Enhanced Heat Transfer for Electronics Applications by Composite Electroless Coatings

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The electronics industry is highly concerned with thermal management. A broad array of devices, including fans, blowers, heat sinks, thermoelectric coolers, thermal gels, and special materials, have been developed for this task.[1] As smaller and more sophisticated electronic equipment is created for use in a growing variety of applications and environments, thermal management devices must evolve to meet new challenges and increased demands. Composite electroless coatings are layers of metals or alloys in which fine particulate matter is codeposited. This paper presents experimental work that demonstrates the enhanced thermal or heat transfer properties imparted to substrates with composite electroless coatings. A discussion of the heat transfer requirements of electronic applications is also given in relation to existing methods of thermal transfer, the limitations of these methods, and the utility of composite electroless coatings in satisfying these needs. The work reported herein focused on composite electroless nickel coatings with diamond and silicon carbide, although additional work has been accomplished with other materials as well. This novel research is presented as an introduction to a concept being expanded with the development of other deposit methods, matrices, and particulate matter for enhanced thermal transfer and insulation.

HEAT TRANSFER

Countless applications in a wide array of industries require enhanced thermal properties, which include conduction or insulation. The electronics industry is particularly concerned with such thermal management. When the use of a single material is not adequate or practical to achieve certain desired thermal properties, the use of coatings or composites is a widely accepted alternative. This article presents the enhanced thermal transfer properties of composite electroless coatings.

Certain ceramic materials, plastics, and textiles have been widely utilized for their thermal insulating abilities. Common examples of such applications range from Styrofoam cups to fiberglass insulation. A number of methods has been developed to apply heat insulating materials to various articles including the employment of composite electrolytic plating. Heat insulating particles, such as zirconia, yttria, ceria, silica, alumina, titania, and mullite, have been codeposited within an electrolytic plated metal matrix.[2]

Conversely, materials, such as copper, silver, aluminum, and diamond, are well known for their excellent thermal conductivity properties. Examples of their use in the electronics industry include aluminum fuses, copper and aluminum heat sinks, silicone elastomer gap fillers, and a variety of proprietary thermal conductive solid, liquid, and flexible materials. Heat transfer in electronic applications is a field that has generated much commercial interest and consequent research and development, especially concerning heat sinks used to draw heat away from critical components that would be negatively affected by the heat. The automotive and aerospace industries are two other notable fields concerned with enhancing heat transfer, especially in preserving their integrated electronic components.

Because the outstanding heat transfer properties of diamond are well recognized, a wide array of methods has been developed to produce an article comprised of, or coated with, diamond or "diamondlike" materials such as microwave chemical vapor deposition (CVD), thermal filament CVD, high frequency CVD, electron cyclotron resonance microwave CVD, direct current plasma CVD, ion plating physical vapor deposition (PVD), ion beam sputtering PVD, ion deposition PVD, ion beam deposition PVD, composite electrolytic plating, as well as others.[3]

The applicability of many of these diamond or "diamondlike" materials has been limited by numerous factors including poor adhesion, brittleness, nonuniformity, substrate incompatibilty, geometry constraints, thickness restrictions, and cost.

Despite these limitations the electronics industry has pursued many of these methods of using dia-

Figure 1. Examples of common heat sink geometries.

mond for improved heat transfer, especially for heat sinks. An example of one specific method for manufacturing diamond heat sinks by the insertion of diamond or polycrystalline cubic boron nitride into gaps in a base material, growing diamond on the surface of this unit, and then removing the base material is described by Yamamoto et al.[4] Other processes have also been developed for producing diamond-covered members for heat sinks and other applications.[5]

Because the use of certain theoretically ideal materials, such as diamond, is often not possible for any number of reasons, including physical limitations and economic factors, efforts have been made to produce composites of two or more materials that are more practical, economic, and effective to achieve the desired thermal characteristics. One such method uses a composite of diamond particles compacted into a porous body, which is then infiltrated with a brazeable material such as copper-silver.[6] Other work with this objective has involved hot pressing diamond-metal compacts.[7] Much of this work was undertaken towards the objectives of electronic applications.

Geometry also plays an important role in generating desired heat transfer properties. A variety of methods are employed to produce components in the electronics industry with increased surface areas or textures to promote heat transfer. Heat sinks, for example, come with countless configurations of fins, prongs, and other projections to increase the surface area of the heat sink/atmospheric interface. Figure 1 displays some common heat sink geometries.

Despite these efforts, use of certain materials with desirable heat transfer properties is still not possible or practical in many applications. This article presents a method to impart the heat transfer properties of various materials to articles via composite electroless plating. This method provides the heat transfer properties of the particulate matter via a process compatible with a very wide array of substrates of nearly any geometry, at a much lower cost than many other deposition processes. Composite electroless plating can even be used to coat an object of a specific geometry where the substrate is subsequently removed by mechanical, chemical, or other means to leave a composite structure with properties useful in heat transfer applications.

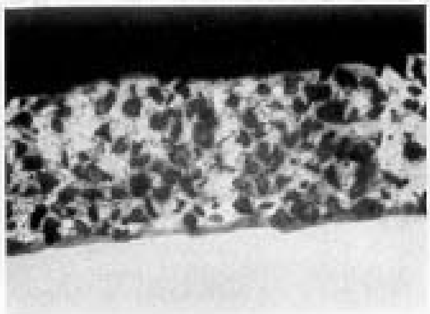

Figure 2. 1,000× cross section of composite diamond electroless nickel coating.

COMPOSITE ELECTROLESS PLATING

Composite plating is a technology well documented and widely practiced in both electrolytic and electroless plating. The development and acceptance of composite plating stems from the discovery that the inclusion of particles within a plated layer can enhance various properties of the plated layer, and, in many situations, actually provide entirely new properties to the plated layer. Cross-sectional Figure 2, taken at 1,000× magnification, is an example of a composite electroless coating; in this situation diamond particles are codeposited within a 25-micron-thick layer of electroless nickel. Particles of selected materials can provide characteristics that include thermal properties, wear resistance, lubricity, corrosion resistance, phosphorescence, friction, light absorption, altered appearance, as well as others.

To date, the most developed metal matrix of composite electroless coatings is electroless nickel (an alloy of 88–99% nickel with the balance of phosphorus, boron, or a few other possible elements). These coatings can be tailored to meet the specific requirements of an application by the proper selection of the nickel's alloying element(s) and their respective percentages in the plated layer. Electroless nickel is commonly produced in one of four alloy ranges: low (1–4% P), medium (6–8% P), or high (10–12% P) phosphorus, and electroless nickel-boron containing 0.5 to 3% B. Each variety of electroless nickel thus provides a unique combination of hardness, corrosion resistance, nonmagnetism, solderability, brightness, internal stress, and lubricity.[8]

The application of composite electroless coatings is subject to certain special challenges because it requires the introduction of insoluble particulate

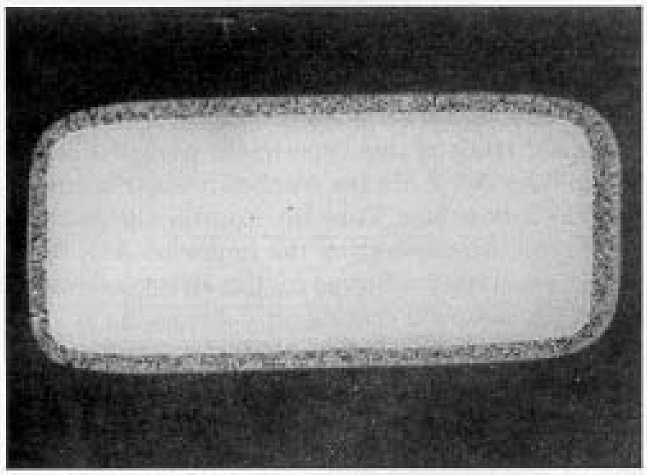

Figure 3. 100× cross section demonstrates uniformity of composite diamond electroless nickel coating.

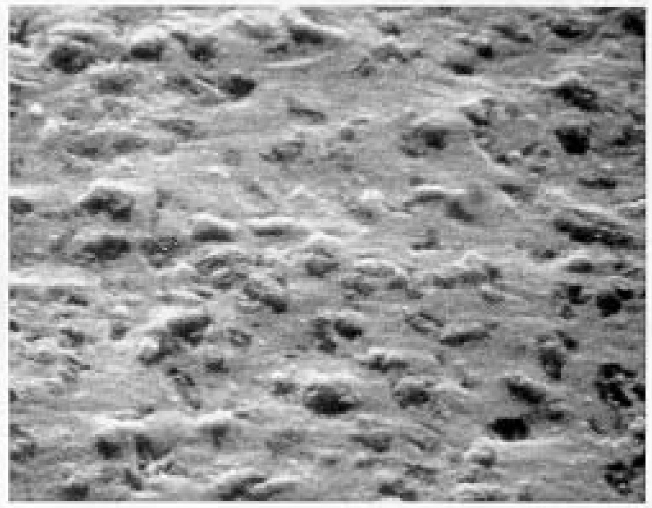

Figure 4. Surface topography of composite electroless nickel coating as plated.

matter into the plating bath for codeposition into the coating. The natural incompatibility between an inherently unstable, surface-area-dependent plating bath and an extraordinary loading of insoluble particles has been overcome by the precise addition of particulate matter stabilizers or PMSs, as explained in U.S. Patents 4,997,686,[9] 5,145,517,[10] 5,300,330,[11] and 5,836,616.[12] The methods disclosed therein have made composite electroless nickel plating reliable and commercially viable by modifying the Zeta potential (or charge) of the particles. The selection of specific PMSs depends on the type of particle being codeposited.

As with conventional electroless nickel, these composite coatings can be applied to numerous substrates, including metals, alloys, and nonconductors, with outstanding uniformity of coating thickness to complex geometries. Cross-sectional Figure 3 at 100× demonstrates this conformity. These coatings may be heat treated after plating to enhance their hardness and their adhesion to the substrate. Most composite electroless nickel coatings can operate at continuous temperatures of 400°C (750°F), depending on the nature of the codeposited particles. These coatings have a shear strength of 20,000 to 45,000 psi (138–310 MPa) on aluminum substrates, and 30,000 to 60,000 psi (207–414 MPa) on steel substrates.[13] These versatile properties of electroless nickel coatings provide numerous advantages compared to many other coating methods such as those listed earlier.

Particles with various heat transfer properties suitable for composite electroless nickel incorporation can be up to approximately 10 microns in size. Development to date has focused on particles with narrow size distributions in the range of 0.2 to 6 microns.

Depending on the particle sizes and certain plating conditions, composite electroless coatings can be produced with a particle density of up to 40% by volume, although densities of 15 to 25% are more common for commercial applications where wear resistance is a key factor. For heat transfer applications where wear is of lesser concern, the higher range of particle density is considered preferable.

EXPERIMENTS

Aluminum tubes (alloy 6061) with an outside diameter of 2.0 in., wall thickness of 0.065 in., and length of 8.0 in. were treated as indicated below, with one tube left untreated as a control. Three tubes were plated with identical thicknesses of different coatings. One tube was sand blasted to produce a roughened surface texture similar to that of the composite electroless coatings to determine if it is the surface roughness, the coating composition, or a combination of factors that is responsible for the enhanced heat transfer properties of these coatings. See Figure 4 for an example of the surface topography of a typical composite electroless coating.

- Tube 1 = control (no surface treatments)
- Tube 2 = 25-micron-thick layer of composite electroless nickel with 4 micron diamond plated on outside wall by the plating bath commercially known as NiPlater 800
- Tube 3 = 25-micron-thick layer of electroless nickel plated on outside wall by the plating bath commercially known as NiPlater 130
- Tube 4 = 25-micron-thick layer of composite

Table I. Results for Example 1

Time in Minutes	Temperature °C, Tube 1	Temperature °C, Tube 2
0	83.0	83.0
9	72.0	70.0
19	65.8	64.2
34	55.8	52.5
64	40.8	36.8
Loss Rate:	0.66	0.73

Table II. Results for Example 2

Time in Minutes	Temperate °C, Tube 1	Temperature °C, Tube 2
0	112.0	112.0
9	89.9	83.8
15	79.9	71.8
21	71.0	62.8
65	41.8	35.0
Loss Rate:	1.08	1.18

electroless nickel with 1,200-grit silicon carbide plated on outside wall by the plating bath commercially known as NiPlater 700

- Tube 5 = sandblasted with silicon carbide at 100 psi to produce a rough surface

Prior to testing, each tube was sealed with a cork on one end to form a liquid-tight seal. The tubes were clamped to a ring stand with insulated clamps and placed in a vertical position with the open end facing up. Thermometers were then suspended from other clamps so that their bulbs were in the centers of the tubes and 4.0 in. above the seals. Various hot liquids were subsequently poured simultaneously into the different tubes with suspended thermometers. The temperature of the hot liquid in each tube was recorded as a function of time. The rate of heat loss over time for the liquid in each tube provides a measurement of the respective tube's (and its surface treatment) heat transfer properties. This "loss rate" is calculated as the initial temperature minus the final temperature divided by the duration in minutes of the experiment. All experiments were conducted in a laboratory with an ambient temperature of 19.8°C.

Example 1

Three hundred ml of water heated to 83°C was poured simultaneously into Tubes No. 1 and 2. The results are shown in Table I.

Repeat trials of this experiment gave similar results; Tube No. 2 always reached a lower temperature than the control Tube No. 1 during the duration of the run, demonstrating the improved heat dissipation properties achieved by the electroless nickel composite diamond coating on Tube No. 2.

Example 2

In this experiment all conditions used in Example 1 were identical except that the tubes were filled with 300 ml of commercial (Prestone) antifreeze (ethylene glycol) at 112°C. The results are shown in Table II.

These results confirm the improved heat dissipation properties achieved by the electroless nickel composite diamond coating on Tube No. 2 compared to the control Tube No. 1 with a different liquid.

Example 3

Tubes No. 2, 3, and 5 were tested in the same experimental apparatus as in Example 1, with water at 85°C. The results are shown in Table III.

Again this experiment clearly shows that Tube No. 2 with the electroless nickel composite diamond coating was the most effective in dissipating heat. It further demonstrates that the presence of the diamond particles on Tube No. 2 is more effective in heat dissipation than Tube No. 3, which is coated identically to Tube No. 2 with the exception of the diamond particles.

Example 4

Experimental conditions were the same as described in Example 1 with water at 86°C in Tubes 2, 4, and 5. The results are shown in Table IV.

This example again demonstrates the effectiveness of the electroless nickel composite diamond coating for heat dissipation. It also shows the improved results of Tube No. 4 with an electroless nickel composite silicon carbide coating.

Table III. Results for Example 3

Time in Minutes	Temperature °C, Tube 2	Temperature °C, Tube 3	Temperature °C, Tube 5
0	85.0	85.0	85.0
5	78.5	79.5	80.2
15	65.0	68.0	67.0
25	56.2	60.2	59.0
Loss Rate:	1.15	0.99	1.04

Table IV. Results for Example 4

Time in Minutes	Temperature °C, Tube 2	Temperature °C, Tube 4	Temperature °C, Tube 5
0	86.0	86.0	86.0
5	67.0	69.5	70.0
27	51.8	54.0	55.0
42	43.8	46.5	47.2
Loss Rate:	1.00	0.94	0.92

Table V. Results for Example 5

Time in Minutes	Temperature °C, Tube 1	Temperature °C, Tube 2	Temperature °C, Tube 3	Temperature °C, Tube 5
0	89.0	89.0	89.0	89.0
8	83.0	80.0	81.5	82.0
31	68.3	61.8	66.0	65.0
45	61.4	54.0	58.9	57.0
63	56.0	48.1	53.0	51.2
75	51.0	43.0	48.0	46.0
Loss Rate:	0.51	0.61	0.55	0.57

Example 5

Five different tubes were tested simultaneously with the identical conditions of Example 1 and water at 89°C. The results are given in Table V.

The results of this expanded side-by-side example show the superiority of both electroless nickel composite coatings (Tubes No. 2 and 4) compared to the control Tube No. 1, blasted only Tube No. 5, and Tube No. 3 with electroless nickel without codeposited particles.

CONCLUSIONS

The two composite electroless nickel coatings evaluated by the methods of the experiments presented in this article demonstrate a significant propensity to transfer heat. Examples 1 and 2 show a consistent increase of 9.3 to 10.6% heat loss rate for Tube No. 2 in comparison to the control Tube No. 1. Example 3 demonstrates that the codeposited diamond particles on Tube No. 2 are the cause of the enhanced heat transfer as this tube dissipated 16.2% more heat than Tube No. 3 with electroless nickel alone and no particles. While it was theorized that the slightly increased surface roughness of the composite coatings may be the mechanism by which these coatings facilitate heat transfer, Example 3 shows that Tube No. 5, which was only sand blasted to produce a roughened surface similar to that of Tube No. 2, transferred 10.5% less heat than Tube No. 2 with the composite diamond electroless nickel coating. The significance of the particles in enhancing heat transfer is further demonstrated in Example 4 where both the diamond and silicon carbide composite electroless nickel coated tubes (No. 2 and 4 respectively) dissipated 8.7 and 2.2% more heat than blasted Tube No. 5. Further supporting these conclusions is Example 5 where the blasted Tube No. 5 had greater heat transfer than the control, and the composite diamond electroless nickel coated Tube No. 2 had 19.6% greater heat transfer during this example with the longest duration.

These results of enhanced heat transfer are considered significant from both scientific and industrial perspectives. For the electronics industry the ability to provide this property from a process that is well established and versatile for substrates of numerous materials and geometries is attractive. Additional work is underway to evaluate similar composite coatings with different properties such as matrices, particulate matter, particulate size, and coating thicknesses for optimized heat transfer.

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