemical engraving, and chemical deburring are closely relatedprocesses. Special coatings called mask ants protect areas from which the metal is not to be removed. The purpose of etching is to optically enhance microstructural features such as grain size and phase features. Etching selectively alters these microstructural features based on composition, stress, or crystal structure. The most common technique for etching is selective chemical etching and numerous formulations have been used over the years. Other techniques such as molten salt, electrolytic, thermal and plasma etching have also found specialized applications. The process is used to produce pockets and contours and to remove materials from parts having a high strength-to-weight ratio. Moreover, the machining method is widely used to produce micro components for various industrial applications such as micro electro mechanical systems (MEMS) and semiconductor industries.

Photochemical machining (PCM) is one of the least well-known non-conventional machining processes. It is a type of chemical machining. Itemploys chemical etching through a photoresist stencil as the method of material removal over selected areas. The technique is relatively modern and became established as a manufacturing process about fifty years ago. The processing technology has been kept a closely-guarded secret within a small number of industrial companies but despite this, the sales of parts made by PCM at the end of the twentieth century was approximately US$ 6 billion.

Chemical machining method may be the oldest nontraditional machining method which is used to shape copper with citric acid in The Ancient Egypt in 2300 BC. Until the 19th century this process was widely used for decorative etching. The development of photography provided a new dimension to chemical machining and in 1826 J.N. Niepce was the first to use a photoresist made from bitumen of Judea asphalt for etching pewter (an alloy of 80-90% of tin and 10-20% of lead). William Fox Talbot (1852) patented a process for etching copper with ferric chloride, using a photoresist made from bichromated gelatin (GB Patent No:565). John Baynes, in 1888, described a process for etching material on two sides using a photoresist which was patented in the USA (US Patent No: 378423).

The main industrial application of chemical machining developed after the war. In 1953, North American Aviation Inc. (California USA) used the process to etch aluminium components for rockets. The company named the process "chemical milling" and patented it (US Patent No: 2739047) in 1956. The machining method is called in different names such as etching, chemical etching, wet etching, etc. Chemical machining process is mature and well established. It is simple to implement. There is no additional cleaning step needed. Chemical machining is the cheaper machining process. These are the factors contributing to the popularity of chemical machining.

The major process characteristics of chemical machining are material removal rate, accuracy and surface finish. The main challenges for the process are the same as its characteristics. Material removal rate is dependent on the selected etchant. Accuracy of the process may be affected by the under cutting behavior in simple contouring.

The main uses of chemical machining are to create shallow, wide cavities on plates, sheets, forgings and castings to reduce weight. This is very heavily used in electronics manufacturing. This technique is commonly used to make flat springs, metal bookmarks, encoder wheels, lead frames for IC chips, sieves and filters used in medical applications, microwave oven filters, heat sinks that are attached to printed circuit boards etc.

In this study, chemical machining process was described its importance as nontraditional machining process. The steps of process were discussed in detail. The tolerances, material removal rate, accuracy, surface finish and dimensional factors of machined parts were examined. Another issue facing by chemical machining is the environmental problems. The environmental effect on chemical machining and the solutions were mentioned.

PRINCIPLE

The main working principle of chemical machining is chemical etching. The part of the workpiece whose material is to be removed, is brought into the contact of chemical called etchant. The metal is removed by the chemical attack of etchant. The portion of workpiece where no material is to be removed, is masked before chemical etching.

Chemical machining is the stock removal process for the production of desired shapes and dimensions through selective or overall removal of material by controlled chemical attack with acids or alkalis. The mechanism is to use chemical reaction between the material of the work piece and some chemical reagent, so that the products of the reaction can be removed easily. Thus the surface of the workpiece is etched away, exposing the lower layers, and the process is continued until the desired amount of material is removed.

A typical chemical machining setup is as shown in the below figure 1.

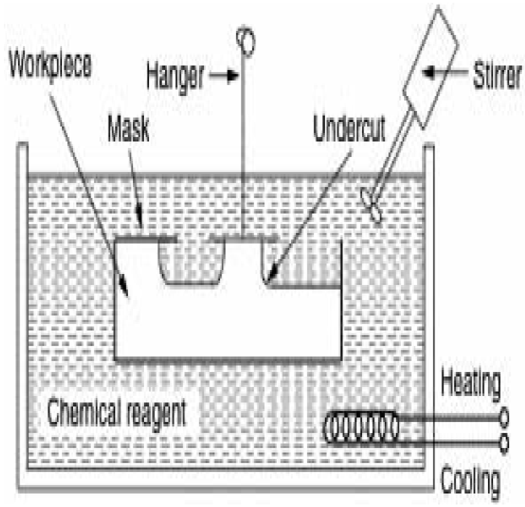

Figure 1: Typical Chemical Machining Setup [1]

Chemical blanking is used chiefly on thin sheets and foils. In most applications photoresist (photosensitive masking) is used to define the location on the work piece at which the material is to be etched.

Chemical contour machining or chemical milling is used mainly to produce three-dimensional shapes by selective or overall removal of metal from relatively large surface areas. The main purpose is to achieve shallow but complex profiles, reduction in weight by removing unwanted material from the surface as in the case of the skin of an aircraft.

METHODOLOGY

Procedure for Chemical Machining

`Chemical machining process has several steps for producing machine parts. These are given below:

- **Workpiece Preparation:** The workpiece material has to be cleaned in the beginning of chemical machining process. The cleaning operation is carried out to remove the oil, grease, dust, rust or any substance from the surface of material. A good cleaning process produces a good adhesion of the masking material. There are two cleaning methods; mechanical and chemical methods. The most widely used cleaning process is chemical method due to less damages occurred comparing to mechanical one. Ultrasonic cleaning machine is applied with using special cleaning solution and heating is beneficial during the cleaning process.
- **Coating with Masking Material:** The next step is the coating cleaned workpiece material with masking material. The selected masking material should be readily strippable mask, which is chemically impregnable and adherent enough to stand chemical abrasion during etching.
- **Scribing of the Mask:** This step is guided by templates to expose the areas that receive chemical machining process. The selection of mask depends on the size of the work piece material, the number of parts to be produced, and the desired detail geometry. Silk-screen masks are preferred for shallow cuts requiring close dimensional tolerances.
- **Etching:** This step is the most important stage to produce the required component from the sheet material. This stage is carried out by immerse type etching machine. The Work piece material is immersed into selected etchant and the uncovered areas were machined. This process is generally carried out in elevated temperatures which are depended on the etched material. Then the etched work piece is rinsed to clean etchant from machined surface.

- **Cleaning Masking Material:** Final step is to remove masking material from etched part. The inspections of the dimensions and surface quality are completed before packaging the finished part.

Maskants and Etchants Used in Chemical Machining

Maskants

Masking material which is called maskant is used to protect workpiece surface from chemical etchant. Polymer or rubber based materials are generally used for masking procedure. The selected maskant material should have following properties.

- Tough enough to withstand handling
- Well adhering to the workpiece surface
- Easy scribing
- Inert to the chemical reagent used
- Able to withstand the heat used during chemical machining
- Easy and inexpensive removal after chemical machining.

Multiple maskant coatings are used to provide a higheretchant resistance. Long exposure time is needed when thicker and rougher dip or spray coatings are used. Various maskant application methods can be used such as dip, brush, spray, roller, and electrocoating as well as adhesive tapes. When higher machined part dimensional accuracy is needed, spraying the mask on the workpiece through silk screen would provide a better result. Thin maskant coating would cause severe problems such as notwithstanding rough handling or long exposure times to the etchant. The application of photoresist masks which are generally used in photochemical machining operation, produce high accuracy, ease of repetition for multiple partetching, and ease of modification.

Table 1: Masking Materials for Various Chemical Machined Materials

Work Piece Material	Masking Material
Al and alloys	Polymer,Butyl rubber, neoprene
Fe and alloys	Polymer, Polyvinyl chloride, Polyethylene butyl rubber
Nickel	Neoprene
Magnesium	Polymer
Cu and alloys	Polymer
Titanium	Polymer
Silicon	Polymer

Etchants

Etchants are the most influential factor in the chemical machining of any material. Various etchant are available due to workpiece material.

- High etch rate
- Good surface finish
- Minimum undercut
- Compatibility with commonly used maskants

- High dissolved-material capacity
- Economic regeneration
- Etched material recovery
- Easy control of process.
- Personal safety maintenance

Figure 2 shows the etch profile development.

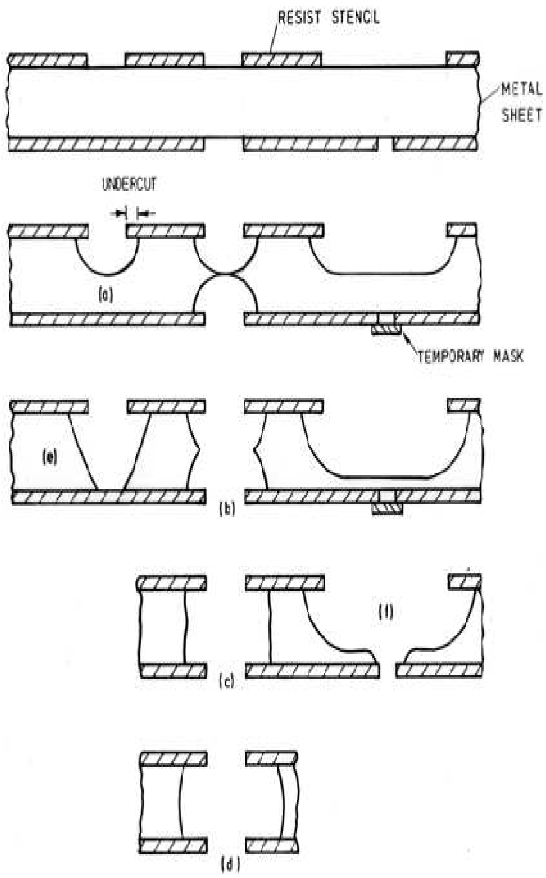

Figure 2: Etch Profile Development (from Top to Bottom) as Etching Time Increases [2]

Different etchants are commercially available or the required etchant can be prepared in shop. Ferric chloride (FeCl3) is the most widely used etchant in chemical machining. It is mainly used for etching iron-based alloys as well as copper and its alloys, aluminium, etc. Cupric chloride (CuCl2) is generally applied for copper and copper based alloys in electronics industry because various regeneration systems are available for the waste etchant. Alkaline etchants are introduced to the fabrication of electronic components such as printed circuit board.

Typical applications of chemical machining are the following. Chemical blanking can be used make burr-freeetching of printed-circuit boards (PCB), decorative panels, thin sheet-metal stampings, and the production of complex or small shapes. Chemical milling is used for the weight reduction of space launch vehicle.

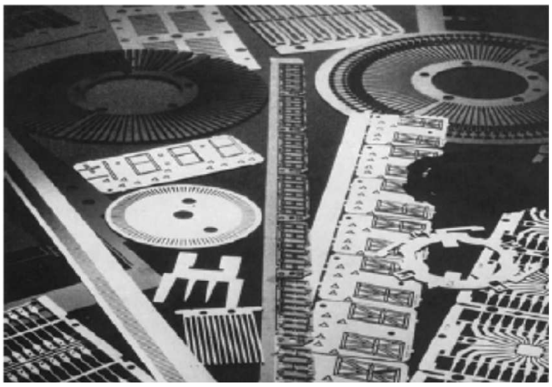

Figure 3: Parts Made by Chemical Blanking [3]

Laser-Chemical Machining (LCM)

In laser-chemical machining (LCM) the advantages of both laser machining and ECM are combined using an etching liquid which is injected coaxially to the laser beam, enhancing the machining quality. However, the dynamics of the laser light absorption, heat, chemical reactions, hydrodynamics and transport phenomena cause within a certain range of parameters a disturbance of material removal. External and internal sources could be responsible for the disturbances which can be explained due to interface instabilities.

Since LCM is a temperature driven process, increased laser power results in increased material removal rates. This effect is used to machine work pieces with a higher processing speed. However, high reaction rates lead to increased formation of hydrogen which could result in gas bubbles. Furthermore, high laser power results in high surface temperature which could cause etchant boiling and again result in gas bubbles too. Thus disturbance of material removal can occur.

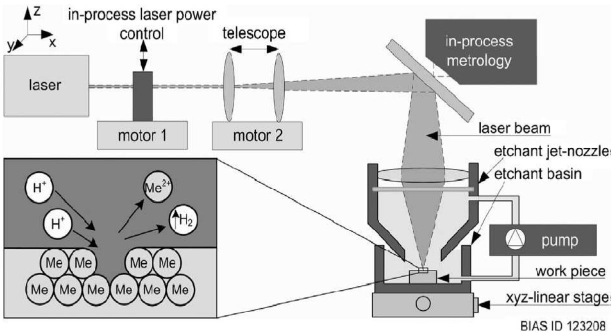

Figure 4: Laser-Chemical Machining Principle and Mechanisms [4]

Table 2: Experimental Setup Specification [4]

Experimental setup specifications.

Setup	Version 1	Version 2
Telescope design	2 Lenses	5 Lenses
Laser spot diameter	59 µm§	24 µm§§
Optical path	App. 3040 mm	App. 1171 mm
Etchant jet velocity	1.8 m/s and 2.3 m/s	3.5 m/s

Selective material removal using LCM is based on the laserinduced thermochemical reactions between an etchant and metal atoms on the surface of the work piece and is possible for all metals with material specific passivation layer. The passivation layer is locally reduced under formation of hydrogen and water soluble metallic salts caused by thermal influence of the laser. The chemical material removal within the reactive fluid is driven by the temperature-dependent proton activity of the redox reaction, and is mainly responsible for the formation of the electrochemical potential.

Another fundamental influence on material removal beside the thermal activation of chemical reactions is the mass transport limitation. These transport limitation of the etching processes leads to a reduced removal rate. The etchant jet-stream provides a fast exchange of the reactants, which results in increased removal rates. Thus a continuous wetting of the surface with fresh etchant is the basic requirement for the chemical removal reaction. On the other hand it should be kept in mind that the etchant is also cooling the surface, which might reduce the etching speed or inhibit the chemical reaction.

New Etchant for Chemical Machining of St304

Chemical machining is prone to pitting problems and obtaining better surface finish in chemical machining of St304 is very difficult. Therefore a new etchant is needed for the chemical machining of St304. New etchant is a mixture of H_2O+ HCl + HNO_3+ HF + H_2COOH + TEA (triethanolamine).Scan electron microscope (SEM) and roughness tests were employed to observe the surface topography.

RESULTS AND DISCUSSIONS

Material Removal Rate

Material removal rate is chiefly dependent on the selected etchant. However etchants that remove metal faster tend to have many side effects including reduction in surface finish, increased undercutting, higher heating, greater chance of etch rate with temperature and attack on the bond between the maskant and the work piece. The etch rate is generally limited to 0.02-0.04 mm/min when surface finish and accuracy are not important, the etch rate as high as 0.1-0.2 mm/min have been achieved. Although these penetration rates seem to be low, overall metal removal rates are quite high. In an aircraft industry, the metal removal rate on an aluminium is reported to be about 140cm^3/min. Table 2 gives the material removal rate for various materials.

Table 3: Material Removal Rate [5]

Material	Etch Rate mm/min	Tolerance mm
Aluminium	0.025	+/- 0.025
Magnesium alloys	0.033	+/- 0.025
Stainless steel	0.13	+/-0.025
Titanium alloys	0.13	+/-0.09

Accuracy

The undercutting behavior in simple contouring is essentially the same as in chemical blanking. Undercut per edge is approximately equal to the depth of cut. Each factor in chemical contouring is defined as the undercut divided by the depth of cut which is the reverse of that defined in chemical blanking. Allowance for undercut is made in the design itself. With optimum time, temperature and solution control, accuracies of the range of +/- 0.01 mm can be achieved on relatively shallow depths of cut. Tolerance on depth of cut for various materials are shown in table 3.

Table 4: Tolerance on Depth of Cut in Chemical Machining [5]

Material	Depth of Cut (0-1.3)	Depth of Cut (1.3-2.5)	Depth of Cut (2.5-6.4)	Depth of Cut (6.4-13)
Al alloys	+/-0.025	+/-0.040	+/-0.050	+/-0.075
Fe alloys	+/-0.050	+/-0.075	+/-0.100	+/-0.150
Ti alloys	+/-0.075	+/-0.100	+/-0.150	+/-0.250
General	+/-0.050	+/-0.075	+/-0.100	+/-0.150

Maximum taper, when produced by slow immersion or withdrawal rates, is usually 0.08mm for 100mm depth in steel and 0.08mm in aluminum alloys. Sharp radii cannot be produced in the cutting direction.

Surface Finish

Initial surface waviness and defects are not greatly altered in contouring most metals, but may be smoothened out to a certain extend. The quality of finish is lower for extrusions, forgings and castings. The surface finish obtained may be around 5 µm. Aluminium alloys show better surface of the order of 1.6 µm.Hydrogen embrittlement may occur owing to the absorption of hydrogen in chemical machining in some metals. Aluminium alloys are not subjected to hydrogen embrittlement. Considerable care should be taken to avoid hydrogen embrittlement in steel, stainless steel, copper alloys and nickel alloys. If hydrogen embrittlement occurs, it can be overcome by heating the work piece 120^0c for 1 to 4 hours. The surface produced by CHM process are otherwise stress free and show no thermal effects.

Environmental Issues

Environmental issues in chemical machining operations maybe the most important factor affects the machining process should be used or not. Most of the chemicals such as cleaning solutions, etchants, strippers etc. are very hazardous liquids. Therefore handling and disposal of them are very costly. Industrial trend of using these chemicals are to select more environmentally accepted ones for chemical machining process. Moreover, regeneration of waste etchant and etched metal recovery from waste etchants have been studied and there could be a suitable regeneration or recovery systems for some etchants like $FeCl_3$, $CuCl_2$ and alkaline etchants.

Laser-Chemical Machining

The resulting process boundaries for machining of Stellite 21were determined experimentally.

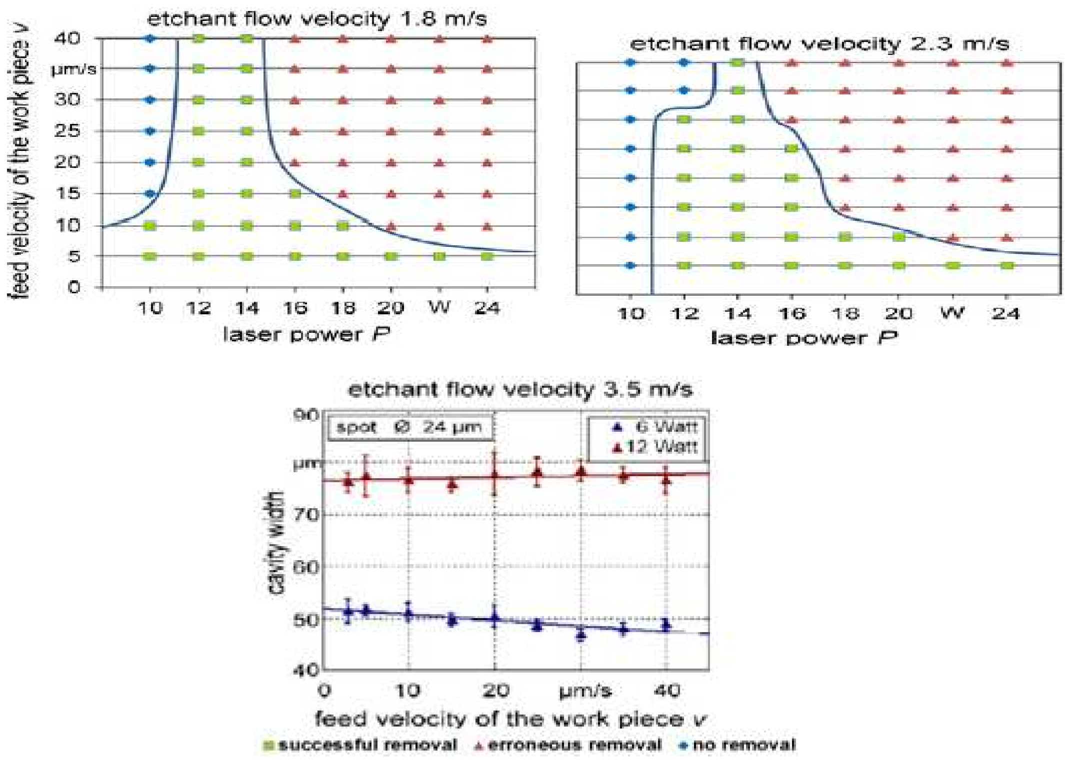

Figure 5: Process Windows for Stellite 21 for LCM Setup Version with an Etchant Flow Velocity of 1.8 m/s and 2.3 m/s [6]

It is shown that increasing flow velocities of the etchant determines higher laser powers in order to guarantee a successful removal of material. Increased flow velocity leads to increased cooling of the work piece surface. No material removal is detected when laser power is too low. Due to this cooling effect the boundary between no removal and successful removal is shifted. Higher laser powers and in part lower feed velocities are necessary to guarantee a successful removal. Furthermore the boundary between successful removal and erroneous removal isshifted too. It is shown that with an increased etchant flow velocity the range of erroneous removal paths decrease and it is possible to machine successful removal paths using higher feed velocities.

A New Etchant for the Chemical Machining of St304

It is found that by adding TEA (triethanolamine) to the etchant H_2O + HCl + HNO_3+ HF + H_2COOH, an improvement in surface finish is observed. The etched surface when the TEA solution is added becomes smoother but the corrosion rate is reduced. TEA solution behaves like an absorbent protector. It reduces the chemical reaction rate between specimen and etchant. TEA also decreases the difference between the rate of corrosion of grain and grain boundaries, therefore not only surface finish is improved but also the pitting defects and grain boundaries attack is reduced and a smother surface is obtained. It is concluded that for machining of St304 adding 5–10% of TEA to the etchant solution (H_2O + HCl + HNO_3+ HF + H_2COOH) can be recommended. In order to increase the rate of machining (to compensate the reduction of machining rate due to adding TEA) the temperature of the etchant was increased.

CONCLUSIONS

Material removal rate, accuracy, surface finish and environmental issues are the major challenges what chemical machining face. Rate of removal of material is dependent on the type etchant used for the machining process. Etchant which remove metal in a faster manner will have many side effects including surface finish, higher heating etc. So the etchant should be selected in such a way that it should balance among all these problems. Undercutting is the issue which reduces the accuracy of machining. Hydrogen embrittlement also causes alterations. If hydrogen embrittlement occurs, it can be overcome by heating the work piece 120^0c for 1 to 4 hours. The surface produced by CHM process are otherwise stress free and show no thermal effects.

Chemical machining greatly affects the environment since it make use of chemical etchants. Regeneration of waste etchant and etched metal recovery from waste etchants are the acceptable ways to control the environmental impacts.

To improve the material removal rate of chemical machining is to combine both laser machining and chemical machining. In laser-chemical machining (LCM) the advantages of both laser machining and ECM are combined using an etching liquid which is injected coaxially to the laser beam, enhancing the machining quality.

Adding small amount of of TEA to the etchant solution (H2O +HCl+HNO3+HF+H2COOH) improves surface roughness. Increasing the temperature of the etchant increases the oxidising power (machining rate) and decreases the surface finish values.

Adding 5–10% of TEA to the etchant solution decreases the difference between the rate of corrosion of metal grain and grain boundaries, which results in better surface finish.

ACKNOWLEDGEMENTS

The authors would like to thankfully acknowledge the support from Dr. K M Peethambaran, Head of the Department, Mechanical Engineering and Principal, Government College of Engineering, Kannur.

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