

HEAT PIPE THERMAL MANAGEMENT APPARATUS

This application claims the benefit of U.S. Provisional Application No. 60/065,418 filed November 13, 1997.

5 This invention relates to a heat pipe apparatus for thermal management, and more particularly to improved thermal management devices comprising a heat pipe and molded heat sink components. Still more particularly, the invention relates to a thermal management apparatus comprising a heat pipe component in thermal communication with a heat sink component wherein the heat sink component comprises a moldable, thermally conductive, filled polymer and preferably an injection
10 moldable, thermally conductive, filled liquid crystal polymer. Preferably, the thermal management apparatus will be formed as a unitary structure by an insert molding operation.

The market segment for electrical devices such as for windings of motors, transformers and solenoids is increasingly moving to miniaturization of such devices. This in turn leads to a rise in internal equipment operating temperature resulting in not only a need for higher temperature ratings
15 on insulation materials used for these applications, but also a need for improved methods for removal and dissipation of heat. Heat generation is also a problem in a great variety of electronic devices comprised of a semiconductor component, such as, for example laser diodes, light-emitting diodes, thyristors, microwave electron transfer devices and the like. Semiconductor or multichip modules that consist, for example, of monocrystalline silicon having millions of transistors
20 positioned on or near a single surface of the chip produce considerable amounts of heat energy in operation. Removal of byproduct heat is important to the lifetime of electronic components and the art has continually sought improved thermal management systems and methods for managing the high levels of heat output associated with such devices.

Thermal management has long been the subject of extensive study and research. Early practice
25 relied on the use of heat sinks, including carriers and housings, constructed of metals and alloys selected for their high thermal conductivity, and such devices continue to find wide use. More recent innovations and modifications in materials have included, for example, combinations of metal housings with metal-coated diamond chips or wafers, intended to take advantage of the fact that diamonds have the highest thermal conductivity known. The obvious shortcomings of devices based
30 on diamond, particularly including the practical considerations imposed by the limited size of diamond components, as well as high cost, led to the development of metal matrix composites containing diamond particles as a filler to increase thermal conductivity. Other solutions for thermal

management problems designed particularly for use with high power density devices include liquid-cooled heat sink structures and chip module housings that rely on liquid nitrogen as the coolant.

A disadvantage of the prior art structures lies in the complexity associated with their fabrication.

Generally, thermal management devices have been constructed of metal, primarily because of the

5 requirement for excellent heat transfer characteristics in combination with good mechanical properties. There are substantial coefficient of thermal expansion (CTE) differences between most

metals used in thermal management devices and the electronic components that will be cooled, as well as between these components and the plastic case and components housing the devices. These

differences may impose substantial mechanical stress on mating components, providing

10 opportunities for failure during use. Matching CTE properties of heat sink materials with those of semiconductors requires the use of dense alloys that are difficult to machine and adds significantly

to the weight of the device. Compensating for large differences in CTE is also practiced, but this requires complex designs that are difficult to fabricate. Further, effective dissipation of the heat by

convection is a function of surface area. As thermal loads increase it becomes necessary to employ

15 convective heat exchange components with still larger surface areas, again adding weight and impacting design flexibility.

Lower density materials have been suggested as metal replacements in thermal management.

Particularly attractive are structures comprising carbon or crystalline graphite; both materials are highly thermally conductive, have substantially lower densities than the metals they replace and may

20 be made into structures with a low and even negative CTE. Although light weight graphite structures and carbon-carbon composites are known and accepted for use in heat sink and other thermal management applications, fabricating complex structures from these materials is generally difficult and thus such components may be more costly than those constructed from metal.

Thermoplastic resins with good molding properties are readily available as are castable and

25 moldable thermoset resins. However, resins generally have a high thermal expansion coefficient and are poor conductors of heat. Few are capable of withstanding thermal cycling over a wide range of

temperatures without undergoing failure through creep or warping or, in the case of rigid thermoset resins, cracking or similar failure due to thermomechanical stress. Adding fillers to resins as a

method for reducing CTE and thereby improving dimensional stability is well known and widely

30 used in the resin formulating arts and may also be found useful for improving thermal conductivity.

Particulate materials including conductive carbon or graphite fillers, spherical particles of various metals, glass or carbon black, non-spherical metal or ceramic particles, stainless steel filaments, aluminum fibers and the like are disclosed in the art and characterized as particularly useful where

improved thermal conductivity is desired. However, where resins containing these fillers have been employed for thermal management purposes only modest improvement has been realized. Commonly, filled thermoset resins used commercially in the electronics industry have thermal conductivities on the order of 2 to 4 W/mK, while injection moldable filled thermoplastic formulations are disclosed with thermal conductivities in the 4 to 9 W/mK range. The thermal conductivity of even the most conductive of the filled resin formulations disclosed in the art falls below 10 W/mK, while most commercially-available filled resins comprising such highly conductive fillers as metallic filaments and the like are still much lower in thermal conductivity, generally as low as 2 to 3 W/mK. Filled resins, and particularly filled thermoplastic resins, thus have found limited acceptance and are generally better suited for use where thermal loads are low and where minimizing the size of the heat exchange device is not an important design factor.

More recently, computer manufacturers have turned to heat pipes as means for efficiently and rapidly transferring heat away from a heat source such as a microprocessor semiconductor component for further dissipation. Typically a heat pipe will be a hollow metal tube partially filled with a fluid, although alternative forms include heat pipes comprising a solid heat conducting material may also be employed in these structures. In use, the evaporator or heat input zone of the heat pipe will be thermally coupled either directly to the semiconductor structure being cooled or, more commonly, to an interposed heat sink in thermal communication with the device. Heat removed to the condenser or heat dissipation zone of the heat pipe will be dissipated into the surroundings by means of thermally coupled cooling fins or a second heat sink element such as a thermal plate or the like.

Good thermal transfer between the components is important for effective and efficient operation and the metal fins and heat sink elements are therefore generally swaged, soldered or brazed to the heat pipe. Alternatively, the components may be held in mechanical contact by fasteners, clamping devices or the like, and thermally conductive adhesives have also been employed for these purposes. Where the heat pipe element of an assembly is intended to be displaced, for example, rotably or slidably relative to a heat sink element while in use and therefore cannot be permanently attached thermal grease has been employed to fill airgaps and provide continuous contact region between the contacting surfaces of the parts. See U.S. 5,598,320. Hinged computing devices have also been disclosed wherein a heat pipe serves as the pintle or hinge pin to transfer heat to the display housing through the gudgeon receiving the pintle. See U.S. 5,621,613.

It is also known in the art to fabricate heat pipe panels having internal micro heat pipes by forming channels within a substrate followed by enclosing the channels. For example, heat panels of vapor

deposited tungsten or tungsten-rhenium alloy having internal tubular passageways forming micro heat pipes have been disclosed. See U.S. 5,598,632.

Although the use of heat pipes may greatly improve the efficiency of heat removal, it will be understood that the removed heat will then be dissipated, normally into the surroundings, generally requiring the use of heat sinks, such as thermal panels or the like. In practice these latter components most often have taken the form of a rigid metal structure such as a thermal plate placed in thermal communication with the environment, for example, as an external feature or structural component of the case of portable electronic devices. Requirements imposed by the thermal management device are thus seen to continue to impact and restrict design flexibility, as well as to increase the overall weight of the device.

The art continues to seek more flexible solutions for thermal management problems. Even when further improvements in heat removal have been achieved, heat loads have continued to increase with the demand for ever smaller electronic devices. Heat sinks necessarily must increase in size to provide adequate dissipation of the removed heat to the surroundings, in turn impeding the trend toward miniaturization. A thermal management apparatus comprising heat dissipating means formed of thermally conductive, lower density, readily molded structural materials suitable for use as the case component of an electronic device would be a useful advance in the thermal management art.

SUMMARY OF THE INVENTION

The improved thermal management apparatus of this invention comprises a heat pipe in thermal communication with a molded, thermally conductive heat sink comprising a filled, thermally-conductive resin. The resin can be thermoplastic or thermoset. Examples of thermoplastic resins which are suitable for this invention include liquid crystal polymers (LCPs), aliphatic polyamides, polyphthalamides, acrylonitrile butadiene styrene resins (ABS), and polyaryl ether resins such as PPO and PPS resins. Several thermoset resins, including epoxy resins, cyanate resins, thermoset polyesters and phenolic resins are also suitable for use in the present invention. Thermoset resins are particularly useful when transfer molding is used to manufacture the molded heat sink. Other molding techniques such as compression and injection molding can also be used.

In one preferred embodiment the heat sink component is injection molded from a thermally-conductive, filled liquid crystal polymer. The heat pipe will be positioned in the molded heat sink to place selected portions of said heat pipe in thermal communication with the heat sink, preferably by insert molding to afford an integral unitary construction having excellent thermal transfer

characteristics and without the need for thermal grease or the like. In another embodiment the heat sink component is compression molded from a thermally-conductive, filled epoxy resin.

The good thermal properties and dimensional stability and the excellent mechanical strength of filled LCP resins together with low mold shrinkage and ease of fabrication by injection molding into parts having close tolerances and very thin sections make these thermally conductive molding compounds particularly well-suited for constructing components having complex designs that are highly desirable and useful in thermal management, particularly for electrical and electronic devices.

DETAILED DESCRIPTION

In the preferred embodiment, the thermal management devices of this invention will comprise at least one heat pipe, together with one or more molded thermoplastic or thermoset heat sink components. For the purposes of this invention, a heat sink includes any structure to which heat is transferred.

The thermoplastic and thermoset formulations suitable for these purposes will be thermally conductive, preferably having a thermal conductivity greater than about 15 W/mK and as great as 600 W/mK or more, readily moldable at temperatures that will not cause damage to the heat pipe, and with high melt flow at the molding temperature. Still more preferred will be thermoplastic formulations which may be described as having high tensile modulus values, generally greater than 7×10^6 psi, approaching the stiffness and rigidity of lighter metals including magnesium and aluminum.

A preferred thermoset formulation suitable for use in this invention will comprise a thermoset resin, such as an epoxy resin, filled with discontinuous pitch-based carbon fiber. Thermoset resins are well known and described in the art and are characterized by having low viscosity in the uncured state which facilitates wet out of the carbon fibers.

A preferred thermoplastic formulation suitable for use in the practice of this invention will comprise a liquid crystal polymer (LCP) resin filled with discontinuous pitch-based carbon fiber.

LCP resins are well known and described in the art. Those further characterized as thermotropic liquid crystal polymers (LCP) exhibit optical anisotropy when molten, together with a remarkably low melt viscosity at melt fabrication temperatures. When further compounded with high levels of filler, even to levels as great as 75 wt% based on weight of resin and filler, such LCP resins maintain good melt processing character and moldability.

The preferred LCP resins are aromatic polyesters derived from monomers selected from one or more aromatic dicarboxylic acids and one or more aromatic diols, together with one or more aromatic hydroxycarboxylic acids.

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Representative of aromatic dicarboxylic acids useful in forming the LCP resins useful in the practice of this invention are aromatic dicarboxylic acids such as terephthalic acid, 4,4'-diphenyldicarboxylic acid, 4,4'-triphenyldicarboxylic acid, 2,6-naphthalenedicarboxylic acid, diphenylether-4,4'-dicarboxylic acid, diphenoxyethane-4,4'-dicarboxylic acid, diphenoxybutane-4,4'-dicarboxylic acid, diphenylethane-
5 4,4'-dicarboxylic acid, isophthalic acid, diphenyl ether-3,3'-dicarboxylic acid, diphenoxyethane-3,3'-dicarboxylic acid, diphenylethane-3,3'-dicarboxylic acid and naphthalene-1,6-dicarboxylic acid, and derivatives of the aforementioned aromatic dicarboxylic acids substituted with alkyls, alkoxy groups or halogens such as chloroterephthalic acid, dichloroterephthalic acid, bromoterephthalic acid, methylterephthalic acid, dimethylterephthalic acid, ethylterephthalic acid, methoxyterephthalic acid
10 and ethoxyterephthalic acid.

Aromatic diols which may be found useful in forming the LCP resins include hydroquinone, resorcinol, 4,4'-dihydroxydiphenyl, 4,4'-dihydroxytriphenyl, 2,6-naphthalene diol, 4,4'-dihydroxydiphenyl ether, bis(4-hydroxyphenoxy)ethane, 3,3'-dihydroxydiphenyl, 3,3'-dihydroxydiphenyl ether, 1,6-naphthalenediol, 2,2-bis(4-hydroxyphenyl)propane, 2,2-bis(4-
15 hydroxyphenyl)methane, etc., and alkyl, alkoxy or halogen derivatives of the aforementioned aromatic diols, such as chlorohydroquinone, methylhydroquinone, 1-butylhydroquinone, phenylhydroquinone, methoxyhydroquinone, phenoxyhydroquinone, 4-chlororesorcinol, 4-methylresorcinol, etc.

Aromatic hydroxycarboxylic acids which may be found useful in forming the LCP resins include 4-hydroxybenzoic acid, 3-hydroxybenzoic acid, 6-hydroxy-2-naphthoic acid and 6-hydroxy-1-naphthoic acid, etc., and alkyl, alkoxy or halogen derivatives of the aromatic hydroxycarboxylic acids such as 3-methyl-4-hydroxybenzoic acid, 3,5-dimethyl-4-hydroxybenzoic acid, 2,6-dimethyl-4-hydroxybenzoic acid, 3-methoxy-4-hydroxybenzoic acid, 3,5-dimethoxy-4-hydroxybenzoic acid, 6-hydroxy-5-methyl-2-naphthoic acid, 6-hydroxy-5-methoxy-2-naphthoic acid, 3-chloro-4-hydroxybenzoic acid, 2-chloro-4-hydroxybenzoic acid, 2,3-dichloro-4-hydroxybenzoic acid, 3,5-dichloro-4-hydroxybenzoic acid, 2,5-
25 dichloro-4-hydroxybenzoic acid, 3-bromo-4-hydroxybenzoic acid, 6-hydroxy-5-chloro-2-naphthoic acid, 6-hydroxy-7-chloro-2-naphthoic acid and 6-hydroxy-5,7-dichloro-2-naphthoic acid, etc.

LCP resins comprising thio-containing analogs of these monomers, e.g. aromatic thiol-carboxylic acids, dithiols and aromatic thiol phenols, as well as the amide analogs derived from hydroxylamines and aromatic diamines, are also known in the art, and these resins may also be found useful in the
30 practice of this invention.

As stated, the polymers useful in the practice of this invention will be those LCP resins that are anisotropic in the melt. Those skilled in the art will understand that whether the polymer will be anisotropic in the melt will be determined by the particular components selected, the composition

ratios in the polymer and the sequence distribution and will thus select monomers and composition parameters according to experience and following knowledge and practice common in the LCP resin art.

The LCP resins especially preferred for use in the practice of this invention will contain at least about 10 mol%, preferably from about 10 to about 90 mol% of repetitive units containing a naphthalene moiety such as, for example, a 6-hydroxy-2-naphthoyl, 2,6-dioxynaphthalene or 2,6-dicarboxynaphthalene moiety or the like. Particularly useful are polyesters containing from about 10-90 mol%, preferably about 65-85 mol%, more preferably 70-80 mol% of such naphthalene units together with about 90-10 mol%, preferably 20-30 mol% hydroxybenzoic acid-derived units. Polyesters containing from about 30 to about 70 mol%, preferably about 40 to about 60 mol% of hydroxybenzoic acid units, from about 20 to about 30 mol% of 2,6-naphthalene diol-derived units and from about 20 to about 30 mol% terephthalic acid-derived units may also be found useful.

Further representative of the LCP resins that may be found useful are polyesters containing from about 20 to about 40 mol%, preferably 20-30 mol% of 6-hydroxy-2-naphthalic acid-derived units, from 10 mol% to about 50 mol%, preferably about 25-40 mol% hydroxybenzoic acid-derived units, from 5 mol% to about 30 mol%, preferably about 15-25 mol% hydroquinone-derived units and from 5 mol% to about 30 mol%, preferably about 15-25 mol% terephthalic acid-derived units; polyesters containing from about 10 - 90 mol% of 6-hydroxy-2-naphthalic acid-derived units, from 5 to about 45 mol% terephthalic acid-derived units and 5 to about 45 mol% of hydroquinone-derived units; polyesters containing about 10-40 mol% 6-hydroxy-2-naphthalic acid-derived units, together with about 10-40 mol% each of terephthalic acid-derived units and hydroquinone-derived units; and polyesters containing about 60-80 mol% 6-hydroxy-2-naphthalic acid-derived units, together with about 10-20 mol% each of terephthalic acid-derived units and hydroquinone-derived units.

The molecular weight of the LCP resins employed in the practice of this invention, as represented by the resin intrinsic viscosity (I.V.), will be at least approx. 0.1 dl/g, preferably will lie in the range of from about 0.1 to about 10.0 dl/g when dissolved at 60°C. in pentafluorophenol at a concentration of 0.1 wt%.

LCP resins and methods for their preparation are well known and widely described in the art, and a number of suitable LCP resins are readily available from commercial sources. Particularly suitable are the LCP resins sold by Amoco Polymers, Inc. as Xydar® LCP resins.

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Thermally conductive fillers suitable for use in the practice of this invention include aluminum nitride, boron nitride, alumina, graphite, pyrolytic graphite, aluminum, copper and other metallic particles, diamond, silicon carbide, and preferably, carbon fibers.

Carbon fibers suitable for use in the practice of this invention include highly-graphitized carbon fiber having a high thermal conductivity and a low or negative coefficient of thermal expansion produced from pitch. As used herein, the term "carbon fibers" is intended to include graphitized, partially graphitized and ungraphitized carbon reinforcing fibers or a mixture thereof. The preferred carbon fibers will be pitch-based carbon fiber having a thermal conductivity greater than about 600 W/mK, preferably greater than about 900 W/mK, and still more preferably greater than 1000 W/mK. Fiber with even greater thermal conductivities, as high as 1300 W/mK up to the thermal conductivity of single crystal graphite, 1800 W/mK and higher will also be suitable. Thermally-conductive formulations may also be obtained using pitch-based carbon fiber having a thermal conductivity as low as 300 W/mK.

Pitch-based carbon fiber with thermal conductivities falling in the range of from 600 W/mK greater than 1100 W/mK, a density of from 2.16 to above 2.2 g/cc and a very high tensile modulus, from 110×10^6 psi to greater than 120×10^6 psi, is readily obtainable from commercial sources. Commercial carbon fiber is ordinarily supplied in the form of continuous carbon fiber tow or yarn comprising a plurality, usually from 1000 to 20,000 or more, of carbon filaments 5 to 20 microns in diameter with the axially-aligned filaments providing strength in the fiber direction of the tow.

Generally, where discontinuous fiber is employed the fiber may either be chopped tow, generally greater than 1/4" in length, ordinarily from about 1/4" to about 3/4" in length, or a carbon particulate with a length of from about 25 to 1000 microns, preferably from about 50 to about 200 microns obtained by milling or granulating carbon fiber.

The thermoplastic resins, including LCP resin, and carbon fiber may be readily combined and compounded generally by following processes and procedures commonly employed in the resin compounding art. For example, discontinuous carbon fiber may be dry mixed or similarly combined with the dry resin in any convenient form using any suitable, conventional mixing means and then fed to a compounding extruder, thereby producing a filled extrudate which may be chopped for use in further fabrication steps. Alternatively, thermoplastic resins together with the requisite quantity of carbon fiber in the form of continuous carbon fiber tow may be fed to a single screw extruder and extruded as a strand or pultruded, chopped to form pellets and collected. Thermoset resins and carbon fiber may be readily combined and compounded by dry blending or compounded by way of mixers,



extruders, stirrers, roll-mills, and impregnation devices such as prepreg machines. In addition, dipping, spraying or other coating processes may also be used.

As is generally known in the art, further processing of resin formulations containing glass fiber, carbon fiber or similar brittle fiber fillers using shearing means such as extruders, injection molding machines or the like generally will cause fiber breakage and further reduce the size of the fibrous particulates. The average size of the particulates in filled and molded articles produced by high shear processing means then will generally lie in the range of from 35 to 200 microns, irrespective of whether the fiber was initially supplied in the form of continuous tow or as chopped or milled fiber, and the aspect ratio filler will be greater than about 4 and range on average up to about 10. When processed using low-shear conditions, for example, through compression molding or transfer molding or when used in a flowable formulation as found in potting resin applications, the fiber damage and breakage will be minimized and the articles will then contain substantially greater length fibers, ranging from 100 microns to as great as 1/4", i.e., the original length of the chopped tow fiber, with a correspondingly higher aspect ratio, generally above about 10.

Generally, the filled resin formulations useful in the practice of the invention will comprise from about 20 to about 80 wt%, preferably from about 45 to about 80 wt% and still more preferably from about 60 to about 75 wt% carbon fiber and, correspondingly, from about 80 to about 20 wt%, more preferably from about 55 to about 20 wt% and most preferred from about 40 to about 25 wt% resin. The formulations may further include such plasticizers and processing aids, as well as thermal stabilizers, oxidation inhibitors, flame retardants, additional fillers including reinforcing fillers and fiber, dyes, pigments and the like as are conventionally employed in the compounding arts for use with such molding resins. It will be readily recognized that the utility of the filled molding compounds of this invention lies in the substantial thermal conductivity exhibited by the material. These additional components, as well as the amounts employed, will thus be selected to avoid or at least minimize any reduction in the thermal conductivity of the formulation.

The filled resin will preferably be injection molded with the heat pipe using an insert molding operation to provide a unitary structure. Insert molding processes typically include providing an insert within the mold and injecting the plastic material about the insert or desired portions of the insert to complete the component. In the practice of this invention a heat pipe is inserted within the mold and the filled LCP resin is then injected to surround the desired portion of the heat pipe, filling the mold to form the heat sink. The filled LCP resin, upon cooling, forms a molded heat sink component having a near interference fit at all points of contact with the surface of the heat pipe thereby affording excellent heat transfer between the components.

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As will be understood, the heat pipe is subject to being damaged when subjected to high temperatures or pressures. Heat pipes are intended to operate in particular environments and within a particular range of temperatures depending in part upon the working fluid, the materials of construction and the design. To prevent bursting of the heat pipe by overpressuring, the end seal of heat pipe may be
5 designed to rupture when subjected to temperatures significantly above the design upper limit. Further, subjecting a heat pipe to high external pressure or other severe mechanical stress may cause the pipe to bend or distort and become inoperable. Highly filled polymers are generally difficult to injection mold and form a viscous melt that flows with difficulty, requiring high injection pressures together with stock temperatures well above the polymer melt temperature in order to fill the mold
10 cavity. Non-uniform flow of the highly viscous melt within the mold cavity will subject the heat pipe insert to severe mechanical stress, causing the pipe to distort and even become bent or folded. Filled LCP resins such as those employed in the practice of this invention generally will have a low melt viscosity, and will permit molding using relatively low melt temperatures in the range 400-700° F (200-370° C), well within the design limit for many heat pipes. Moreover, excessive injection
15 pressures are not required to fill the mold thereby avoiding damage to the heat pipe through mechanical stress.

Inasmuch as these formulations are thermoformable, any of a variety of conventional molding equipment and processes adaptable for use in insert molding operations may be employed to mold the filled LCP resin with the heat pipe to form unitary thermal management devices according to the
20 invention.

A wide variety of extrudable and injection moldable thermoplastic resins other than LCP resins are generally known in the art, and such resins, when filled with high modulus carbon fiber to provide thermally conductive resins that are injection moldable, may also be found suitable for the purposes of this invention. For example, aliphatic polyamides including those widely available commercially such
25 as nylon 6, nylon 6,6, nylon 4,6, nylon 11 and the like; polyphthalamides, including the commercially available polymers of one or more aliphatic diamines such as hexamethylene diamine, 2-methylpentamethylene diamine and the like with terephthalic acid compounds as well as copolymers thereof with additional dicarboxylic acid compounds such as isophthalic acid, adipic acid, naphthalene dicarboxylic acid and the like; polyarylate resins including polyethylene terephthalate (PET) resins,
30 polybutylene terephthalate (PBT) resins and the like; arylene polycarbonate resins including poly(bisphenol A carbonate); the well known polyaryl ether resins such as PPO resins, including the thioether analogs thereof such as PPS resins and the like and the corresponding sulfone- and ketone-linked polyaryl ethers such as polyether sulfones, polyphenylether sulfones, polyether ketones,

polyphenyl ether ketones and the like, are well known and filled and unfilled resin formulations containing such thermoplastics are readily available from a variety of commercial sources.

Such thermoplastics, when filled with thermally conductive fillers particularly including carbon fiber as described herein above, may be suitably thermally-conductive for many thermal management applications. However, to obtain the high level of thermal conductivity needed for use in heat sinks for heat dissipation without requiring a significant increase in surface area, and in other thermal management applications where high thermal loads are anticipated, it is necessary to employ a high level of carbon fiber loading, generally at least as great as 45 wt%, preferably from 50 to 80 wt%. When filled to these levels, most such thermoplastic materials may become quite difficult to mold, requiring pressures and elevated temperatures not as well suited for insert molding operations using heat and pressure sensitive inserts such as heat pipes or the like.

Thermally conductive, filled thermoset resins are also known and many are used commercially as thermally conductive potting, encapsulating, adhesive and coating materials as well as sheet molding compounds, bulk molding compounds or the like, particularly for thermal management in electronic applications. Conventional thermoset resins including epoxy resins, cyanate resins, novolacs, resoles and similar thermosetting phenolic resins, thermoset polyesters, and the like may usefully be combined with chopped carbon fiber tow or milled or granulated carbon fiber as described herein above to provide thermoset molding resins and materials with thermal conductivity suitable for use in thermal management devices. Such formulations may be formed and fabricated by conventional means, ordinarily by use of compression molding or transfer molding processes, or by use of a B-staged resin composition in a thermoforming step or the like. When appropriately formed and then thermoset or cured, filled resin articles may be produced with high thermal conductivities, from 2-5 W/mK to as high as 80-100 W/mK or more depending upon the level of filler employed, together with the dimensional stability at elevated temperatures that generally is recognized to be characteristic of most thermoset materials. Filled elastomers that may be thermoformed and cured to provide tough, flexible parts are also known in the art, and these also may be made thermally conductive through use of suitable fillers.

EXAMPLES

Materials employed in the following examples include:

- 30 K-1100X Carbon fiber, obtained as ThorneI® UHM carbon fiber K1100X from Amoco Performance Products with published specifications including a tensile modulus of about 130×10^6 psi, a density of 2.21 g/cc, and a thermal conductivity of 1100 W/mK.

P-120 Carbon fiber, obtained as ThorneI® carbon fiber P-120 from Amoco Polymers, Inc. with published specifications including a tensile modulus of 120×10^6 psi, a density of 2.17 g/cc, and a thermal conductivity of 900 W/mK.

E600X Carbon fiber, obtained as ThorneI® carbon fiber E-600X from Amoco Polymers, Inc. with published specifications including a tensile modulus of 120×10^6 psi, a density of about 2.14 g/cc, and a thermal conductivity of 600 W/mK.

Radel A Polyether sulfone resin, obtained as Radel® A3800 polyaryl ether sulfone from Amoco Polymers, Inc.

PPA-1 Polyphthalamide resin, obtained as Amodel® polyphthalamide resin from Amoco Polymers, Inc.

Nylon 6,6 Polyhexamethylene adipamide

LCP Liquid crystal polymer, obtained as Xydar® SRT 900 resin from Amoco Polymers, Inc.

Mechanical properties were determined according to ASTM standardized testing methods unless otherwise noted.

Thermal conductivities were obtained from measurement of power/heat input and temperature differentials along multiple paths and determination of cross-sectional heat flow under steady-state conditions. Calibration of the device was made using aluminum or copper panels of known thermal conductivity.

Thermal conductivity is calculated using the Fourier Conduction Law

$$q = KA \frac{\Delta T}{\Delta X},$$

where q = power input; A = cross-sectional area; K = thermal conductivity; ΔT = temperature differential between resistive thermal devices in the direction of thermal flow; and ΔX = distance between temperature measurement devices. The data are reported in W/mK.

Filled Resin Formulations

Example 1. Chopped K-1100 carbon fiber tow with a nominal length of 1/4" was dry mixed with Xydar LCP resin pellets and extrusion compounded and chopped to provide pellets of filled resin containing 45 wt% target levels of carbon fiber. Test specimens (6"x6"x1/16") were prepared by injection molding the dried resin pellets using a HPM 75 ton injection molding machine. Properties are summarized in Table I.

Examples 2-5. The procedures of Example 1 were substantially followed in providing a series of filled Xydar resins at levels of 10, 45 and 60 wt% carbon fiber. The pellets were injection molded as in Example 1 to provide flat panels and 4"x4"x1/8" test specimens. Thermal conductivities are summarized in the following Table I.

Table I. Xydar LCP Resins Filled With Chopped K1100 Carbon Fiber.

Ex. No.	1	2	3	4	5
Fiber content ¹ (wt%)	45	10	45	45	60
Mold Temp. °F	-	220°	150 - 220°	100°	100°
Thermal conductivity					
flow dir. (w/m °K)	23.9	7.5	21.1	20.7	21.4
transverse (w/m °K)	13.2	8.1	20.4	21.2	21.3
Spec. Gr. (g/cc)	1.66	1.44	1.66	1.66	1.72
Tensile Str. (Kpsi)	15.4	-	-	-	-
Tensile Mod. (Mpsi)	4.7	-	-	-	-
E (%)	1.5	-	-	-	-
Flex Str. (kpsi)	22.2	20.6	25.6	25.0	24.8
Flex Mod. (Mpsi)	3.8	1.8	4.9	4.6	5.0
Vol. Resist (ohm-cm)	1.5	-	-	-	-
HDT, 264 psi (° F)	-	251	275	274	276
Izod Impact					
unnotched (ft-lbs)	6.4	13.1	10.9	11.7	1.4
notched (ft-lbs/in.)	3.2	-	-	-	-

Notes: 1. Fiber Content = nominal wt% fiber.

It will be apparent that formulations comprising less than about 20 wt% carbon fiber are lacking in thermal conductivity. Although there is some variation, the filled materials may be molded to be anisotropic with respect to thermal properties, or substantially isotropic in the plane of the molded article. It appears that for most systems, there is some fiber alignment along the fiber plane, with the greater degree of alignment occurring most often in the flow direction. However, the properties normal to the flow plane indicate that little three-dimensional fiber orientation occurs for most injection moldings.

Compositions according to the invention may also be manufactured using other thermoplastic resins to provide thermally-conductive parts.

Examples 6 and 7 Continuous K-1100X carbon fiber was compounded with Radel polyether sulfone by feeding continuous fiber together with the polysulfone resin to a Killion 1.5" single screw extruder, extruding the compounded resin into strand, and chopping the strand to form filled polysulfone pellets. The feed rates were controlled to provide strand with 18 wt% and with 33 wt% target levels of carbon fiber. The pellets were then dried and compression molded to provide 4" by 4" by 1/8" coupons for use as test specimens. Properties are summarized in Table II.

Example 8 Pultruded rod was prepared from nylon 6,6 resin by feeding the resin and continuous K1100x carbon fiber to the extruder at a feed rate controlled to provide rod having 60 wt% target level of carbon fiber. The pultruded rod was chopped to give 1/2" pellets. Test plaques were injection molded from dried pellets using an HPM 75 ton injection molding machine. Properties are summarized in Table II.

Examples 9, 10 and 11 Chopped E-600X carbon fiber tow with a nominal length of 1/4" was dry mixed with PPA-1 resin pellets and extrusion compounded and chopped to provide pellets of filled resin containing 10, 50 and 70 wt% target levels of carbon fiber. Test specimens were prepared by injection molding the dried resin pellets as previously described. Properties are summarized in Table II.

Table II

Ex. No.	6	7	8	9	10	11
Resin type ¹	Radel	Radel	nylon 6,6	PPA-1	PPA-1	PPA-1
Fiber type ²	K1100	K1100	P-120	E 600X	E 600X	E 600X
Fiber content ² (wt%)	18	33	(60)	10 (9.6)	50 (44)	70
Fiber length ² (μ)	50	50	80	80	80	-
Thermal conductivity						
flow dir. (W/mK)	13	18	37	-	15.2	33.8
transverse (W/mK)	-	-	27	-	19.7	21.0
thickness (W/mK)	-	-	-	-	1.7	5.8
CTE						
flow dir. (ppm)	-	-	4.5	-	10.3	6.4
transverse (ppm)	-	-	19	-	6.0	16.1

Notes: 1. For resin identification, see text. 2. For fiber identification, see text; Fiber Content = nominal wt% fiber; values in () are actual, determined by gravimetric analysis; Fiber Length = average fiber length in molded sample, determined microscopically.

Compositions according to the invention may also be compression molded to provide thermally-conductive parts.

Example 12 A composition consisting of 50 wt% Radel polyether sulfone and 50 wt% chopped K-1100 carbon fiber tow with a nominal length of 1/4" was prepared by solution impregnation. The mixture was compression molded to provide thermal property test specimens. The in-plane (or x and y direction) thermal conductivities were 90.4 W/mK and 102.9 W/mK. The coefficient of thermal expansion was 4.0 ppm/°F.

Example 13 A dry blend consisting of 50 wt% Radel polyether sulfone powder and 50 wt% chopped K-1100 carbon fiber tow with a nominal length of 1" was compression molded to provide thermal property test specimens. The in-plane (or x direction) thermal conductivity was 67.8 W/mK. Some wetting-out difficulties were observed.

Example 14 A dry blend consisting of 50 wt% Radel polyether sulfone powder and 50 wt% P-120 carbon fiber milled or granulated to give 200 micron particles was compression molded to

provide thermal property test specimens. The in-plane (or x direction) thermal conductivity was 37.0 W/mK. Some wetting-out difficulties were observed.

Thermoset resins such as the common epoxy potting resins may also be filled with carbon fiber, molded and cured to give thermally-conductive parts.

- 5 Example 15 A filled epoxy composition consisting of 70 wt% epoxy resin and 30 wt% P-120 carbon fiber milled or granulated to give 200 micron particles was prepared by combining the liquid resin and the particulate and hand mixing, then pouring into a mold and allowing the plaque to cure, providing a thermal property test specimen. The in-plane (or x direction) thermal conductivity was 15 W/mK.

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Insert Molded Thermal Devices

- Example 16 A thermal device comprising a 3 mm x 160 mm heat pipe and an injection molded heat sink was constructed, using the 60 wt% carbon fiber-filled LCP resin formulation of Example 5. The mold cavity, measuring 12mm x 12 mm x 96 mm, was fixtured to center and support the heat pipe inserted into the mold cavity. The closed mold was then injected with filled LCP resin
15 formulation, using an HPM 75 ton injection molding machine as previously described. After ejecting the cooled molding, the centering fixture was removed to provide a heat pipe embedded at the condenser portion to a length of 51 mm in the injection-molded resin. The block was then milled to form a plurality of fins 1mm in thickness and 4-5 mm in height, centered on and disposed normally to the axis of the heat pipe and spaced 1 mm apart along the embedded length. The overall
20 weight of the heat sink was 12 grams. The source end of the heat pipe was imbedded to a length of 14 mm in a heat transfer block. The heat transfer block was electrically heated at a constant power input of 5.5 watts. Temperature of the source and the ambient temperature were measured by thermocouples, the rise in the temperature for constant power input being inverse to the ability of the structure to dissipate heat.

- 25 The die/source temperature was 71° C, while the ambient temperature was 23° C, giving a thermal resistance of 8.6° C/watt.

- Comparative Example A 3 x 160 mm heat pipe was attached at the condenser end and with an embedded length of 95 mm to a commercial cast magnesium finned heat sink measuring 13 mm x 20 mm x 140 mm in length, having a weight of 26 grams. Thermal adhesive was applied to the
30 contacting surfaces between the heat sink and the heat pipe. The source end was embedded to a length of 14 mm in a heat transfer block, and heated as in Example 16. The die/source temperature was 71° C, and the ambient temperature was 25° C, giving a thermal resistance value of 8.3 °C/watt.

It will thus be seen that the injection molded heat sink provides substantially the same degree of heat dissipation as the larger and considerably heavier cast magnesium heat sink of the prior art.

It will be apparent that the invented molded thermal management devices represent a substantial advance in the art and provide significantly improved materials for use in thermal management applications. The thermally conductive resin formulations used in forming the devices of this invention are readily fabricated using conventional processing means, and are generally tough materials having excellent mechanical properties and good dimensional stability. These improved thermally conductive resin molding compounds may find wide application for use in fabricating thermal management components.

It will thus be seen that the thermal management devices of the invention may be described as comprising a heat pipe together with a molded heat sink, wherein the heat sink component is preferably insert molded with the heat pipe to form a thermal management device having an integral unitary construction. The thermally conductive heat sink component may be further characterized as molded from filled thermoplastic or thermoset molding compounds having, depending upon the amount of conductive filler in the formulation, a thermal conductivity greater than about 5 W/mK, preferably greater than about 10 W/mK, and more preferably from about 80 to as great as 600 W/mK and still more preferably from about 100 to about 450 W/mK, together with an unusually low coefficient of thermal expansion, again depending upon the type and level of conductive filler, of generally less than 10 ppm/°C. The filled thermoplastic injection molding compounds employed in the more preferred embodiments of the invention may be further described as comprising from about 80 to about 20 wt%, preferably about 50 to about 20 wt% of a thermoplastic LCP resin and about 20 to about 80 wt%, preferably about 50 to about 80 wt% carbon fiber, said carbon fiber having a thermal conductivity greater than about 600 W/mK, preferably greater than about 750 W/mK, more preferably greater than about 900 W/mK, and still more preferably greater than 1000 W/mK.

It will be understood that the filled resin formulations may further comprise such plasticizers, processing aids, stabilizers and the like as are conventionally used in the resin compounding and molding resin arts. The formulations are particularly suited for use producing thermal management devices for electrical and electronic use, where the art has lacked suitable, readily-fabricated materials with high thermal conductivity.

Further modifications and variations will be readily apparent to those skilled in the resin arts. For example, it will be readily understood by those skilled in the art that a wide variety of thermal management devices may be designed employing a plurality of heat pipe components embedded in

heat sink, including heat spreader or thermal plane, components in an insert molding operation. The use of further or post-molding operations are also contemplated, including overmolding the thermal management device, optionally including attached electrical or electronic components, for example to provide an attached, hermetically sealed housing. Such further embodiments and modifications
5 will be seen to fall well within the skill of those engaged in the art and thus will be understood to lie within the scope the invention as defined by the appended claims.



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Claims:

1. A thermal management device comprising at least one heat pipe and a molded heat sink in thermal communication therewith, said heat sink comprising a filled resin composition having a thermal conductivity greater than about 5 W/mK, said composition comprising from 10 to 80 wt% thermally conductive filler and from about 90 to about 20 wt% resin, based on total weight of filler and said resin.
2. A thermal management device comprising at least one heat pipe and a molded heat sink in thermal communication therewith, said heat sink comprising a filled resin composition having a thermal conductivity greater than about 10 W/mK, said composition comprising from 10 to 80 wt% carbon fiber and from about 90 to about 20 wt% resin, based on total weight of carbon fiber and said resin.
3. The thermal management device of Claim 2 wherein said resin is a liquid crystal polymer.
4. The thermal management device of Claim 2 wherein said resin is a thermoset resin.
5. The thermal management device of Claim 2 wherein said resin is a thermoplastic resin.
6. A thermal management device comprising at least one heat pipe and an injection molded heat sink in thermal communication therewith, said heat sink comprising an injection moldable filled resin composition having a thermal conductivity greater than about 10 W/mK, said composition comprising from 20 to 80 wt% carbon fiber and from about 80 to about 20 wt% liquid crystal polymer, based on total weight of carbon fiber and said polymer.
7. A thermal management device comprising at least one heat pipe and an compression molded heat sink in thermal communication therewith, said heat sink comprising an compression moldable filled resin composition having a thermal conductivity greater than about 10 W/mK, said composition comprising from 20 to 80 wt% carbon fiber and from about 80 to about 20 wt% thermoset resin, based on total weight of carbon fiber and said resin.
8. The device of Claim 2 wherein said carbon fiber is pitch-based carbon fiber having a thermal conductivity greater than about 300 W/mK.
9. The device of Claim 2 wherein said carbon fiber is pitch-based carbon fiber having a thermal conductivity greater than about 600 W/mK.
10. The device of Claim 2 wherein said composition has a thermal conductivity in the range of from about 15 W/mK to about 600 W/mK.



11. The device of Claim 9 wherein said carbon fiber has a thermal conductivity greater than about 1000 W/mK.
12. The device of Claim 9 wherein said carbon fiber has a thermal conductivity in the range of from 600 to about 1800 W/mK.
- 5 13. A thermal management device according to Claim 1 wherein said device is insert molded to provide a unitary construction having said heat pipe component imbedded in said molded heat sink component.
14. A thermal management device according to Claim 2 wherein said device is insert molded to provide a unitary construction having said heat pipe component imbedded in said molded heat sink
10 component.
15. A thermal management device according to Claim 4 wherein said thermoset resin is selected from the group consisting of: epoxy resins, cyanate resins, thermoset polyesters and phenolic resins.
16. A thermal management device according to Claim 5 wherein said thermoplastic resin is selected from the group consistitng of: polyamides, polyphthalamides, acrylonitrile butadiene styrene
15 resins, polycarbonates, polyaryl ether resins, polyphenylenesulfide resins, polysulphones and polyethersulfones.

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