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A New Method for Etching Surfaces of Bearings and Other Machine Elements

The method relates to the production of shallow recesses in surfaces by etching. Recesses in metal surfaces are particularly suitable for use in sliding bearings for rotating components and in some other machine elements. Frequently, such recesses have a depth of 10 microns or more and are made in the form of intricate groove patterns on curved surfaces. According to the new method, etching fluid is caused to flow by means of a flow guiding template onto areas determined by this template along the surface to be etched. The etching rate on the areas to be etched is controlled by adjustment of the flow velocity of the etching fluid and the slit height of the flow guiding template. The recesses or grooves are deeper when the flow velocity of the etching fluid and the slit height are both higher. The paper gives a brief description of the new etching method and a comparison with other fabrication methods such as photochemical etching and electro-chemical machining. The new method appears to be preferable to others for large series production. The paper concludes with theoretical work in which the etching process is explained in terms of mass transfer by convective diffusion and with some experimental results using a simplified flow guiding template design.

Introduction

In many rotating machines, rolling element bearings are used. Ball bearings are perhaps most widely applied. In a number of rotating machines, however, rolling element bearings are considered to be less attractive and bearings with sliding surfaces or sliding bearings are used as an alternative. Some of the reasons why rolling element bearings are considered to be less attractive are: cost, life-time, speed limitation, load limitation, friction, incompatibility of oil with process fluid, compactness, running accuracy, etc. In the last ten years a large number of special types of sliding bearings has been developed and many have been thoroughly analyzed and tested.

A more promising type of sliding bearing is the grooved type. One of the surfaces of this sliding bearing is provided with shallow recesses in the form of a groove pattern. Fig. 1 shows a journal with grooves in the pattern of a herringbone. In the machine, this journal is running in a bearing and the grooves will pump the lubricant into the narrow slit between journal and bearing. When running journal and bearing will be completely separated by a film of lubricant and wear should be negligible.

Another grooved bearing is shown in Fig. 2.

It is a thrust bearing and one of the sliding surfaces is provided with a groove pattern. When rotating in the right direction, the grooves will pump the lubricant in between the surfaces and the bearing should be so designed that the sliding surfaces are separated by a lubricant film while in operation. Other grooved bearings are neither cylindrical nor radially flat but conical, spherical or a combination of several shapes. For the sake of brevity, these are not described in this paper.

As far as applications are concerned, grooved bearings can be found in vacuum cleaners, gyroscopes, fly wheels, liquid sodium pumps, small gas compressors and several other high speed flow machines. Grooved bearings are very often lubricated by greases and oils but several other fluids such as water, gas and liquid sodium have also been shown to be useful as a lubricant. There are several applications outside the bearing field where grooved surfaces have been found to be useful as part of a machine element, e.g. shaft seals and viscosity meters.

Candidate Methods for Producing Grooved Surfaces

There are several methods for producing grooved surfaces and the more important ones are listed below:

1. **Mechanical Machining.** For prototype cylindrical bearings of larger diameters and some other applications, grooves have been ground and milled. Milling on normal milling machines is impractical because the lead angle of the groove pattern is too high. Grinding on universal grinding machines gives very accurate groove depths and widths but the cost will be prohibitive for most applications.

2. **Photochemical Etching.** Photochemical etching is the most widely applied process for producing groove patterns on a large number of sizes and geometries. The surface is covered with a light-sensitive layer, locally exposed to light, and, subsequently, developed. At the end of the photochemical part of the production process, a layer of lacquer covers that part of the surfaces that should not be provided

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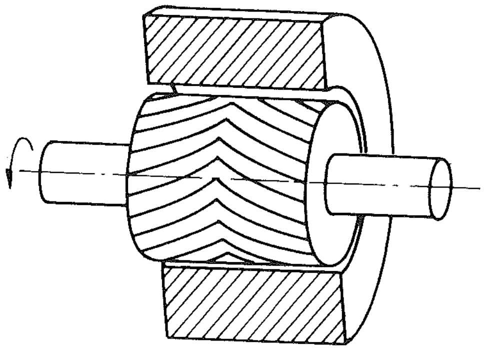

Fig. 1 Herringbone grooved journal bearing

with grooves. In the second part, the surface is immersed in the etching liquid or sprayed. This is the machining part of the process and the conditions are controlled in order to obtain grooves of a controlled depth. Finally, the surface is cleaned and the lacquer is removed.

It is typical of these first two methods that no use is made of a template during the actual machining of the groove pattern. All following methods make use of such a template and most of them are well known:

3. **Electro-Chemical Machining.**
4. **Electro-Discharge Machining.**
5. **Vacuum Deposition/Sputtering.**
6. **Grit Blasting.**
7. **Mechanical Deformation.**
8. **Sintering.**

All these methods are potentially useful, but for our purpose, intermittant batch type series production has as common disadvantages that the auxiliary production equipment is expensive and that the templates or masks might be prone to wear.

Therefore, the objective of our production development work is to find a method that

1. makes use of a reusable template in processing the groove pattern in order to make the number of production operations as small as possible
2. minimize the cost of the auxiliary production equipment
3. minimize the wear of the template

Etching by Means of a Flow Guiding Template

According to the new method, etching fluid is caused to flow by means of a flow guiding template onto areas determined by this template along the surface to be etched, see Fig. 3. The upper part of the figure shows a cross section along two grooves. It is shown where the etching fluid enters the template and, subsequently, flows locally along the surface. The gap between template and surface is kept as small as possible where the surface should not be etched and rather wide where the etching should take place.

The lower part of Fig. 3 shows the flow path of etching fluid. The flow path coincides with the groove shape. The final depth of the groove on the surface is controlled by many factors, the more important ones are the depth of the groove on the template and the flow velocity of the etching fluid. It can be expected that the groove depth on the surface will be most difficult in locations near entry and exit of the etching fluid.

An extensive description of etching by means of a flow guiding template can be found in the patent specification [1].

Convective Diffusion

An important contribution to the work described in this paper is the theoretical part by J. H. G. Verhagen. In an internal report he outlined that our method for making grooves is a chemical process governed by convective diffusion. A theoretical basis for this and other related processes can be found in a book by the Soviet author G. V. Levich, *Physiochemical Hydrodynamics,* published by Prentice Hall International, Inc., 1962 [2].

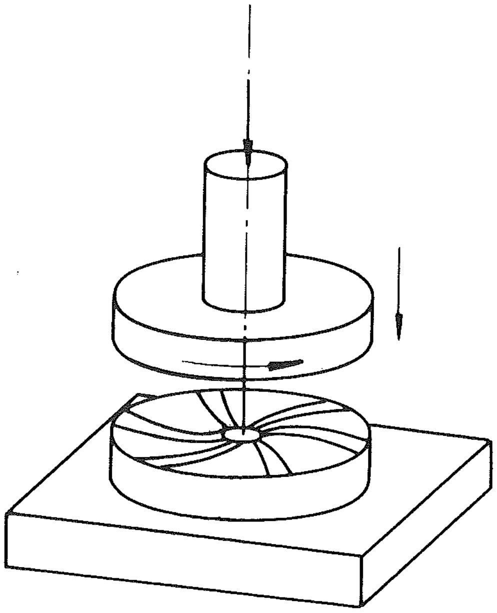

Fig. 2 Spiral groove thrust bearing

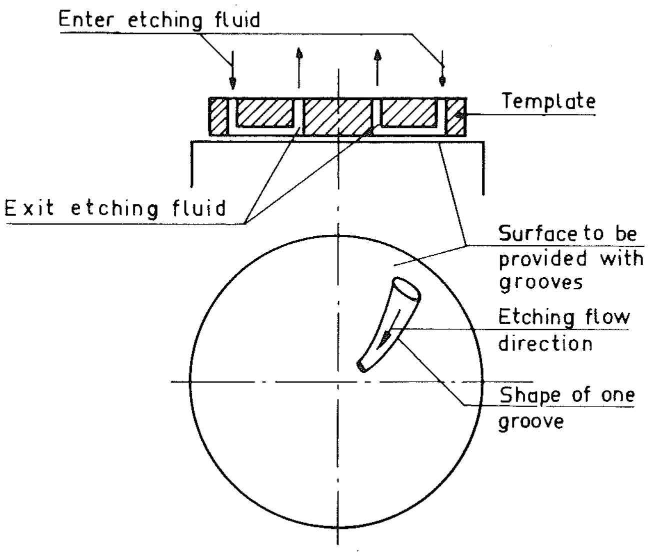

Fig. 3 Etching by means of a flow-guiding template

In a quantitative description, Verhagen makes the following simplifying but plausible assumptions:

1. the chemical reaction produces negligible heat and gas bubbles
2. the rate of chemical reaction is high with respect to the speed by which reaction products are carried away.

These first and second assumptions imply that the highest concentration of metal in the fluid occurs on the metal surface and that the transport of metal away from the surface is a matter of ion diffusion in the fluid and of flow of the metal solution.

Further simplifying assumptions are:

3. the fluid is incompressible
4. the diffusion coefficient is constant for the entire process
5. the diffusion rate and the flow velocity are independent of time
6. the flow and the diffusion are of the boundary layer type
7. the flow is laminar.

Within this set of simplifying assumptions several types of flow diffusion types can be studied such as

1. flow immediately below the channel where the etching fluid enters the template, characterized by stagnant flow

2. flow in the entry part of the gap between template and surface to be provided with grooves, characterized by a gradual change in shape of flow profile.

3. flow in the gap between template and surface characterized by a "steady" flow profile.

The theoretical treatment shows that the etching rate $(dh)/(dt)$ is highest for flow types (1) and (2) and that these higher rates can be attained locally by making the channels in the template as narrow as possible.

Flow type (3) will be present over the major part of the groove length. Differences in etching rate over this major part can be kept as small as possible by gradually narrowing the gap between template and surface in flow direction or by narrowing the width of the groove in the flow direction. For the configuration shown in Fig. 3, the etching fluid should flow from outside to inside in order to be able to make the eventual depth of the groove as uniform as possible.

The following equation gives an order of magnitude of the etching rate

$$\frac{dh}{dt} = \frac{c}{\rho}\left(\frac{D^2u}{hl}\right)^{1/3}$$

where

$\frac{dh}{dt}$	etching rate (increase of gap height per unit time)	(m/s)
c	maximum concentration of metal in etching fluid (solubility)	(kg/m^3)
ρ	density	(kg/m^3)
D	diffusion coefficient	(m^2/s)
u	etching fluid mean flow speed	(m/s)
h	gap between template and surface to be provided with grooves	(m)
l	groove length	(m)

The equation shows that the etching rate can be increased by a higher flow velocity, a smaller gap, a shorter groove length, etc. By inserting typical values for a steel and an etching fluid, it can be shown that the etching rate $(dh)/(dt)$ will be about 10^{-6} m/s or lower.

Higher rates are possible by using fluids with a solubility much higher than 10 kg/m^3 or by increasing the etching fluid flow speed to such an extent that the flow will become turbulent. For the time being, a theoretical treatment enabling us to develop an etching process with etching rates in the order of 10^{-6} m/s has been considered to be satisfactory.

Preliminary Experimental Results

Two types of preliminary tests have been carried out. In the first type of test, disc specimens of the bearing steel to be etched[1] are immersed in the etching fluid and are rotated at several rotational speeds and during a number of time periods. The composition of the bearing steel is 0.01 C, 0.003 Si, 0.003 Mn, 0.018 Cr and 0.0035 Mo. Ferric chloride solution in water has been considered to be a suitable etching fluid for this particular steel and has been used in several concentrations.

Results of experiments with a disc of 30 mm diameter running at 26.6 rps during 60 seconds are shown in Fig. 4.

The etching rate can be seen to depend strongly on the concentration of ferric chloride in the etching fluid. This behavior has been explained in chemical terms but will not be presented in this paper. Eventually, a mass concentration of 10 percent ferric chloride has been selected for further tests. Admittedly, the etching rate will not be maximum at this percentage but several other advantages were found in subsequent experiments such as no problems with gas bubbles (hydrogen) in the etching fluid and a minimum drop in etching rate with time. The last phenomenon is caused by the fact that not all constituents of the steel chemically react with the etching fluid, some of these (carbon and carbides) stay behind on the surface to be grooved and tend to slow down with the etching rate. Fortunately, all material staying behind on the surface can be brushed away quite easily after the chemical and cleaning treatment. The second type of test comes close to the actual production method of grooved surfaces, see Fig. 5. The etching fluid is pumped into the template via a central hole. The bearing surface to be provided with grooves is pressed against the template. The etching fluid enters the gaps or recesses in the template after having left the central hole. The bearing surface is etched locally and a groove pattern will be formed according to the pattern on the template.

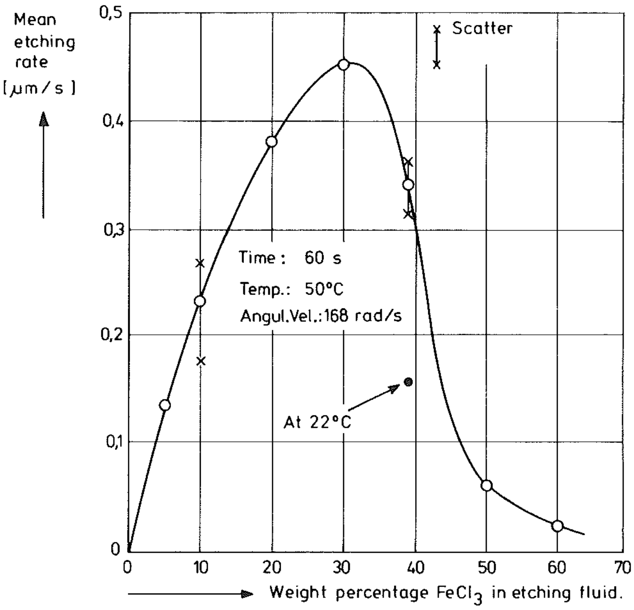

Fig. 4 Etching rate versus Fe Cl$_3$ aeq concentration

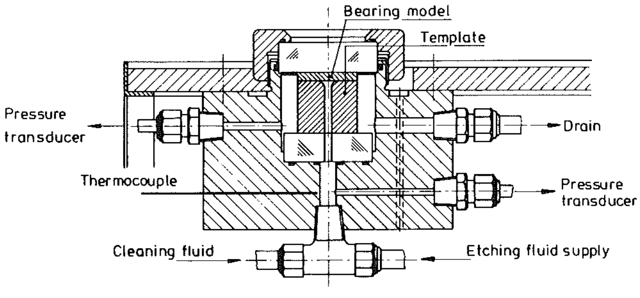

Fig. 5 Experimental etching apparatus

Fig. 5 also shows that the etching fluid can be switched off and that a cleaning fluid can be pumped into the gaps subsequently. At the same time, the set-up shown in Fig. 5 makes it possible to measure pressures, temperatures and flow rates. The main experimental results are shown in Figs. 6, 7, and 8. One of the groove patterns that has been produced is shown in the upper half of Fig. 8. It should be noted that most practical bearings should have spiral grooves and not radial ones as shown in the figure. Groove patterns like the one shown in Fig. 8 have been made in order to facilitate the development of the production method.

Fig. 6 shows experimental results in graphical form. The order of magnitude of etching rates and the eventual etching depths are in agreement with the theoretical work.

Deviations occur due to: the formation of a layer of nonsoluble carbon and carbides, local turbulence effects, inaccuracies of the shape of the template, etc.

Tests 1K–7K deal with specimens that have not been hardened and are difficult to interpret. They might indicate that a reliable etching method is not possible for the nonhardened material.

More consistent results have been obtained using hardened ma-

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[1] Bearing steel unhardened or hardened to 700–800 Vickers.

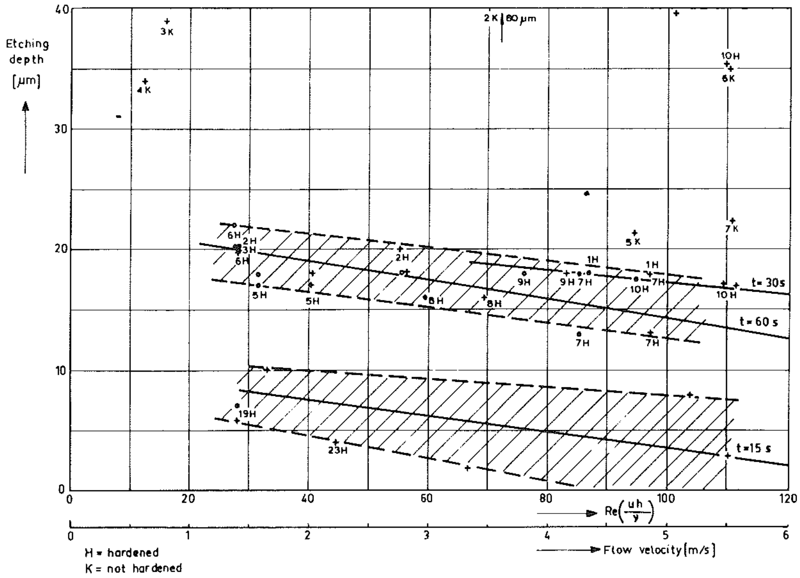


Fig. 6 Flow velocity versus etching depth

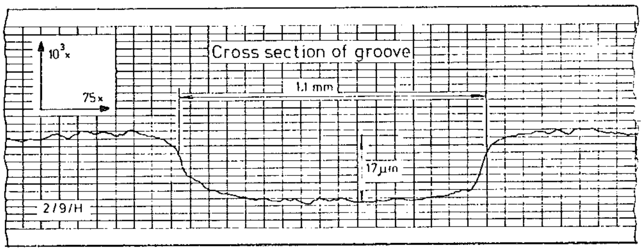


Fig. 7 Cross section of etched groove

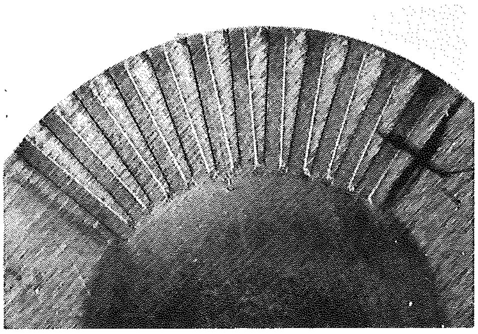
terial. The overall etching rate is lower than with nonhardened specimen and the roughness is smaller as well. The etching depth increases from 0–15–30 seconds and remains almost constant subsequently. This can be explained by the formation of the layer of carbon and carbides, see drawn lines for 30 and 60 s in Fig. 6.

Apart from etching times, other variables have been tested. Data points 1H–8H have as common characteristic that the etching time was 60 s. All these points have a gap depth of 0.1 mm, with the exception of 2H and 3H with 0.5 mm. The drawn line gives averaged values of the groove depths that have been produced. The dotted lines indicate the scatter found in the groove depths. The main portion of this scatter is due to differences in depth between entrance and exit of a groove. In order to make the groove depth more uniform, the channel in the template should not be constant and should narrow in flow direction. The remaining part of the scatter is due to differences in surface roughness, template material, gap width, etc.

A similar set of drawn and dotted lines is shown in Fig. 6 for an etching time of 15 s. An attempt to reduce the scatter has been made for an etching time of 30 s.

A scatter of 10–20 percent in groove depth is considered to be acceptable if such a scatter is unevenly distributed over the surface.

Figs. 7 and 8 show surface quality before and after the etching process. Fig. 7 shows a cross section of a groove and Fig. 8 a tracing along the length of the groove. The surface quality in the groove was judged to be acceptable.



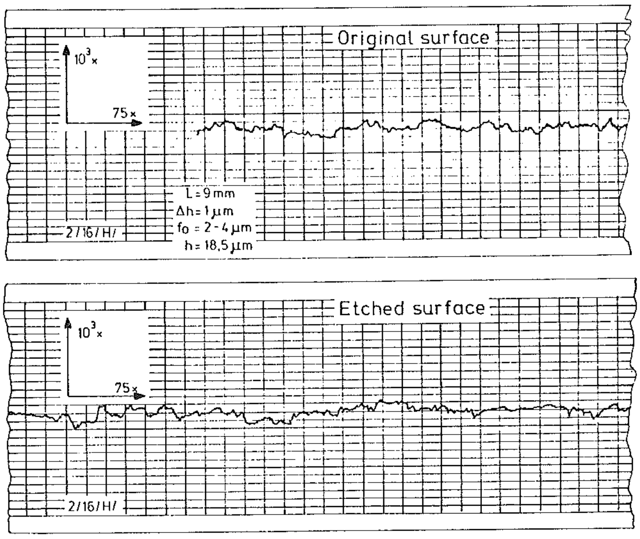


Fig. 8 Surface roughness originating from ground surface

Further Development Work

The main objectives of further development work are:

(1) to produce spiral grooves or straight grooves depending on the application

(2) to produce grooves on cylindrical, conical and spherical surfaces

(3) to extend the size range down to a few millimeters in diameter

Some results of this work will be published in the future.

Acknowledgments

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References

1 British patent Nr. 14230005 Groove Pattern", RCN 121.
2 Levich, G. V, *Physiochemical Hydrodynamics,* Prentice Hall International, Inc., 1962.
3 Appendix: J. H. G. Verhagen, "An Etching Process Based on the Convective Diffusion Mechanism".

APPENDIX

"An etching process based on the convective diffusion mechanism," J. H. G. Verhagen.

Extract

1. **Problem.** An etching fluid flowing two-dimensionally by means of a flow guiding template design consisting of a nonetching surface and the surface to be etched. The problem is to design the slit height (h) in the flow direction (x) such that $h(x)$ is independent on x at any time (t). Then $h(x, t)$ can be expressed as $h(x).f(t)$.

The dimensions of the slit are in the order of magnitude $h = 0{,}1$ mm and $l = 20$ mm. The etching depth is 1–10 μm. Two assumptions have been made:

—The chemical reaction does not produce heat or gas bubbles.

—The etching rate is large compared with the speed by which the reaction products are being removed.

The last assumption means that at the metal surface to be etched the concentration of reaction products is the equilibrium concentration. In that case the process will be controlled by diffusion.

2. **Description of the Diffusing Process.** In an incompressible fluid, without external forces and with a constant diffusion coefficient (D) the diffusion process can be described by:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} = D\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} \tag{1}$$

The axes x and y are as indicated in Fig. 9.

Assuming the process is stationary and the diffusion boundary layer is small compared with the slit length, equation (1) reduces to:

$$u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} = D\frac{\partial^2 c}{\partial y^2} \tag{2}$$

The mass transport from the etching surface is

$$j = -D\left(\frac{\partial c}{\partial y}y\right) = 0 \tag{3}$$

If the slit height is to be independent on x then

$$j = \text{constant and} \left(\frac{\partial c}{\partial y}\right)_{y=0} = \text{constant}$$

This is certainly true if $c = c(y)$.

In equation (2) this means $v = v(y)$.

This can be realized with only one defined shape $h = h(x)$.

Practical reasons make it desirable to know also the etching process for a constant split width. The different types of flow in the proposition of Fig. 9:

A. flow immediately below the channel where the etching fluid enters the template, characterized by stagnant flow.

B. flow in the entry part of the gap between template and surface to be provided with grooves.

C. fully developed Poiseuille-flow in the part following the entry part.

The mass transport in the different sections follows from equation (2).

A. $j = -D\left(\frac{\partial c}{\partial y}\right)y = 0$ is constant,

as v is not dependent on x. (4)

B. $$j = 0{,}34\frac{Dc_0\sqrt{u}}{\sqrt{\nu x}}\left(\frac{\nu}{D}\right)^{1/3} \tag{5}$$

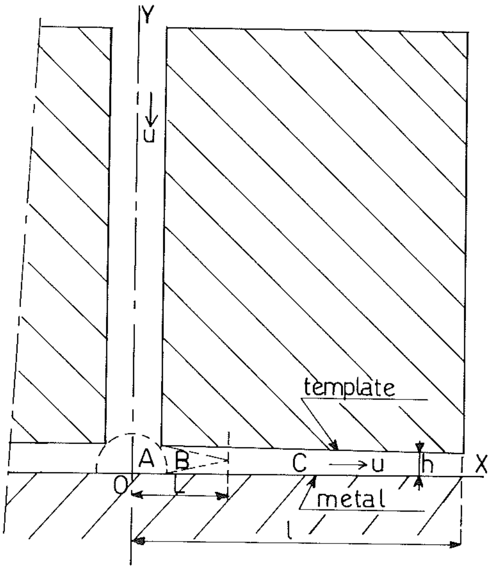

Fig. 9 Zones of flow

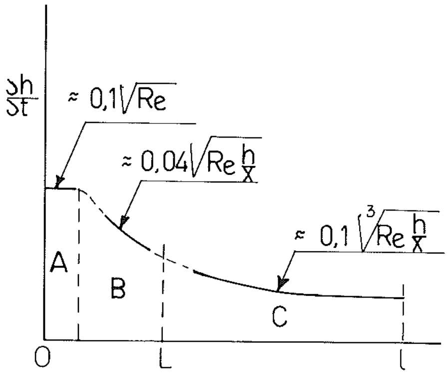

Fig. 10 Etching rate along flow path

with $L \approx 0, 16$ Reh

C. $$j = -D\left(\frac{\partial c}{\partial y}\right)_{y=0} = \text{coeff. D.c}_0\left(\frac{\overline{U}}{Dhx}\right)^{1/3} \tag{6}$$

where the coefficient is exactly equal to 1.

Now the etching rate $\frac{\partial h(x)}{\partial t} = \frac{j}{\rho_{\text{metal}}}$. Thus $\frac{\partial h(x)}{\partial t}$ is known:

with $D = 10^{-9}$ m^2/s
$\nu = 10^{-6}$ m^2/s
$c_0 = 10$ kg/m^3
ρ metal $= 8000$ kg/m^3
$h \approx 10^{-4}$ m

it can be concluded: Fig. 10

section B: $\frac{\partial h}{\partial t} = 4.\,10^{-2}\sqrt{\frac{\text{Re}}{x}}$ μm/s

section C: $\frac{\partial h}{\partial t} = \text{coeff. } 10^{-1}\,\text{Re}\left(\frac{h}{x}\right)^{1/3}$ μm/s

section A: $\frac{\partial h}{\partial t} = 10^{-1}\sqrt{\text{Re}}$ μm/s.

4. **Determination of $h = f(x)$ if the Etching Rate is Independent on x.** Two types of flow are possible:

1. Flow velocity is too small for the inertia part to be of any significance:

$$\frac{\text{inertia terms}}{\text{viscous terms}} \approx \frac{u \cdot \dfrac{\partial u}{\partial x}}{\partial^2 u/\partial y^2} \approx \frac{uh^2}{\nu \cdot 1} \ll 1 \qquad (7)$$

Then the equation of flow:

$$\frac{1}{\rho}\frac{dp}{dx} = \nu \frac{\partial^2 u}{\partial y^2}; \frac{\partial p}{\partial y} = 0 \qquad (8)$$

and the continuation of flow:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad (9)$$

The solution is:

$$u = \frac{-h^2}{2u} \cdot \frac{dp}{dx} \cdot y/h(1 - y/h)$$

$$v = +u \frac{dh}{dx} \cdot y/h$$

This fits only by approximation with small values of y/h if:

$$\frac{1}{h^3} \cdot \frac{dh}{dx} = \text{constant}$$

This is true if the diffusion boundary layer δ_0 is small compared with h.

δ_0 follows from the diffusion equation

$$v \frac{\partial c}{\partial y} = \frac{D\partial^2 c}{\partial y^2} \text{ when } y = \delta_0$$

Then $j = \quad -D\left(\dfrac{\partial c}{\partial y}\right)_{y=0} \approx \dfrac{Dc_0}{h_0}\left(\dfrac{uh^2{}_0}{Dl}\right)^{1/3}$

and the etching rate:

$$\frac{\partial h}{\partial t} = \frac{D \cdot c_0}{\rho_{\text{metal}}} \approx 0,1 \left(\text{Re}\,\frac{h}{l}\right)^{1/3} \mu m/s. \qquad (10)$$

2. The case where the viscous boundary layers of opposite walls keep separated and laminar as well. The bulk flow here is of the potential flow type. In the case of an etching rate in the boundary layer that is independent on x it can be shown that in the bulk flow a pressure distribution will be present which is comparable with that in a potential theoretical stagnant flow

$$\frac{dh}{dt} \cong \frac{c_0 D}{\rho_{\text{metal}}}\left(\frac{\nu}{D}\right)^{1/3}\sqrt{\frac{u}{\nu L}} \qquad (11)$$

A numerical computation of the flow and diffusion process in this case is possible.