ADDITIVE-BASED PROCESS FOR PRODUCING MICRO-CHANNEL DEVICES

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ABSTRACT
A micro-channel device is formed from a rigid template of a suitable material, such as wax, by forming a continuous electrically-conductive structure over the rigid template to thereby define channels. The rigid template is then removed, thereby forming the micro-channel device. Examples of micro-channel devices include micro-channel thermal management units and micro-channel chemical reactors. Micro-channel chemical reactors can be formed by coating interior walls of the micro-channel device with a suitable catalyst.
Anodic DC Process Variables

- Peak current density
- Duty cycle

Cathodic PC Process Variables

- Peak current density
- Duty cycle
- Frequency

Cathodic PRC Process Variables

- Peak cathodic current density
- Peak anodic current density
- Cathodic duty cycle
- Anodic duty cycle
- Frequency

FIG. 2
FIG. 5

FIG. 6

FIG. 7

FIG. 8

Poor Surface Contact  Optimal Surface Contact

Heated Surface
FIG. 10

- Time (seconds)
- Temperature (°C)

Water Pump or Fan Turned Off
Water Pump or Fan Turned On
Fin & Fan HX
RIL HX at 20 mL/min
RIL HX at 110 mL/min

No HX Present
Fin & Fan

- 20 mL/min
- 110 mL/min
ADDITIVE-BASED PROCESS FOR PRODUCING MICRO-CHANNEL DEVICES

RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Application No. 62/303,650, filed on Mar. 4, 2016. The entire teachings of the above application are incorporated herein by reference.

GOVERNMENT SUPPORT

[0002] This invention was made with government support under contract number DE-SC0011232 from Department of Energy SBIR Phase I and II. The government has certain rights in the invention.

BACKGROUND OF THE INVENTION

[0003] Electronic systems are used extensively throughout our society ranging from cell phones and laptop computers, to medical/office equipment, industrial and military systems, avionics, and automotive systems. These electronic systems have continued to shrink in size while delivering higher levels of performance, which are benefits that have greatly improved the products and processes that the electronic systems serve. However, a major cause of electronics failure is inadequate power dissipation. And this challenge is getting more difficult—continues increases in circuit density and clock rates have increased heat fluxes to over 1000 W/cm², challenging all thermal management products in terms of performance and cost.

[0004] The challenges for micro-channel devices employed in electronics thermal management vary, for example, from removing 5 W/cm² on a printed wiring board (PWB) to 2000 W/cm² for a semiconductor laser. The former heat flux is easily dissipated using a finned heat exchanger and a fan, whereas the latter requires novel two-phase fluid cooling solutions. New electronic system designs for computer data servers, hybrid electric vehicles, avionics, medical and office equipment, and telecommunications have heat removal requirements in the 100-1000 W/cm² range as well as specifications for keeping device touch temperatures at less than 100°C. Accordingly, new thermal management technologies are needed that are lightweight, easy to manufacture, and can operate with either single-phase or two-phase fluids.

[0005] Despite clearly demonstrated merits to the use of micro-channels for removing heat, they are not readily available in the commodity micro-channel thermal management unit and reactor market. For example, micro-channel thermal management units having a 100 micron channel size generally are not available for purchase, unlike heat pipes, fins, and liquid-cooled meso-channel systems. Furthermore, a major challenge is the incorporation of advanced internal component designs in these micro-channel formats using a practical industrial manufacturing process that is cost-effective. Present methods to perform such designs are custom-made to order and inordinately expensive.

[0006] Therefore, a need exists for a method of manufacturing micro-channel thermal management units that overcome or minimize the above-mentioned problems.

SUMMARY OF THE INVENTION

[0007] The invention generally is directed to an additive-based process for producing micro-channel devices, such as microchannel thermal management units, micro-channel chemical reactors, and separators. “Additive based,” as defined herein, means electrolytically depositing metal to define micro-channels of the microchannel device, as opposed to subtractive based processes that etch, mill, etc. material away from a block of material. A chemical reactor is made by, for example, 1) subsequently coating the walls of the micro-channels with a catalyst that chemically converts fluids that traverse the micro-channels, or 2) designing the micro-channels with multiple manifolds that enable separate reactant streams to be fed to the unit that subsequently meet and react in the micro-channels.

[0008] In one embodiment of the method of the invention, shown in FIGS. 1A-1F, after a 3-dimensional flow network template is produced (FIG. 1A), it is made conductive so that copper or aluminum can subsequently be electroformed over the solid flow network structure (FIG. 1B). Using a suitable technique, such as is known in the art, a continuous metal coating is formed over the template. In one embodiment, as electrolytic plating method is employed, wherein the template flow network is coated with a 10-150 micron thick layer of copper or aluminum to encapsulate the flow network (FIG. 1C). Afterwards, the internal template solid flow network, or rigid template, is dissolved to expose a continuous network of micro-flow channels. FIG. 1D) This assembly represents the “core” of the thermal management system or chemical reactor, shown in FIGS. 1E and 1F. With this manufacturing method, a continuous thermally conductive pathway is created all about the flow surfaces that minimizes contact junctions and where a low resistance flow regime is also obtained internally. Once the internal solid core template is dissolved, the resulting micro-channel structure is capable of having fluid flow through the conduits, manifold, and channels per the heat exchange or chemical reactor design.

[0009] This invention has many advantages. For example, in one embodiment the invention is a new manufacturing approach for making micro-channel based thermal management units and chemical reactors. In one embodiment, the invention is an additive-based technology where the flow channels are formed with a dissolvable template that is encapsulated with either copper or aluminum. The process uses a dissolvable material that is extruded into a solid form, or a rigid template, that defines fluid flow regions in the thermal management unit or chemical reactor. This fluid flow region can define varying sized shapes, converging and diverging ducts, integrated venturi nozzles, manifolds, multi-channels, pores, wicks, etc. The diameter of the fluid flow region defined can vary, for example, from less than 1 micron upwards to about 6000 microns, and can have varying-sized shapes and 3-dimensional design characteristics.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010] The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawings will be provided by the Office upon request and payment of the necessary fee.

[0011] FIGS. 1A-1F are a representation of one embodiment of a method of the invention for producing micro-channel device of the invention.

[0012] FIG. 2 is a representation of various types of electroplating waveforms that can be employed when electroplating a rigid template by a method of the invention.
FIG. 3 is a photograph of spiraled cylindrical micro-channels formed by a method of the invention.

FIGS. 4A-4C are a series of photographs representing a venturi nozzle template (FIG. 4A), a rigid template (FIG. 4B), and a microchannel (FIG. 4C) device formed from the rigid template of FIG. 4B by a method of the invention.

FIG. 5 is a cylindrical micro-channel with a 625 μm inner diameter and a 25 μm wall thickness of one embodiment of a microchannel device formed by a method of the invention (100 μm between graduation marks).

FIG. 6 is a cylindrical micro-channel with a 250 μm inner diameter and an 88 μm wall thickness of another embodiment of a microchannel thermal management unit formed by a method of the invention.

FIG. 7 is a schematic representation of relatively poor and improved surface contact between micro-channels and a heated source.

FIG. 8 is a photograph of a semi-circular micro-channel structure with a 300 μm base by 212 μm high flow area formed by a method of the invention.

FIGS. 9A and 9B are a perspective view of a cross-section view, respectively, of a micro-channel array of one embodiment of a microchannel thermal management unit formed by a method of the invention with 3960 μm wide and 381 μm high channels.

FIG. 10 is a plot of thermal response of one embodiment of a micro-channel thermal management unit formed by one embodiment of a method of the invention.

FIG. 11 is a photograph of an internal view of micro-channels of a microchannel thermal management unit formed by a method of the invention.

FIG. 12 is a photograph of a prior art micro-channel HX at 2"x2", 45 g, 1000 μmx3000 μm channels.

FIG. 13 is a photograph of a prior art micro-channel HX at 2"x2", 227 g, 500 μmx1000 μm channels.

FIG. 14 is a photograph of one embodiment of a micro-channel HX at 2"x3", 2 g, 5000 μmx127 μm channels formed by a method of the invention.

DETAILED DESCRIPTION OF THE INVENTION

The invention generally is directed to an additive-based process for producing a micro-channel device, such as a microchannel thermal management units, microchannel chemical reactors, and separators. “Additive based,” as defined herein, means electroplating, electroless plating, or other methods commonly known.

In one embodiment of the method of the invention, shown in FIGS. 1A-1F, after a 3-dimensional flow network template is produced (FIG. 1A), it is made conductive so that copper or aluminum can subsequently be electroformed over the solid flow network structure (FIG. 1B). Using a suitable technique, such as is known in the art, a continuous metal coating is formed over the template. In one embodiment, as electrolytic plating method is employed, wherein the template flow network is coated with a 10-150 micron thick layer of copper or aluminum to encapsulate the flow network (FIG. 1C). Afterwards, the internal templated solid flow network, or rigid template, is dissolved to expose a continuous network of micro-flow channels. (FIG. 1D). This assembly represents the “core” of the thermal management system or chemical reactor, shown in FIGS. 1E and IF. With this manufacturing method, a continuous thermally conductive pathway is created about all the flow surfaces that minimizes contact junctions and where a low resistance flow regime is also obtained internally. Once the internal solid core template is dissolved, the resulting micro-channel structure is capable of having fluid flow through the conduits, manifold, and channels for the heat exchange or chemical reactor design.

In another embodiment, the template-based manufacturing method of the invention starts by defining the thermal management fluid flow pathways with a dissolvable material. Waxes are one suitable template material in that they are inexpensive and can be tailored with specific softening and melting points. Depending on the extrusion or casting method employed, the wax properties can be customized to improve workability before the wax hardens into its final shape. A suitable solvent, such as is known in the art, can be employed to dissolve the wax, and then recovered and reused, along with the solvent, for subsequent manufacturing operations. Examples of suitable solvents include hexane and trichloroethylene. It is also possible to employ a slurry solution of wax and a suitable solvent, such as hexane, to preferentially place and deposit wax in the flow field structure by evaporating the solvent. Other dissolvable template materials can be employed, such as dextrose-based solutions that can be dissolved in water.

Casting wax with a softening temperature between about 62° C. and 68° C. is one example of a suitable material that is relatively easy to manipulate at room temperature, as well as being removable with warm hexane, trichloroethylene, or water. Wax generally has a low rate of thermal expansion and, therefore, does not crack as it cools. Processing of wax typically includes casting, extruding, and cutting to form template structures by suitable methods, such as are known in the art.

Extrusion and casting of a wax flow field generally are employed during the templating manufacturing process. Depending on the complexity of the micro-channel thermal management unit, micro-channel chemical reactor, or separator, for example, a number of manufacturing process steps are employed. In one embodiment, such as for designs that have a myriad of flow passages, manifolds, bends, venturi nozzles, etc., the manufacturing process forms these individual components with wax separately and subsequently “glues” them together by localized spot melting of the component ends.

Extrusion methods, for example, can readily heat and melt wax in a chamber employing nozzles with varying designs to produce channels as the wax solidifies upon
exiting the nozzle. Suitable extrusion devices, such as those known in the art, produce varying-sized wax shapes and sizes dictated by the extrusion nozzle and where the draw rate is employed to impart selected size and thickness parameters. From a manufacturing perspective, this extrusion process can produce specific micro-channel wax components (e.g., a 80 µm x 140 µm rectangular channel that is 2" long) into a parts bin and subsequently employed during assembly of a micro-channel thermal management unit by a method of the invention.

[0031] Alternative suitable materials for the template include plastics and metals. For example, plastic materials including nylon and polypropylene may be used to define the initial template that is subsequently coated with a plastic or aluminum layer, and then which the plastic template is removed via solvents, melting, or burning the plastic away. In another embodiment, metal templates may also be used as the initial template. For example, aluminum may be used as the template structure that is subsequently coated with a copper layer, and then which the aluminum is removed via dissolving it with a solvent, acid, or base.

[0032] Casting of micro-channel components is another suitable manufacturing process step of the method of the invention that can employ, for example, silicone molds. Wax components can be cast and subsequently stamped if necessary into desired shapes. For instance, wax can be cast into sheets (e.g., 2"x4" sheets that are 127 µm high) where cuts can subsequently be made to the cast sheet to remove wax, leaving behind narrow micro-channel flow passages.

[0033] Once a collection of flow-field components has been produced in wax, the final process is to use jigs that aid in the assembly of these components, enabling components to be melted locally to form continuous flow passages. These jigs can be made, for example, out of stainless steel blocks that have milled-out regions to contain the various wax flow components during assembly operations. Since they only serve to help align wax flow components, these jigs are reusable.

[0034] Once wax-based templates have been formed, a next step in one embodiment of the method of the invention is to make the wax surface electrically conductive so that a suitable metal, such as copper or aluminum, can be electroplated over it. After the metal (copper or aluminum, for example) has been electroformed over the wax structure, the wax template material is then removed. The thermal management device can then be finished by adding, for example, fittings and connection mounts.

[0035] To electrolytically deposit a suitable electrically conductive surface, such as copper or aluminum onto the wax template, the template surface must first be made electrically conductive. Suitable electroless copper and electroless silver, such as are known in the art, are examples of suitable materials that can be employed to make the wax surfaces of the template electrically conductive.

[0036] For electroless copper, the method of making the rigid template electrically conductive consists, in one embodiment, of four stages including surface roughening, sensitization, activation, and electroless copper deposition. The surface roughening stage can be carried out employing a 0.1 M potassium permanganate solution between room temperature and 55°C, for a period of time in a range from 0.5 to 5 minutes, while maintaining the concentration at about 0.1 M. The sensitization stage can employ a tin chloride solution at room temperature at concentrations ranging from 0.037 M to 0.37 M. The treatment time of the sensitization stage can range from 30 minutes to 15 hours at the various concentrations. The activation stage includes, for example, a silver nitrate solution at room temperature with concentrations ranging from 0.025 M to 0.123 M. The treatment time for this stage can be maintained, for example, for about 1 minute. The electroless deposition stage can employ an electroless copper solution, which varies from room temperature to 55°C with treatment times from 5 to 30 minutes.

[0037] Once the wax template has an electrically conductive surface, it is electroplated with a suitable metal, such as copper or aluminum. The choice of copper is based upon its ease of electroplating by employing, for example, standard circuit board copper plating methodologies. A standard copper plating solution employed in the circuit board industry (42 g/1 CuSO₄·5H₂O in 241 g/1 H₂SO₄) can be employed for the micro-channels. Although copper may not be a preferred material for lightweight micro-channel thermal management units because of its relatively higher density (8.98 g/cc) than aluminum (2.7 g/cc), its high thermal conductivity (387 W/m•C) makes it an attractive metal for many micro-channel systems in comparison to aluminum's thermal conductivity of 202 W/m•C. Aluminum can be electroformed with an ionic liquid-based electrolyte solution in the temperature range of 60-100°C (which requires use of a higher melting point wax template). A suitable aluminum ionic liquid electrolyte system, such as is known in the art, can be employed to electroform aluminum including, for example, 1-ethyl-3-methylimidazolium chloride (EMIM chloride) with aluminum chloride salts. With this approach, a nitrogen blanket can be applied over the electrolyte, while aluminum is electroformed over the wax core at rates of, for example, 1 micron/minute. A suitable additive, such as is known in the art, ensures that the film deposits are essentially free of dendrites, are highly solid, and adhere strongly to the substrates. When targeting a 40 micron thick aluminum wall thickness, for example, this electrodeposition process generally will require about 40 minutes.

[0038] The electrodeposition process can employ, for example, direct current (DC), pulse current (PC), or periodic reverse current (PRC) waveforms to deposit metal onto a wax template. PRC waveforms have been widely employed in the plating and semiconductor industries to control mechanical and physical attributes of metal deposits. A diagram showing DC, pulse current (PC), and PRC waveforms is shown in FIG. 2.

[0039] The DC waveform shown in FIG. 2 is self-explanatory with a constant current of i, and a time period of T. The most common PC waveform, also shown in FIG. 2, is a cathodic rectangular pulse. It consists of a peak cathodic current, i, switched on for a time period called the on-time, and zero current for a time period t₀, called the off-time (relaxation time). During the off-time, the electroactive species diffuse back to an electrode surface, helping the surface concentration to recover a bulk concentration level before the next pulse. The sum of the on-time and the off-time is known as the pulse period and the inverse of the pulse period gives the frequency of the pulse. The duty cycle of the pulse is defined as the ratio of the on-time to the period of the pulse. In the reverse pulse technique, an anodic pulse of short on-time is applied following the cathodic pulse. The PRC pulse shown in FIG. 2 incorporates a cathodic pulse of i₁ for a time t₁, then an anodic pulse is applied with a current
magnitude of \( i_2 \), and time \( t_2 \), PC and PRC techniques have been employed to produce deposits with 1) better adherence to the substrate, 2) low internal stress, 3) smaller grain size, and 4) higher tensile strength.

[0040] Once the micro-channels have been coated with either copper, aluminum or other suitable metal or metals, the next step in the process is to dissolve the wax core. A great advantage of using waxes is that they are easily dissolved in certain solvents such as hexane or trichloroethylene. Even without dissolving the wax, it may be melted out of the structures using hot water or a dry inert atmosphere to avoid oxidation. The dissolved wax and solvents can be recovered and re-used, helping to minimize waste and material costs.

[0041] Once the wax template is removed from the micro-channels, the ensuing structure is completed by attaching flow fittings and mounting supports to the unit. These mounting units may also be incorporated earlier into the micro-channels during the electrodeposition process to encapsulate them.

[0042] One example of a method of the invention of manufacturing thermal management units includes creating a silicon mold that defines a fluid flow regime of the thermal management unit. This silicon mold can be re-used to cast additional thermal management devices.

[0043] To initially create the silicon mold that is employed to produce a dissolvable wax template, two approaches typically can be employed. One approach employs red sprue wax 20-270 from CR Hill Company that is melted and formed by hand or other tools into various designs that define the thermal management flow regime. Alternatively, a 3D printer is employed to make a die that defines the fluid flow regime of the thermal management unit. A 3D printer allows alteration of the size and shape of the channels and to make a variety of different dies to create various molds. Once the die is made, the bottom of the die (such as the flat surface of the device which comes in contact with the heat source) is securely adhered to a suitable acrylic, such as is known in the art. The acrylic is placed around the die to create walls to contain the silicon. Using Silpak, Inc. brand silicone, the silicone base and silicone catalyst are mixed and poured into the mold template. Air is vacuumed out to prevent any air bubbles from forming in the mold which could potentially lead to unwanted pockets in the silicon mold. Once all air is vacuumed out of the silicon, the mold is cured at about 100°C for about 3 hours. The silicon mold is then removed from the mold die where the silicon mold is used to create the wax manifold designs.

[0044] Red sprue wax can be employed to create wax template designs. The wax is heated to about 100°C, and poured into the silicon mold. Directly after the wax is poured into the mold, a Kapton® sheet can be placed on the wax and pressed to ensure a smooth flat surface. The Kapton® sheet remains on the wax for about 10-15 minutes while the wax cools. The Kapton® sheet is then removed from the wax, and the wax template can be removed from the silicon mold by gently bending the silicon surrounding the device.

[0045] Once the wax template is removed from the silicon mold, an electroless silver spraying process can be performed on the wax template to provide a conductive surface prior to electrolytic plating. This process employs a cleaner solution, degreaser solution, wetting agent, sensitizer solution, reducer solution, and silver solution which, such as can be purchased from Peacock Laboratories, Inc., for example, which provides instructions for both the preparation of the solutions as well as the silvering process and provides the spray gun(s) required for the process. The wax template is initially sprayed with the cleaner solution then rinsed with distilled water, sprayed with the wetting agent, and rinsed with distilled water (this step can be repeated, for example, 3-5 times before moving onto the next step), sprayed with the sensitizer solution then rinse with distilled water (this step can be repeated 5-7 times, for example, before moving onto the next step), sprayed with the silver and reducer solutions through a double nozzle silver spray gun and rinsed with distilled water. Copper can then be electroformed onto the silver-coated wax template.

[0046] In another embodiment, a copper deposition process employs two separate copper electroforming baths. The first bath employed can be, for example, RIO GRANDE MIDAS® bright electroforming copper solution 335-074. The second bath employed can be a copper electroforming solution made up of 80 g/L CuSO₄·5H₂O, 225 g/L H₂SO₄, and 75 ppm CuCl. The electroplating waveform recipe employed for both baths are as follows:

- **[0047]** Pulse Frequency (Hz): 9.09
- **[0048]** Duty Cycle—Cathodic(%), Anodic(%): 90.1%, 1.8%, 8.1%
- **[0049]** Peak Current Density (mA/cm²)—Cathodic, Anodic: 12.5, 74.9
- **[0050]** Average Current Density (mA/cm²) Cathodic, Anodic: 11.3, 1.5, 9.8
- **[0051]** Direction Time—Forward (ms), Reverse (ms): 99.1, 10.9
- **[0052]** Forward—On (ms), Off (ms): 90.1, 0
- **[0053]** Reverse—On (ms), Off (ms): 2, 8.9

[0054] The silver-coated wax template device is submerged vertically into the MIDAS bath and is electroplated for 2 hours employing a stir bar for agitation. The template is then removed and immediately placed into a suitable copper solution, such as is known in the art, while the power supply is actively on, and is also plated for about 2 hours using a stir bar for agitation. Once the copper electroforming process is complete, the device is rinsed with distilled water and dried immediately by employing a fan to prevent water staining. The wax can then be removed from the device.

[0055] Trichloroethylene (TCE) is employed as the solvent to dissolve the wax. The plated wax device is submerged in TCE (heated to 75°C) until all wax has been dissolved. The plated device is then submerged into clean TCE (heated to 50°C) to remove any additional wax that could have been left as a thin layer on the device. The copper plated device is then rinsed with distilled water and dried immediately to prevent water staining. The resulting thermal management device is then ready to function as a thermal management unit.

**EXEMPLIFICATION**

**Example 1**

[0056] To illustrate the simplicity of this manufacturing process for producing micron-sized thermal management components, a number of heat exchanger flow components were produced ranging from straight cylindrical channels to 3-dimensional designs that have integrated flow control components such as venturi nozzles. The templating material and extrusion process defined the regions for the fluid flow, whereas the electroformation process controlled the
deposit thickness and uniformity about the templated structure. These thermal management devices were fabricated and cross-sectioned to examine the openness of the flow channels, the cross-sectional flow area, and the plating thickness.

[0057] At the simplest level, templates were extruded into straight cylindrical channels and even spiraled channels, as shown, for example, in FIG. 3. Such spiral designs can be used for wrapping cooling loops around cylindrical batteries or capacitors in support of electric vehicle cooling for instance. Micro-channels were formed having varying diverging or converging regions to influence fluid flow behavior, as illustrated, for example, in FIG. 4 for a two-phase fluid micro-channel prototype. This system had a lower micro-channel region with a flow channel height of 381 microns that can contact a heat source located beneath it. Connected to the top of this lower micro-channel section were three venturi nozzles that fed an upper channel. Evaporated fluid from the bottom could flow through the venturi nozzles that subsequently cool and condenses the fluid on the top plane where the liquid coolant would flow along the side walls toward bottom channels. With this device the phase change of the fluid helps dissipate heat.

[0058] A cross-section of a cylindrical channel is shown in FIG. 5 showing a 625 µm inner flow diameter and a 25 micron wall thickness. These channel dimensions were dependent on the template extrusion and electroformation process where variations in the process conditions produced different-sized channels. This is illustrated in FIG. 6 for a 250 micron inner diameter and a thicker wall thickness of 88 microns. Reasonably good uniformity was shown with the wall thicknesses in these cross sections.

[0059] One of the advantages of this template-based manufacturing process was the ability to exactly define the channel structures that could be used with, for example, power amplifier modules. FIGS. 9A and 9B are photographs of a perspective view and a cross-sectional view, respectively, of a micro-channel array structure that has fluid flow manifolds located on opposing ends of micro-channel ribs. The cross-section of the micro-channels shows relatively consistent channel sizes that are about 3950 microns wide and about 381 microns tall (10 mm between the 20 and 30 graduation marks).

[0060] A template-based manufacturing method of the invention was employed to produce a variety of micro-channel structures. FIG. 10 is a plot micro-channel performance evaluation operating on the heated block shown in FIG. 1. This heated block heated a copper plate instrumented with 18 thermocouples across a 2"x3" surface. Applying a uniform heat load to all tests, the average temperature of the copper plate is shown in FIG. 10 without a thermal management unit on the copper plate. Next, an aluminum fin structure 1º high was placed on the copper. The experiment is on to reduce the average plate temperature by 32.6º C. Thereafter, the micro-channel unit was connected to a water pump and operated at two rates, of 20 and 110 ml/min, that dropped the average plate temperature by 42.6 and 48.6º C., respectively.

[0061] The fin structure weighed 108.5 g, whereas the micro-channel array, shown in FIG. 1, weighed 2 grams. This data is summarized in Table 1. The lightweight structure of these components was due to the additive manufacturing process that only places material where needed to hold moving fluids. FIG. 11 shows a photograph of this micro-channel array where the fluid flow manifold was opened up to view the internal channels and a wall thickness that measured 635 microns thick. Electrolytically formed copper walls about 120 microns thick can withstand over 400 psig of pressure without leaks or rupture.

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<td>51.4</td>
<td>48.6</td>
<td>110</td>
<td>24.3 C/g</td>
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*mass accounts only for the fan or micro-channel structure without considering the fan or water pump.

[0062] An examination of commercially available micro-channel cold plates was conducted. One system, shown in FIG. 12, is an aluminum based system of the prior art having dimensions of 2x2 in² and weighing 45 g. The channeling in this product were 1000 microns wide and 3000 microns high. Another system of the prior art, shown in FIG. 13, covered a 2x2 in² region and weighed 227 g. The channels in this unit were smaller, with a 500 micron channel width and 1000 micron height. In comparison, a larger 2"x3" micro-channel copper heat exchanger produced by a method of the invention is shown in FIG. 14 and weighed about 2 g.

[0064] The relevant teachings of all references cited herein are incorporated by reference in their entirety.

[0065] While this invention has been particularly shown and described with references to example embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein.
without departing from the scope of the invention encompassed by the appended claims.

What is claimed is:

1. A method for forming a micro-channel device, comprising the steps of:
   a) forming a rigid template representing channels of a micro-channel thermal management unit, at least a portion of the channels having a cross-sectional diameter in a range of between about 20 and about 6,350 micrometers;
   b) forming a continuous electrically-conductive structure over the rigid template, wherein the electrically-conductive structure defines the channels represented by the rigid template; and
   c) removing the rigid template from the electrically-conductive structure, thereby forming the micro-channel device.

2. The method of claim 1, wherein the electrically-conductive structure defines an inlet and an outlet, and a conduit between the inlet and the outlet, whereby a fluid can be directed through the electrically-conductive structure from the inlet to the outlet to thereby transfer heat from the electrically-conductive structure.

3. The method of claim 2, wherein the rigid template includes at least one material selected from the group consisting of wax, plastic or metal.

4. The method of claim 3, wherein the rigid template is formed by casting, extrusion, stamping individually or collectively.

5. The method of claim 4, wherein the rigid template is removed by at least one of heating, melting, burning, and dissolution of the rigid template within the electrically-conductive structure.

6. The method of claim 4, electrically-conductive structure is formed by electroplating a metal over the rigid template.

7. The method of claim 6, further including the step of making a surface of the rigid template electrically conductive by coating the surface with at least one member of the group consisting of copper, silver, nickel and carbon prior to electroplating.

8. The method of claim 7, wherein the metal electroplated over the rigid template is at least one member selected from the group consisting of copper, aluminum, zinc, nickel, gold and precious metals.

9. The method of claim 1, further including the step of coating the internal walls of the device with a catalyst.

10. The method of claim 9, wherein the catalyst includes at least one member of the group consisting of platinum, ruthenium, palladium, gold, nickel and iridium.