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The anodic dissolution of two heat-resisting alloys, Hastelloy X and Inconel X-750, and of a low carbon steel, SAE 1018, were studied in a channel cell of 0.5 mm gap width under laminar flow conditions in 5N NaCl, NaClO₃, and NaN₃ electrolytes. Overall cell voltage and anode and cathode potential measurements were obtained under galvanostatic conditions; in the current density range of 1 to 35 A/cm². Micrographs and roughness analysis of the anode surfaces provided additional information. The two alloys demonstrated similar electrochemical behavior regardless of the nature of the electrolyte. However, the choice of anion strongly influenced the anodic dissolution of the low carbon steel. For the latter material, the occurrence of passivation phenomena and anodic oscillations of the potential are related to the formation of anodic films. Models are proposed to explain the dependence of these phenomena on the nature of the electrolyte.
I. INTRODUCTION

Electrochemical Machining (ECM) has found several industrial applications in recent years for the shaping of a variety of metals and alloys. Increasing efforts have been directed toward studying the effects of the various controlling variables involved in this process. ECM studies are most conveniently performed in channel type cells in which electrolyte flows at high velocities (10-10,000 cm/sec) between parallel, closely spaced (0.1-0.5 mm) anode (workpiece) and cathode (tool). The metal is oxidized anodically from the workpiece at current densities in the order of 10 to 150 A/cm². The electrode reaction products, which include gases, dissolved and solid matter, are continuously removed by the electrolyte stream.

Most of the recent studies were aimed at clarifying the role of current density, nature of electrolyte and flow rate. Efforts have been centered on work with pure metals, involving primarily copper and iron. Evidence related to passivation phenomena, reaction stoichiometry, steady, as well as oscillatory, anodic potentials observed during dissolution of copper have been reported in the literature. The nature of the anion in the electrolyte stream has been shown to strongly influence the anodic dissolution process of copper.

It is of great practical interest to consider the anodic dissolution of certain engineering materials, and to compare their behavior to what has been observed with copper. For this purpose, a study of the anodic behavior of two heat-resisting alloys and a low carbon steel has been undertaken. 5N solutions of sodium chloride, sodium chlorate and sodium nitrate were chosen as electrolytes. The first one is the most widely used electrolyte
in ECM, the second one is well known for its good dimensional control and surface finish, while the last one is commonly used for iron-base and nickel-base alloys.
II. EXPERIMENTAL

Forced convection conditions were obtained with an experimental flow system described earlier. The electrolyte was pumped continuously through the flow channel cell by means of a positive displacement pump. The flow rate was regulated with a needle valve in connection with a bypass and then measured with a rotameter. Stainless steel pipes were used throughout the system.

The electrochemical cell employed was one which has been used for the study of the anodic dissolution of copper. The rectangular flow channel had a $0.5 \times 8$ mm cross section and a 75 mm length, providing defined hydrodynamic conditions at the electrodes. It was made of epoxy resin with an electrode separation of 0.5 mm. Two glass windows allowed optical observation of the electrode gap space (Fig. 1). All the experiments were carried out in laminar flow at a linear flow rate of 50 cm/s. The corresponding Reynolds number was 350 for a 5N NaCl solution.

Both the anode and cathode had a $3.05 \times 0.53$ mm rectangular shape (area = $1.62$ mm$^2$). A copper cathode was used throughout this study. The anode was made of the studied engineering material cast into epoxy. A stainless steel spacer with a well defined height was used to position the electrode outside the cell. This allowed the electrode surface to be flush with the channel wall. The short dimension of the electrode was oriented parallel to the flow direction to diminish the influence of cathodic gas bubbles on the anodic processes. Two capillaries, drilled into the cell wall, provided for anode and cathode potential measurements.
The constant current power supply* had a maximum output of 3A. The current densities employed ranged from 1 to 35 A/cm².

The duration of dissolution runs was so chosen that the anode surface recessed by less than 20 microns; a distance small with respect to the gap dimension. Anode and cathode potentials were measured against saturated calomel electrodes. The steady-state value of the potential was reached after 1 or 2 seconds. The current was recorded by measuring the voltage drop across a precision shunt. Overall cell voltage, electrode potentials and current were recorded simultaneously on a multi channel light beam oscillograph.**

The materials investigated were Hastelloy X, Inconel X-750 and SAE 1018 steel. The latter is a low carbon steel, the two others were heat-resisting Ni-base alloys commonly used for jet engine turbine blades. Their main components are given in Table I. The anodes were fabricated from cold rolled plates followed by a heat treatment procedure, as reported in Table II. An age-hardening process for high temperature service (above 1100°F) was employed for Inconel X-750.9 The full annealing procedure used for small carbon steel forgings was chosen for SAE 1018.10 No attempt was made to perform a heat treatment for Hastelloy X.

Ten electrodes were prepared from each material investigated. Thus, a freshly prepared anode was used for each experimental run, involving one value of the current density for a given electrolyte. The electrode preparation consisted of mechanical polishing with 0000 emery paper followed by a metallographic polishing process using a 1μ diamond powder.

*Type C618, Electronic Measurements Co. Inc., Eatontown, New Jersey.
**Series 230, Brush Instrument Division, Cleveland, Ohio.
Table I. Main components of the engineering materials investigated (weight %).

<table>
<thead>
<tr>
<th>Material</th>
<th>Ni</th>
<th>Cr</th>
<th>Fe</th>
<th>Mo</th>
<th>Ti</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hasteolly X</td>
<td>43-52</td>
<td>20-33</td>
<td>17-20</td>
<td>8-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inconel X-750</td>
<td>73</td>
<td>16</td>
<td>7</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAE 1018</td>
<td>98-99</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.15-0.20</td>
</tr>
</tbody>
</table>

Table II. Heat treatment used for fabricated anodes.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temp., °F</th>
<th>Time (h)</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hastelloy X</td>
<td>none</td>
<td></td>
<td>none</td>
</tr>
<tr>
<td>Inconel X-750</td>
<td>2100</td>
<td>2</td>
<td>air cooled</td>
</tr>
<tr>
<td></td>
<td>1550</td>
<td>24</td>
<td>air cooled</td>
</tr>
<tr>
<td></td>
<td>1300</td>
<td>20</td>
<td>air cooled</td>
</tr>
<tr>
<td>SAE 1018</td>
<td>1600</td>
<td>0.5</td>
<td>furnace cooled to 1300°F at 50°F/hour</td>
</tr>
</tbody>
</table>
Because of the hardness of the heat-resisting alloys, in order to obtain a good surface finish, the mechanical polishing was continued for 1 to 2 hours. Following the polishing procedures, the electrode was treated in an ultrasonic cleaner in order to remove any solid particles remaining on the surface after polishing. The electrode was then carefully cleaned with detergent and rinsed with distilled water.

After dissolution in a given electrolyte, micrographs of the anode surface were made, generally when dissolution had occurred at a low and at a high current density value. The magnification used was x250 for all the photographs. Subsequent Analysis of the profile and the roughness of the anode surface were performed using a skidless surfanalyzer system.* 5N NaCl, NaClO₃ and NaNO₃ solutions were prepared with technical grade salts and distilled water. All solutions were filtered before using them in the flow channel cell.

*System 150 with drive model 21-1410-01, Clevite Corporation, El Monte, California.
III. RESULTS

5N NaCl Electrolyte

Typical overall cell voltage, anode potential and cathode potential versus time traces for Hastelloy X are shown on Fig. 2. At the beginning of the electrolysis, the cell voltage undergoes irregular low amplitude transients ("fluctuations") of the potential. These fluctuations were more pronounced and lasted longer at higher values of the current density ($i \geq 10 \text{ A/cm}^2$). The fluctuations were always associated with the cathode potential; the anode potential trace remained flat at all currents. The same typical behavior was observed for Inconel X-750.

Two different dissolution modes appeared in studying SAE 1018. At low current densities, an initial plateau in the cell voltage and anode potential trace was followed by a drop to the steady-state value of the potential (Fig. 3). At higher current densities, an initial anodic peak with fluctuations occurred at the beginning of the dissolution. A steady-state value was subsequently reached with periodic transients ("oscillations") of the potential (Fig. 4). These oscillations were due to the anode potential and their amplitude was approximately 1.3 V. The current density trace (not shown on the figures) remained constant and flat for all the experiments.

In addition to the three materials investigated, copper electrodes were used for parallel experiments. As in the case of SAE 1018, the electrochemical behavior of copper demonstrated two dissolution modes. At low values of the current density, the anode dissolved at a constant low voltage. As the current was increased, a high voltage dissolution mode was reached soon after the current was switched on. This behavior
has been a subject of detailed investigations in this laboratory. It is of interest to compare the steady-state values of overall cell voltage, anode and cathode potentials against current density, obtained for each material. Figure 5 illustrates the linear voltage vs current density dependence for Hastelloy X which is also typical of the behavior of Inconel X-750. The dashed lines correspond to experiments carried out at a lower flow rate \((u = 25 \text{ cm/s})\). For the low carbon steel, both cell voltage and anode potential show a step increase in the potential while the cathode potential increases linearly with current density (Fig. 6). A similar behavior was observed for copper, with a more pronounced jump of potential which occurred at a lower value of the current density.

5N NaClO₃ Electrolyte

The anodic behavior of the two heat-resisting alloys in chlorate appeared similar to that in chloride medium. No sharp rise of potential was observed over the whole range of current densities investigated. Cathodic fluctuations were still obtained for the highest values of the current density.

The low carbon steel behaved differently that in chloride. For \(i > 10 \text{ A/cm}^2\), both cell voltage and anode potential showed regular and well defined oscillations as illustrated in Fig. 7. The amplitude of the anodic oscillations was of the same order of magnitude as the anode potential itself. Fluctuations of the cathode potential were of much smaller amplitude with respect to the average potential. At higher values of the current density, the frequency and the amplitude of the oscillations increased (Fig. 8). An initial peak was formed just before
the beginning of the oscillations. Furthermore, after a certain amount of charge was passed, regular oscillations were followed by irregular ones with a lower amplitude.

Regular anodic oscillations were also observed for copper.* The amplitude was larger while the frequency was of the same order of magnitude as with the low carbon steel. At the highest values of the current density investigated, the periodic phenomena did not last for the whole duration of the electrolysis. After one or two oscillations, the potential jumped to a value representing a high voltage dissolution mode. No more oscillations were observed after the jump of potential. In Fig. 9 the frequency and amplitude of the oscillations are plotted against current density for both copper and SAE 1018.

5N NaNO₃ Electrolyte

This electrolyte did not cause significant changes relative to the previously described electrochemical behavior of Hastelloy X and Inconel X-750; the same type of potential-time traces and potential-current density graphs were obtained. Cathodic fluctuations still appeared at high values of the current density.

Small and regular anodic oscillations occurred during the dissolution of SAE 1018 at low current densities (Fig. 10). As the current density was increased, the oscillations became less regular and eventually disappeared just after the beginning of the electrolysis as shown on Fig. 11, an example of the cell voltage undergoing anodic oscillations followed by cathodic fluctuations.

*This typical behavior of copper in chlorate solution is being investigated at present.¹¹
Copper dissolved in a low or in a high voltage dissolution mode depending on the current density. Irregular anodic oscillations which decreased in amplitude as the current density was increased occurred in the high voltage mode. The latter phenomenon was comparable to that observed for SAE 1018.

**Micrographs and Surface Profile Measurements**

Hastelloy X anodes showed the same kind of surface texture for all the electrolytes investigated. Figure 12 is an example of surface texture after dissolution at a high current density value. No drastic change was observed over the range of current density investigated. Surface profile measurements showed the presence of sharp and rounded protrusions over a flat background surface.

Inconel X-750 anode surfaces presented a typical grain boundaries texture independent of the nature of the electrolyte. Figure 13 illustrates grain boundaries and randomly distributed holes. A film layer partially covering the surface could be seen in some micrographs. As for Hastelloy X, the current density did not change the apparent texture of the anode surface.

Unlike for the two alloys, the appearance of low carbon steel surfaces following dissolution depended on current density—and on the nature of the electrolyte. At low current densities, the same surface texture was obtained regardless of the electrolyte used (Fig. 14). The spots have been shown to be holes occurring on a fairly flat surface. At high current densities, the surface texture drastically changed with the nature of the electrolyte as shown on Figs. 15, 16 and 17. In NaCl medium, the surface appears bright with some protrusions and streaks.
occurring in the flow direction. In NaClO$_3$ medium, a bright surface was covered almost entirely with a grey film layer. In NaNO$_3$ medium, a complex texture was obtained with film layers partially covering the surface. Examples of surface analysis traces showing holes and protrusions are given in Fig. 19. Surface profiles of representative specimens before anodic dissolution are given in Fig. 18 for comparison.
IV. DISCUSSION

In order to better illustrate the differences and common features of the four materials in, all steady-state values of overall cell voltages are plotted in Figs. 20-22 against current density for each electrolyte used.

For convenience in discussing the whole experimental results, the two heat-resisting alloys will be considered separately from the low carbon steel. The electrochemical behavior of these alloys appears indeed quite similar, while the carbon steel behaves in a complex way and can be better compared to copper.

Heat-Resisting Alloys

Passivation phenomena, oscillations of potential and anodic film layers have been shown to play an important role in ECM. Surprisingly enough, the present investigation revealed neither a jump of potential nor oscillations for the two alloys. The straight lines obtained in the voltage vs current density plots suggest that the same dissolution mode occurred over the range of current densities investigated. The nature of the electrolyte seems to have no significant influence. The complexity of the alloy composition may lead to an overall behavior which obscures the manifestation of characteristics of a particular component. However, the formation of an anodic film cannot be excluded, nor can it be asserted that a passivation phenomenon may not occur at current densities below 1 A/cm². Some micrographs showed a film layer partially covering the Inconel X-750 anodes surfaces. Therefore, it is not possible to conclude whether the single dissolution mode observed corresponds to an active (low voltage) or to a transpassive (high voltage) dissolution mode.
Fluctuations of the cell voltage were always due to the cathode potential and are related to the hydrogen evolution. Figure 5 shows that both cell voltage and cathode potential are higher when the flow rate is lower, while the slopes of the straight lines do not change. An increase of the electrolyte resistance close to the cathode surface may be explained by the fact that bubbles tend to grow larger when the flow rate is decreased as suggested by Landolt, et al. who have investigated the nature of cathodic hydrogen revolution under ECM conditions.

The occurrence of protrusions in Hastelloy X surfaces can be related to the presence of a well defined intermetallic compound, randomly distributed in the absence of appropriate heat treatment. The age-hardening pretreatment used for Inconel X-750 leads to recrystallization of the alloy. Metallic precipitates at grain boundaries and selective intergranular attacks have been reported by Kahles. As the composition of the two alloys is fairly comparable, it can be assumed that a heat treatment does influence the surface texture, but has no apparent effect on the electrochemical behavior of the alloy.

Low Carbon Steel and Copper

The anodic dissolution of copper and iron in various electrolytes under broad current density and flow conditions has received relatively close attention in the past. It is usually accepted now that passivation is related to the formation of anodic films. The influence of the anion of the electrolyte on the formation and removal of these films is, at present, the subject of intensive investigations. Chlorate solution has been found to be especially suitable with respect to dimensional accuracy and surface finish. More information can, therefore, be
drawn from the literature about the dissolution of metals in chlorate than in chloride or nitrate. For the sake of convenience, the results obtained in the present work in 5N NaClO₃ solution will be discussed first.

Chlorate Solution

By reflection electron diffraction studies, Hoare and his co-workers¹ have shown evidence of films of γ-Fe₂O₃ on soft iron electromachined in NaClO₃ solution. Furthermore, they detected high percentage of oxygen on the anode surface following dissolution in chlorate. In studying the passivation of iron in borate-boric acid solution, Nagayama and Cohen¹² suggested that the inner layer of the oxide film is composed of Fe₃O₄. It is assumed that a protective and porous film of γ-Fe₂O₃ or Fe₃O₄ or a mixture of the two,² is formed on the surface and is responsible for the passivation of iron in chlorate medium.

Taking into account the anodic oscillations shown in Fig. 7, the following model is proposed. At the lowest current densities, the system is active and iron is dissolved as Fe²⁺ ions which can undergo further oxidation.¹ As the current is increased, the surface becomes passivated by the formation of a film of γ-Fe₂O₃ and consequently the potential increases abruptly. The oxide film can be formed by oxidation of either Fe or Fe²⁺¹³ according to

\[ 2 \text{Fe} + 3 \text{H}_2\text{O} \rightarrow \text{Fe}_2\text{O}_3 + 6 \text{H}^+ + 6 \text{e} \quad (1) \]

\[ 2 \text{Fe}^{2+} + 3 \text{H}_2\text{O} \rightarrow \text{Fe}_2\text{O}_3 + 6 \text{H}^+ + 2 \text{e} \quad (2) \]
Chin reported that the rate of $\gamma$-Fe$_2$O$_3$ film growth increases with the increase in the rate of iron dissolution. This leads first to assume that reaction (2) would occur rather than reaction (1). Furthermore, this information allows one to explain why the frequency of the oscillations increases (as shown in Fig. 9) when the current density, and therefore the rate of iron dissolution, increases.

The iron dissolution is inhibited by the film formation process due to the spreading of the oxide, which reduces the area of active sites where the dissolution occurs. Since the film is supposed to be porous, the dissolution of iron to Fe$^{++}$ ions is still possible, though inhibited. An important part of the current is consumed by oxygen evolution, instead of by iron dissolution, according to

$$2 \text{H}_2\text{O} \rightarrow 0_2 + 4 \text{H}^+ + 4 \text{e}^-$$

The film removal could be caused by oxygen bubbles which are generated between the metal and the porous oxide. A mechanical effect would, therefore, cause the removal of the layer.

At higher currents, a first initial peak is observed before the beginning of the oscillations (Fig. 8). It is likely that a film of Fe$_3$O$_4$ is formed by oxidation of either Fe or Fe$^{++}$, which is further oxidized to $\gamma$-Fe$_2$O$_3$. It is not understood why this initial step occurs before the periodic film formation and removal. As the current is increased, the frequency of the oscillations increases, as previously explained. After a certain amount of charge is passed, regular oscillations are followed by irregular ones with a low amplitude. Increasing amounts of Cl$^-$ and decreasing ClO$_3^-$ ion concentration were measured for
extented periods of electrolysis. The following reaction needs to be considered

$$6 \text{Fe}^{2+} + \text{NaClO}_3 + 3 \text{H}_2\text{O} \rightarrow 6 \text{Fe}^{3+} + \text{NaCl} + 6 \text{OH}^-$$

According to Hoar, the chloride ion can penetrate and dissolve films of iron oxides so that the surface is not passivated by a protective oxide film. According to this model, the formation $\gamma$-$\text{Fe}_2\text{O}_3$ is inhibited by the Cl$^-$ ion and the film is removed before spreading over the surface. Thus, dissolution of iron as Fe$^{++}$ ions should play a critical role in the dissolution process. This is in good agreement with the fact that the average of the irregular oscillations corresponds to the initial value of the potential.

One might think that the influence of the chloride ion could be more important than the oxygen bubbles in the periodic removal of the $\gamma$-$\text{Fe}_2\text{O}_3$ film. The model described takes into account that for ECM in chlorates, oxygen liberation at significant rates has been reported. On the other hand, except for extended periods of electrolysis, only small concentrations of chloride ions have been detected. Clearly, further investigations are needed to support or demolish either of these assumptions.

**Chloride Solution**

Hoare and his co-workers, detected neither a film of $\gamma$-$\text{Fe}_2\text{O}_3$ nor the presence of oxygen on iron specimens electro-machined in NaCl solution. No passivation phenomena were assumed to occur in chloride medium. In a later paper, Hoare reported the formation of a porous, nonprotective film on iron in chloride solution, which is removed at
high anodic potentials. More recently, Chin\textsuperscript{3} showed evidence of passivation of a steel anode in NaCl electrolyte. The passivation was attributed to the formation of an adsorbed layer of anodic products. Ferrous compounds, such as Fe(OH)\textsubscript{2}, were assumed to precipitate on the anode surface forming a porous, nonprotective film. In studying the dissolution of copper in NaCl solution, Kinoshita\textsuperscript{6} suggested that a layer of CuCl was formed due to the stability of the monovalent ionic state.

Although the presence of anodic films in chloride medium has been reported in the literature,\textsuperscript{3} no evidence seems to have been obtained about their composition. It is suggested that, in the case of iron as well as in that of copper, usually unstable ionic states become thermodynamically more favorable than the stable ionic states. At the end of the electrolysis, the film could decompose or dissolve as soon as the current is switched off. As reported by Chin,\textsuperscript{3} since the film is very porous, it can be washed away easily with a jet of water. Any attempt to further identify the anodic film products would therefore be difficult.

The overall cell voltage-current density graph shown in Fig. 20 indicates the occurrence of a passivation phenomenon on low carbon steel. The following sequence may be suggested: metal dissolves first as Fe\textsuperscript{++} ions leading to further precipitation of ferrous compounds on the anode surface. By analogy with copper, it is suggested that a thin and porous layer of FeCl\textsubscript{2} is formed which allows the iron dissolution to continue through the pores. At high current densities, small oscillations take place as shown in Fig. 4. The possibility of formation and removal of
ferrous hydroxyde layers cannot be discounted, either. More detailed investigations are needed on this question. It is nevertheless possible to start from a porous and nonprotective film model of ferrous compounds, even if the presence of such a film cannot be proven on the basis of the present investigation. The occurrence of a bright surface with randomly distributed protrusions (Fig. 15) suggests that iron was dissolved in a transpassive dissolution mode.

**Nitrate Solution**

Little information is available about the nature of anodic films in the dissolution of metals in nitrate medium. In studying the dissolution of copper in 2N KNO₃ solution, Kinoshita, et al. detected the presence of Cu₂O as the main constituent of solid anodic products. The onset of passivation was shown to coincide with the limiting transport of dissolved reaction products by convective diffusion. Landolt, et al. reported that passivation of copper anodes occurred with the formation of a thick layer which seemed to disappear just after the current was switched off.

Figure 22 shows a typical graph for the dissolution of copper. The overall cell voltage-current density graph for the low carbon steel is represented by a straight line. This suggests a unique dissolution mode, iron dissolving mainly as Fe⁺⁺ ions. As for the two heat-resisting alloys, it cannot be concluded that dissolution occurs in an active mode. Both figures 10 and 11 show anodic oscillations of low amplitude. It is assumed that small amounts of γ-Fe₂O₃ are formed and removed according to the model previously described. Film layers partially covering the
surface can be seen in Fig. 17. Figure 16 shows the presence of larger granules of solid anodic reaction products in chlorate solution, than in nitrate. Possibly in nitrate medium, the oxide film doesn't spread all over the surface but is restricted to some active sites before being removed. This leads to the assumption that oxygen evolution is more important in nitrate than in chlorate solution. Oxygen analysis and current efficiency measurements would be of interest to bring about a more detailed understanding of the basic phenomena observed throughout this work.
V. SUMMARY AND CONCLUSIONS

The present work was aimed at investigating the gross electrochemical behavior of engineering materials in various electrolytes commonly used in the technical ECM process. Additional information was drawn from micrographs and surface profiles of the materials.

Overall cell voltage and anode potential versus current density graphs show that the two heat resisting alloys dissolve in the same dissolution mode over the range of current densities investigated. Neither an abrupt jump of potential nor anodic oscillations were observed in chlorate, chloride and nitrate solutions. Although the nature of the electrolyte is well known to play an important role in ECM, the anion types employed had no apparent influence on the electrochemical behavior of these alloys. Heat treatment does influence the surface texture and leads to a grain boundary texture with intergranular attack. Evidence was obtained on fluctuations of the potential at high current densities caused by cathodic gas evolution.

On the other hand, the behavior of the low carbon steel shows a strong dependence on the electrolyte anion. Passivation phenomena and anodic oscillations were observed, for the steel as well as for copper, and are related to the formation of anodic film layers. In NaClO₃ solutions, a model is proposed to obtain a better understanding of the relationship between regular oscillations and anodic film formation and removal. In this medium, the film is assumed to be an oxide composed mainly of γ-Fe₂O₃. Two different dissolution modes were observed in chloride solutions. Here, passivation is attributed to the formation
of a layer of adsorbed anodic products. Ferrous compounds are assumed to precipitate on the iron surface as a thin and porous layer. In nitrate solutions, potential-current density graphs indicate a single dissolution mode. This suggests that the main anodic reaction is iron dissolution as ferrous ions. Anodic oscillations with a low amplitude were observed in nitrate as well as in chloride electrolytes; their amplitude was comparable to the average potential in chlorate solutions. It is probably that these phenomena play a significant role in the practical electro-machining process of iron and copper and the excellent ECM properties of the chlorate solution for these materials may be related to anodic oscillation phenomena.
REFERENCES

11. J. Cooper, to be published.
FIGURE CAPTIONS

Fig. 1 Photograph of the electrochemical flow cell.

Fig. 2 Oscillograph traces for Hastelloy X dissolution in 5N NaCl at 20 A/cm².

Fig. 3 Oscillograph traces for SAE 1018 dissolution in 5N NaCl at 2 A/cm².

Fig. 4 Oscillograph traces for SAE 1018 dissolution in 5N NaCl at 15 A/cm².

Fig. 5 Measured potentials during Hastelloy X dissolution in 5N NaCl at two flow rates—u = 50 cm/s, -u = 25 cm/s.

Fig. 6 Measured potentials during SAE 1018 dissolution in 5N NaCl, u = 50 cm/s.

Fig. 7 Oscillograph traces for SAE 1018 dissolution in 5N NaClO₃ at 10 A/cm².

Fig. 8 Oscillograph traces for SAE 1018 dissolution in 5N NaClO₃ at 35 A/cm².

Fig. 9 Measured amplitudes and frequencies of cell voltage oscillations during anodic dissolution of copper and SAE 1018 in 5N NaClO₃, u = 50 cm/s.

Fig. 10 Oscillograph traces for SAE 1018 dissolution in 5N NaNO₃ at 10 A/cm².

Fig. 11 Oscillograph traces for SAE 1018 dissolution in 5N NaNO₃ at 25 A/cm².

Fig. 12 Micrograph of Hastelloy X surface after dissolution in 5N NaClO₃ at 30 A/cm².
Fig. 13 Micrograph of Inconel X-750 after dissolution in 5N NaClO₃ at 30 A/cm².

Fig. 14 Micrograph of SAE 1018 after dissolution in 5N NaClO₃ at 5 A/cm².

Fig. 15 Micrograph of SAE 1018 after dissolution in 5N NaCl at 20 A/cm².

Fig. 16 Micrograph of SAE 1018 after dissolution in 5N NaClO₃ at 15 A/cm².

Fig. 17 Micrograph of SAE 1018 after dissolution in 5N NaNO₃ at 30 A/cm².

Fig. 18 Surface profile measurements before anodic dissolution. a) SAE 1018  b) Hastelloy X.

Fig. 19 Surface profile measurements after anodic dissolution. a) SAE 1018 in 5N NaClO₃ at 5 A/cm²  b) Hastelloy X in 5N NaCl at 20 A/cm².

Fig. 20 Measured cell voltages for the anodic dissolution of copper, SAE 1018, Hastelloy X and Inconel X-750 in 5N NaCl. The IR drop was calculated on the basis of a molar conductance for 5N NaCl of 50 Ω⁻¹ cm² mole⁻¹ (from Chapman-Newman). Flow velocity 50 cm/sec.

Fig. 21 Measured cell voltages for the anodic dissolution of copper, SAE 1018, Hastelloy X, and Inconel X-750 in 5N NaClO₃. Flow velocity 50 cm/sec. Amplitude of the oscillations for SAE 1018. Amplitude of the oscillations for copper.

Fig. 22 Measured cell voltages for the anodic dissolution of copper, SAE 1018, Hastelloy X and Inconel X-750 in 5N NaNO₃. Flow velocity 50 cm/sec.
Fig. 6

Anode potential

Cathode potential

Cell voltage

Current density (A/cm²)
Fig. 7
Fig. 10

- Cell voltage
- Anode potential
- Cathode potential

Time (s)

Cell voltage
Anode potential
Cathode potential
Fig. 12
Fig. 14
Fig. 18

(a)

(b)
Fig. 19
Fig. 21
Fig. 22
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