A New Approach for the Manufacture Of Miniaturized Pattern-Coils

By T. Daenen, W. Messing, M.v.d. Hout, E.J. v. Loenen & B.v.d. Bossche

To provide small motors for ever-diminishing sizes of audio and video equipment, it is necessary to miniaturize the motor coils, yet maintain the needed torque. A new approach to this problem combines lithography, etching and electroplating. The method permits production of coils of great accuracy and reproducibility.

One of the trends in the information society in which we live is that everyone wants to have access everywhere to all kinds of information. Portable consumer products play an ever-increasing role. As a result, small-size audio, video and information storage systems are in great demand. Consequently, the necessary motors must also be miniaturized. Extremely small, high-quality motor bearing systems can be made only if the relative accuracy of the parts can be maintained during miniaturization. One of these parts is the stator with high-quality motor coils.

The electrical efficiency of a motor can be improved by using coils with a high copper filling factor *fv* (copper volume/total volume). The slope $S = K^2/R$ of the torque vs. speed curve has proved to be an important motor parameter. The factor R is determined by the resistance of the stator phases and K is determined, among other things, by the geometry of the coils. With miniaturized wound coils, the copper filling factor lies between 0.4 and 0.6. High values can be achieved only if an orthocyclic winding technique is used. Here the winding of the copper wire approaches the bounds of the geometrical possibilities.

The method used for the manufacture of coils with a high copper filling factor consists of a combination of lithography, etching and electroplating techniques. By order of, and in cooperation with, the Philips Research Laboratories, a new technology was developed for the production of a complete stator. A great advantage of this technology is that the interconnections between the coils and the connecting wires can also be made with lithographic, etching and electroplating techniques. In addition, this method permits coils of great accuracy and reproducibility to be produced and the coil shape can be adapted in a simple manner to the calculated optimum shape. Because of optimization of the technology, coil systems with higher copper filling factors than those of wound coils have been realized. For applications in a planar transformer, coils have been made consisting of five layers and, depending on the number of windings, with a copper filling factor between 0.58 and 0.76. The technology for making such stator coils is described below.

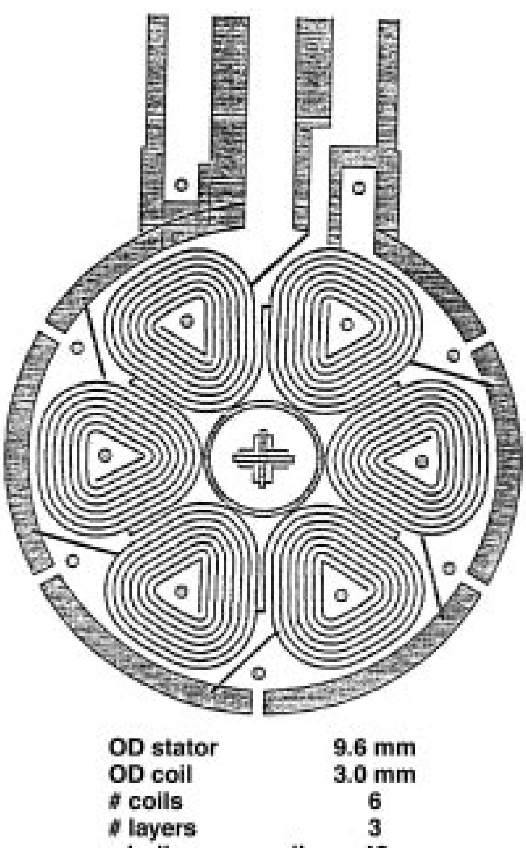

Fig. 1—1.3-in. Concept.

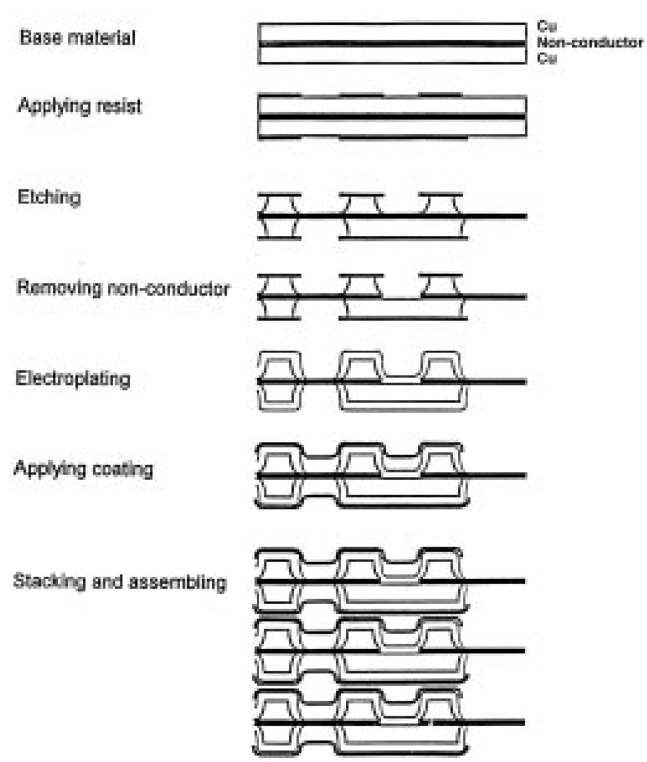

Fig. 2—Process steps for manufacture of etched/electroplated coils.

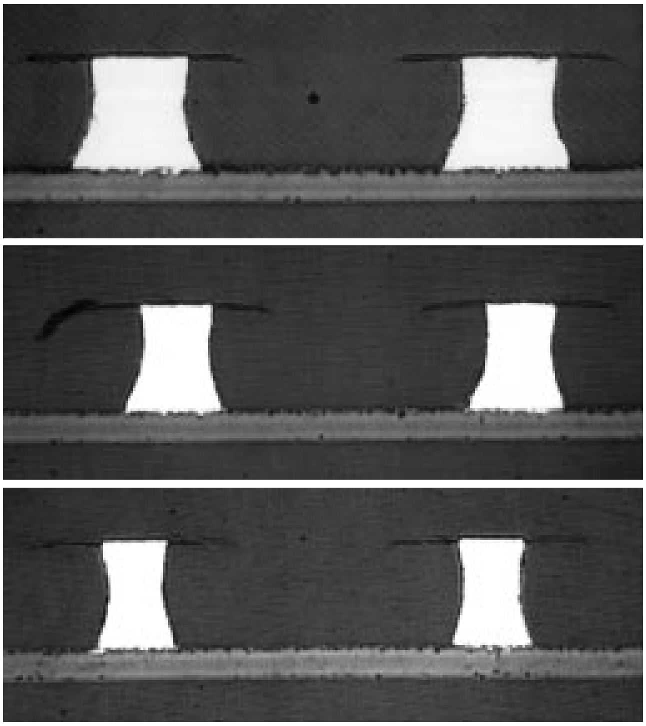

Fig. 3—Etched profiles.

Principles

Depending on the application, a new motor and coil are designed. Shown in Fig. 1 is the basic concept[1] developed for multilayer coil sets suitable for 1.3-in. hard disk drive motors.

The base material used for the coils consists of a non-conductor with a copper layer on either side. The overall thickness of the substrate depends on the application, but a typical composition is 35-12-35 µm or 18-12-18 µm (Cu-non-conductor-Cu).

In Fig. 2, all process steps are shown in chronological order. The substrate is cleaned in a gluconate degreasing bath for 5 min, followed by immersion in 1:1 hydrochloric acid.

The photoresist, which contains an organic bichromate, is applied by means of an immersion process. The thickness of the resist is determined by the pull-up speed and the viscosity of the resist. This process is repeated once to reduce noticeably the presence of pinholes. The ultimate resist layer thickness is approx. 3 µm. The pattern-coil is processed on the substrate by a two-sided contact exposure of the resist with Cr/glass photomasks. The photoresist is developed by immersion in methanol for 5 min.

To achieve a maximum copper filling factor, a test sequence was carried out to optimize the conditions during the etching process. The purpose of this is to obtain the steepest possible etching profile to prevent short-circuits at the bottom of the copper conductors after the electroplating process. Etchants tested were $FeCl_3$ and $CuCl_2$. The base material has a 35-12-35 µm composition.

Experimental Procedure

1. For both etchants, the etching time needed to obtain a gap of 90 µm was determined. This was referred to as the standard etching time (*SE*).
2. The coil pattern was etched at 0.9 *SE*, *SE* and 1.1 *SE*.
3. With $FeCl_3$, etching tests at the three different etching times were made at 30 and 40 °C, and with $CuCl_2$ at 50 °C.

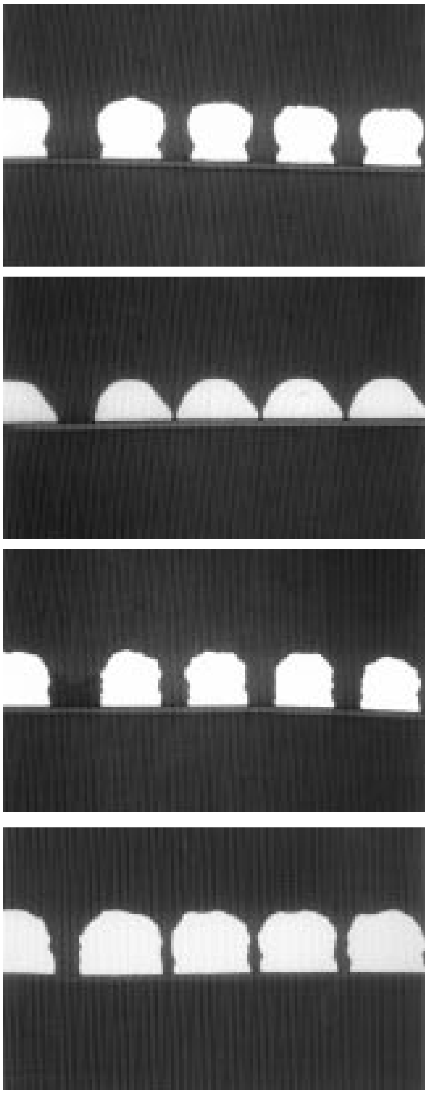

Fig. 4—Cross section photographs: (a) Cutronix; (b) UBAC; (c) Copper 200; (d) Cuprostar LP-1. 200X.

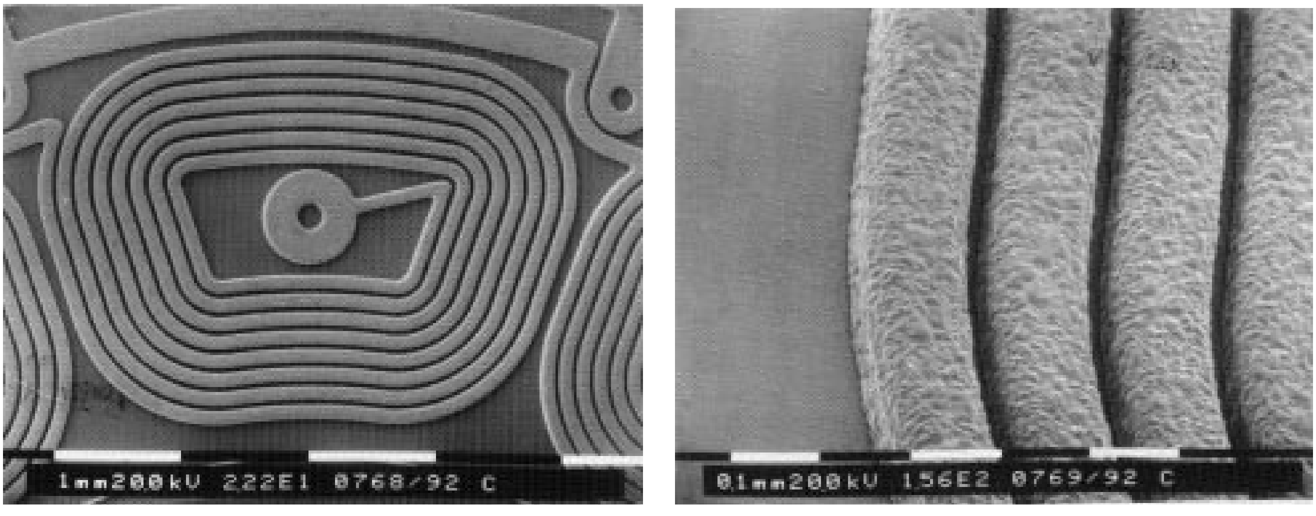

Fig. 5—Details of a mini-motor coil produced in Cuprostar LP-1 bath.

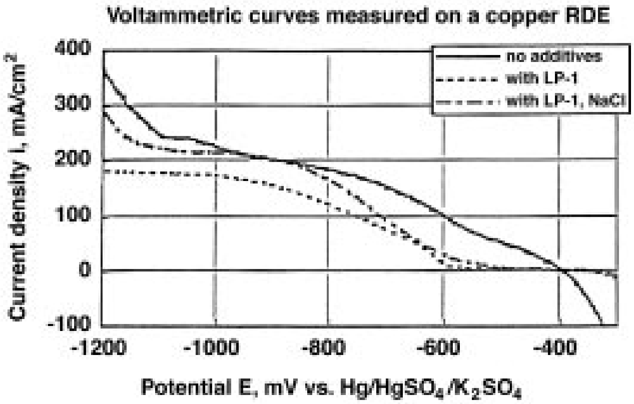

Fig. 6—Current vs. voltage curves of a copper bath with and without an additive, and with an additive + NaCl. Concentrations: 0.35 M $CuSO_4 \cdot 5H_2O$, 2.0 M H_2SO_4.

With the aid of cross sections (SEM), the effect of the various factors on the etching profile was examined. Figure 3 shows the profiles of conductors that were etched for different periods of time in $FeCl_3$ at a temperature of 40 °C. An optimum etching profile was achieved at an etching time of 1.1 *SE*. With this optimum etching time, two percent of the pattern-coils contained a short circuit after electroplating. This number increased up to 22 percent if 0.9 *SE* was used.

To establish an interconnection between the two copper layers (on either side of the substrate) during the copper plating process, the non-conductor must be locally removed beforehand. The method to create the interconnection must be fast and clean, and the material must be removed without any residues being left. Lasering and drilling are two techniques that have proved to be suitable for this purpose. Drilling has the advantage that several substrates can be processed at a time. A disadvantage of this method, however, is that a copper burr is almost impossible to prevent. The diameter of an interconnection is 300 µm.

Electroplating

The purpose of the electroplating process is to interconnect the two copper layers and to increase the copper filling factor. For plating of the etched copper tracks, four copper plating solutions were examined, namely:

Cutronix (matte)
UBAC (bright)
Circuitplate Copper 200 (matte)
Cuprostar LP-1 (semi-bright)

The pattern-coils, used in the experiments described below, were made with the optimum etching time of 1.1 *SE*. The interconnections between the two copper layers were made by means of lasering.

From the cross section photographs, Figs. 4a to 4d, it is apparent that four different types of profile are obtained after electroplating of the etched copper tracks. The etched copper tracks were reinforced at the optimum current densities specified by the suppliers of the plating processes.

It can be clearly seen that with a semi-bright copper plating solution (UBAC) the growth rate during electroplating is greater, widthwise, than longitudinally, which is a result of the good throwing power of this solution. The difference between the matte copper plating solutions is not very great. It was noted with Cutronix that after reinforcement, the tracks are more mushroom-shaped than with the Copper 200 process. The latter process permits a higher aspect ratio to be achieved. The aspect ratio can be defined as follows:

$$\text{aspect ratio} = \frac{\text{track height}}{\text{gap}}$$

The gap between two tracks after electroplating is of concern. The best aspect ratio was achieved with the Cuprostar LP1 process of Blasberg. With this process, an aspect ratio of 5.5 was realized.

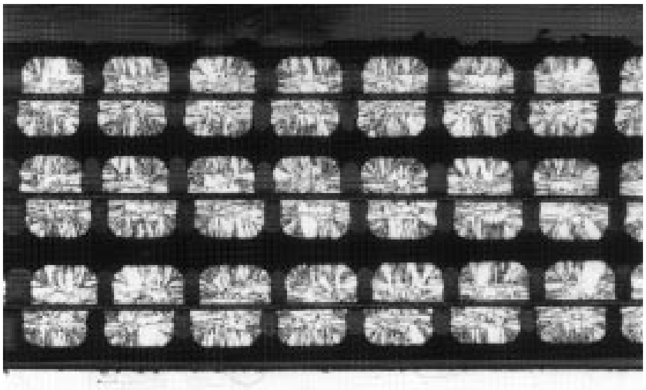

Fig. 7—Stacked coils with fv *= 0.75. 200X.*

Figure 5 shows part of a coil with a copper filling factor of 0.75, obtained with the Cuprostar process. It is specific for this process that it contains an organic additive that ensures that after electroplating, an aspect ratio higher than 2 can be realized. Such additives are in frequent use in the electroplating of printed circuit applications, and generally consist of polymerized glycols, such as polypropylene glycol (PPG), polyoxyethylene glycol and polyethylene glycol (PEG). The electrochemical effect of these polymerized glycols has been investigated by many researchers,[2-4] and several mechanisms for the effect of these additives have been proposed.[5-8] The current vs. voltage curve of a solution with and without an additive clearly shows the inhibiting effect of the additive on copper nucleation (Fig. 6).

In addition to the inhibition effect, the hydrodynamic flow pattern in the bath during electroplating plays a major role. In the gap, particularly, the flow pattern is of importance to the mass transport and thus to the ultimate growth of the copper in the gap. With the aforementioned Cuprostar bath, tracks 70 µm in height were realized, with a gap between 30 and 40 µm (aspect ratios from 1.75 to 2.33) Figure 7 shows a section photograph of stacked coils.

To gain more insight into the copper growth on a microscale and into the influence of the hydrodynamic flow pattern in the plating cell, numerical calculations were made.

Numerical Calculations

Software is being developed for the execution of calculations relating to plating processes in a European Brite Euram program. Our contribution to this program is the modeling of the copper plating process. The objective of the Brite Euram project is: 'Development and evaluation of methods for current density and layer thickness distribution prediction in electrochemical systems.'

A unique aspect of this newly developed software is that it takes into account convection and diffusion, as well as

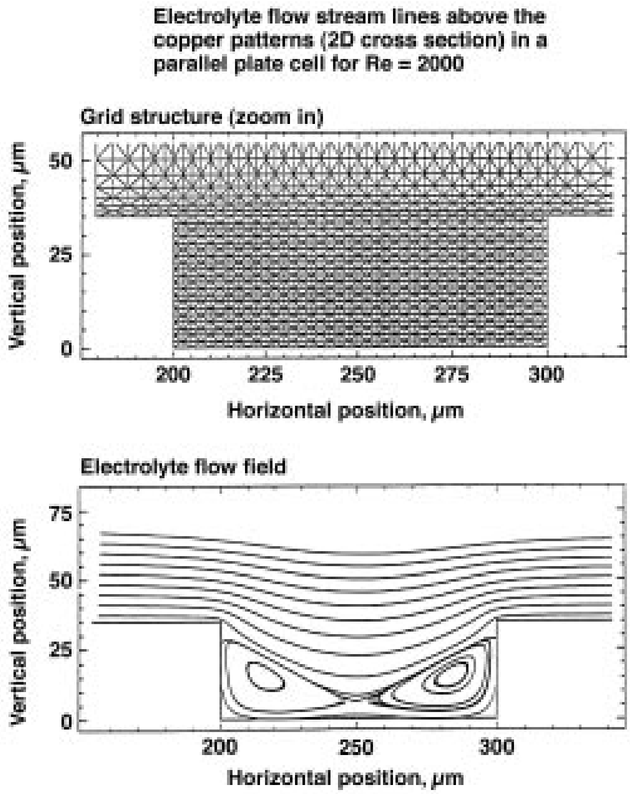

Fig. 8—Calculation of fluid field.

migration when the process is electrochemically modeled. Features of the software in existence and under development include:

- Extension of 1- and 2-D and axisymmetrical systems with *n* ions to 3-D systems with a maximum of four ions
- Ohmic resistance and temperature effects of the electrolyte and electrode
- Homogeneous reaction in the bulk
- Interaction between fluid flow, heat, mass and charge transport
- Changes in electrode shape under the influence of metal deposition

The code being developed in this project is based on the Multi-Dimensional Upwinding Method (MDUM), which originates from the fluid dynamics area, and is an alternative to FEM/BEM.

Model

In cooperation with one of the other Brite Euram partners, simulations of the electrodeposition of Cu on etched copper/steel patterns were carried out in the presence of the organic component, LP1. Within the scope of this project, a parallel plate cell was developed, in which the effect of the electrolyte flow (Reynolds) on the electroplating of the etched copper/steel patterns was investigated. Two limit situations were examined, namely:

1. Conductors perpendicular to the flow;
2. Conductors parallel to the flow.

In the model, the reduction of Cu originating from $CuSO_4$ (0.315 M) is described as follows:

- 2-step reduction of Cu^{+2} ions
- Adsorption of (bi)sulfate ions
- Adsorption of Cu-LP1 complex

The relationship between the voltage and the current density is described with a Butler-Volmer equation. The electrolyte further consists of H_2SO_4 and NaCl.

Simulation of Copper Plating

First, for the purpose of the simulation, a grid structure is defined for the calculation of the fluid field. In Fig. 8, this is shown for a gap of an etched copper pattern of 100 µm (track height 35µm and track width 80 µm), which corresponds with the start of the plating process. Shown beneath is the calculated fluid field for this gap at Re = 2000. The fluid field can be calculated beforehand, because the equations needed in the calculation are not coupled with the electrochemical (mass) balances.

Similarly, a grid is defined for the calculation of the potential field. It is then possible to calculate the potential, concentration and current density distributions from the

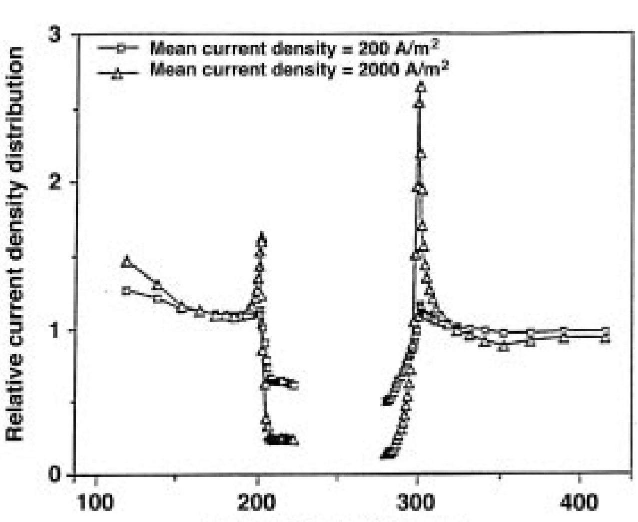

Fig. 9—Calculation of current distribution.

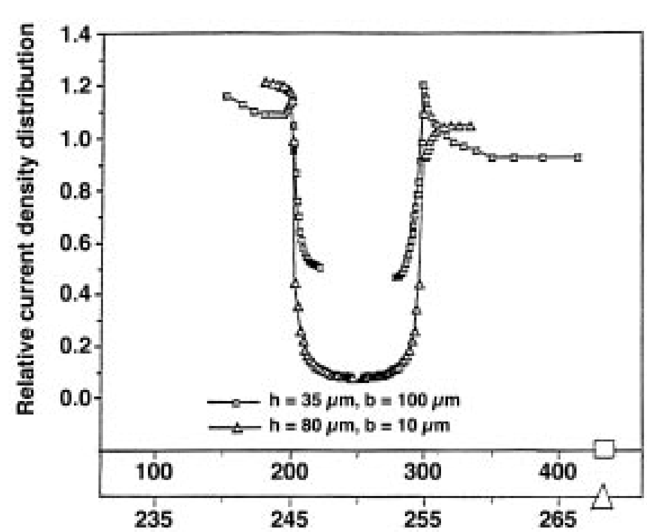

Fig. 10—Current density distribution.

previous calculations. Figure 9 shows the distribution *over the etched copper tracks* at the start of the electrodeposition for two different current densities. The effect between 100 and 200 μm is the consequence of the initial conditions under which the simulation is started.

As might be expected, it can be clearly seen that at the corners of the copper tracks, the growth rate will be higher because of the locally higher current density. This growth is clearly intensified if the current goes in the direction of i_{lim} (2000 A/m^2). Consequently, this model permits (*e.g.*, via a simulation), examination of the effect of the (track height/gap) relationship (aspect ratio).

Figure 10 shows two current density distributions that take place during the copper deposition process, namely:

1. Track height h = 35 μm and gap b = 100 μm. Current density distribution *over* the etched copper conductors at the start of copper deposition.
2. Track height h = 80 μm and gap b = 10 μm. Current density distribution *over* the reinforced copper tracks, at the end of the process (45 μm deposited).

Figure 10 shows that at the end of the process (h = 80, b = 10), the current density between the copper-reinforced tracks drops sharply to a level almost as low as zero. This means that for this situation, which corresponds to the final situation of the electroplating process, the current density distribution is such that there is practically no copper growth other than at the corners of the tracks. Consequently, in the event of further copper deposition, for this pattern there will soon be a short-circuit between the reinforced tracks.

Summary

With the technology described, test series of motor coils have been made in which reproducibility aspects were investigated in particular. It has been demonstrated that with the process developed, it is possible to make flat multilayer coils with a copper filling factor of 0.55 for the 1.3-in. concept.

Compared to wound coils, the technology offers advantages, especially with respect to assembly of the coils. The integration of other functions on the substrate into the coil system is an interesting option. With electrochemical measurements and the newly developed software, it has been demonstrated that a better insight can be gained into the process. In addition, this software can also be used as a tool for optimization of the process, permitting a considerable reduction in costs to be realized, thanks to a decrease in experimental work.

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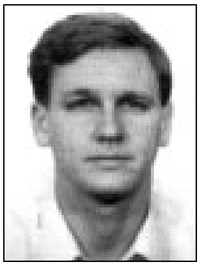

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