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# A REVIEW ON POLYMER HEAT SINKS FOR ELECTRONICS COOLING APPLICATIONS

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*Abstract. The substitution of metallic materials by polymers in heat transfer applications allows reduction of weight and cost of components and is also a chemically and fouling resistant alternative. Although polymers are already used in heat exchangers, their low thermal conductivity is still considered the main limitation for electronics cooling applications. Recent advances in manufacturing polymeric matrix composites together with modern processing techniques have made it possible to overcome the problem of reduced conductivity through the addition of highly conductive reinforcements and the fabrication of thin walls, reducing the overall thermal resistance of heat sinks fabricated with these materials. In this review, some desirable characteristics of polymers are highlighted, as well as the current state of the art of polymer matrix composites. Numerical and experimental works related to polymeric and composite heat sinks for electronics cooling applications are presented, reporting their achieved thermal performance and the advantages and limitations in relation to metallic materials. A shortage of experimental works related to polymeric microchannel-based heat sinks is identified, which is an interesting topic to be explored in future investigations.*

## 1. INTRODUCTION

Thermal management of electronic equipment is an active area of research, considering that heat dissipation in electronic components has gone up many folds with every new design. The heat generated by electronic circuitry must be dissipated to prevent immediate failure and improve long-term reliability (Baby and Balaji, 2012). Several cooling technologies have been used in the past years for electronic thermal management. The use of fins to enhance air-cooling is the simplest and effective heat sink (HS) structure under the cost, space and weight constraints (Shih and Liu, 2004).

Another approach consists of microchannels-based heat sinks, which can dissipate higher heat fluxes than conventional finned heat sinks. According to Ribatski *et al*. (2007), the use of small hydraulic diameter channels can provide a much larger contact area with the cooling fluid per unit of volume, improving the heat transfer coefficient. These heat sinks were first proposed by Tuckerman and Pease (1981), who developed and evaluated a heat sink with 50 x 300 $\mu m^2$ rectangular microchannels, using water as working fluid.

Further benefits can still be achieved with convective boiling heat transfer mechanism inside microchannels, such as enhancement of the heat transfer coefficient and reduction of temperature gradients in comparison with single-phase flow. These attributes have made flow boiling-based heat sinks a prime contender for compact and lightweight cooling systems in satellites, avionics, and portable computers, for example (Qu and Mudawar, 2004).

Materials that are often employed in thermal applications are metals due to their high thermal conductivity and mechanical resistance. In particular, heat sinks are usually fabricated in copper, aluminum, or silicon. Nevertheless, the high density and electric conductivity of conventional metals, in addition to the reduced corrosion and fouling resistances have led researchers to study alternative materials for thermal applications.

Engineers at DuPont were the first to successfully design and manufacture plastic heat exchangers in 1965 (Githens *et al*., 1965 *apud* Cevallos *et al*., 2012). The DuPont plastic heat exchanger (PHX) design consisted of many small-diameter (2 to 6 mm), thin walled (about 5 to 15 percent of the diameter) polytetrafluorethylene (PTFE or Teflon) tubes, bundled and joined at each end to form a rigid honeycomb structure. The overall obtained heat transfer coefficients ranged from 34 W/m²K, for an air/gas exchanger, to 560 W/m²K for water/water exchangers (Cevallos *et al*., 2012).

Development in materials science and engineering has paved the way to overcome some typical complications associated with using polymers in heat exchangers. Adding suitable fillers that possess high thermal conductivity can increase the overall thermal conductivity of the composite by forming a percolating network for thermal transport (Hussain *et al.*, 2017). This expanded the applications of plastic materials to the fields of solar water heating (Wu *et al.*,

2004), automotive radiators (Krásný *et al.*, 2016), water desalination (Song *et al.*, 2010), condensing boilers (Trojanowski *et al.* 2016), and electronics cooling (Lee *et al.*, 2004).

Since the success obtained by DuPont with their plastic heat exchanger, a large amount of work related to PHXs was published, as reported by Joen *et al.* (2009), Chen *et al.* (2016) and Hussain *et al.* (2017). However, the use of polymeric materials in heat sinks does not present the same development of the PHXs. Only few works related to finned heat sinks and even less dealing with microchannels can be found. In this context, this paper presents a brief review of polymers characteristics and works regarding thermally conductive polymeric composites, then an overview of published works related to polymeric heat sinks (PHSs) is exposed, highlighting the main employed materials and the reported advantages of the studied devices. Finally, some topics worth of further investigation are identified, revealing much that can be investigated into polymeric heat sinks.

## 2. POLYMERS IN THERMAL APPLICATIONS

Polymers are long chain organic materials resulting from polymerization, a chemical reaction of smaller units called monomers. Although the use of polymeric materials in thermal applications is recent, polymers have been used for many years in various industrial segments because of their ease of manufacturing, low weight and low cost.

Corrosion and chemical resistance of polymers allowed engineers to substitute high cost resistant metal alloys like Cu-Ni and titanium, commonly used in corrosive fluids (eg. seawater) applications (Chen *et al.*, 2016). In addition, due to the low surface energy of polymers, these materials have higher fouling resistance than metals (Kazi *et al.*, 2010), which increases the life cycle of PHXs and reduces maintenance costs (cleaning and pumping). Low surface energy also provides to polymers the ability to maintain a long-term durability of dropwise condensation (Cheng and Van Der Geld, 2005), which raises the condensation heat transfer coefficient.

The combination of low material cost and low density makes PHSs and PHXs economical alternatives for metallic ones. Furthermore, because of their high electrical resistivity, avoiding electric interferences, polymers have been recently used to manufacture heat sinks for electronics cooling.

Another interesting characteristic inherent to thermoplastic polymers is that they are recyclable, which makes their use attractive in a sustainable context. Moreover, according to El-Dessouky and Ettouney (1999), from an environmental point of view, the energy consumed in the production of a unit of mass of plastic is two times lower than common metals (stainless steel or aluminum). This allows avoiding the consumption of fossil fuels, reducing the emission rates of greenhouse gases and air pollutants.

Reduced values of Young's modulus, mechanical strength and mainly thermal conductivity of polymers have limited the use of these materials in HS and HX designs. The thermal conductivity ($k$) of polymers is about 0.1-0.5 W/m.K, values considerably lower than those of copper (400 W/m.K) and aluminum (235 W/m.K), for example. Table 1 presents a list of some polymeric materials commonly used and their thermal conductivities. Values presented in Tab. 1 were obtained from Joen *et al.* (2009) and Han and Fina (2011).

Table 1. Thermal conductivities of some polymers used in heat exchangers.

| Material | $k$ at 25ºC (W/m.K) |
|---|---|
| Low density polyethylene (LDPE) | 0.3 |
| High density polyethylene (HDPE) | 0.44 |
| Polypropylene (PP) | 0.11 |
| Polystyrene (PS) | 0.14 |
| Polymethylmethacrylate (PMMA) | 0.21 |
| Nylon-6.6 (PA66) | 0.26 |
| Poly(ethylene terephthalate) (PET) | 0.15 |
| Poly(butylene terephthalate) (PBT) | 0.29 |
| Epoxy | 0.19 |
| Polydimethyl siloxane (PDMS, silicone) | 0.25 |
| Polyimide (PI) | 0.11 |
| Polyphenylene Sulfide (PPS) | 0.3 |
| Polyoxymethylene (POM) | 0.29 |

In order to overcome the low thermal conductivity issue of polymers, some approaches to enhance heat transfer have been proposed, such as reducing the wall thickness of heat exchangers, increasing heat transfer area, and using complex geometries. The ease of manufacturing of polymeric materials enabled these approaches. Another alternative is to improve the thermal conductivity by adding reinforcements (or fillers) to polymers, obtaining composite materials.

## 3. THERMALLY CONDUCTIVE COMPOSITES

The addition of thermally conductive fillers in polymeric matrices providing heat-conducting paths through the composite allowed surpassing the difficulties associated with the use of plastics in heat transfer applications. These fillers could be metals, carbon, ceramics or mixtures of them, creating hybrid composites.

Recent advances in synthesis, processing and microanalysis are enabling the routine production of well-characterized materials with structures that vary several nanometers in length range (Cahil *et al.*, 2003). These nanoscale materials have been used in the last years as fillers to polymeric matrix nanocomposites because of their reinforcing efficiency provided by their high aspect ratios. Typical nanomaterials used as composite fillers include, nanoparticles, nanotubes, nanofibers, fullerenes and nanowires (Hussain *et al.* 2006).

Hussain *et al.* (2017), consider the following factors as dominant in the composites properties: filler surface treatment and interfacial structure, filler aspect ratio, alignment and packing structure, filler volume fraction, particle size, shape, purity, polydispersity and intrinsic conductivity.

Table 2 presents thermal conductivity values of composites obtained experimentally by several authors in this decade, as well as the employed matrix and reinforcement materials and their relative content. The reported experimental data refer to measurements at room temperature (~ 25°C), except when the information was not provided by the authors.

It is possible to note the predominance of the use of epoxy resin as matrix material, this can be attributed to the low cost of this material and also because it is commonly used in electronic applications. In relation to reinforcement materials, aluminum-based materials, as aluminum oxide ($Al_2O_3$) and aluminum nitride (AlN), were used in a large number of the works presented in Tab. 2. This can be related to the low cost of these materials compared with metal and carbon-based reinforcements and also because aluminum oxide is inert to most chemical agents.

Table 2. Characteristics of polymeric composites investigated in recent experimental works.

| Reference | Matrix | Reinforcement | Filler dimensions (µm) | Filler content (%) | Thermal conductivity (W/m.K) |
|---|---|---|---|---|---|
| Zhao and Ye (2010) | POM | MWCNTs (pure and PEG-substituted amine modified) | D: 0.02 – 0.04 | 0.5 wt (pure) 0-0.12 vol (modified) | 0.45 0.36-0.78 |
| Moreira *et al.* (2011b) | Polyester | $Al_2O_3$ particles CuO particles | D: 0.03-0.04 D: 0.03-0.05 | 0-10 vol | 0.157-0.27 |
| Sun *et al.* (2011) | Silicone | ZnO particles | D: 0.028-0.132 | 0-15 wt | 0.35-0.65 |
| Cui *et al.* (2011) | Epoxy | MWCNTs MWCNTs ($SiO_2$ coating) | D: 0.05 L: 5-10 | 0.5-1 wt | 0.144-0.213 0.218-0.240 |
| Teng *et al.* (2011) | Polyactide | Vapor-grown carbon nanofibers | D: 0.1 L: 10-20 | 0-10 vol | 0.19-1.24 |
| Hong *et al.* (2011) | PDMS | MWCNTs; $Al_2O_3$ particles | D: 0.01-0.05 L: 10-50 | 0-10 wt | 0.509-1.142 |
| Shahil and Balandin (2011) | Epoxy | Graphene layer | T: 0.00035 | 0-10 vol | 0.2-5.10 |
| Carlberg *et al.* (2012) | Polyimide | Ag particles | - | - | 27 |
| Zha *et al.* (2012) | Silicone | $Si_3N_4$ particles $Al_2O_3$ particles | D: 0.3-3 D: 0.5-3 and 0.02 | 0-30 vol[1] | 0.16-1.62 |
| Chen *et al.* (2012) | PMMA | $Al_2O_3$ powder | D: 0.04; 0.4 | 20-40 vol | 0.48-1.40 |
| Tang *et al.* (2012) | Polyester | Graphene powder | D: < 20 | 0-1.45 vol | 0.19-0.542 |
| Yu *et al.* (2012) | Epoxy | AlN powder | D: 6.01 | 40-60 vol | 1-2.7 |
| Park *et al.* (2012) | PPS | MWCNTs BN powder | D: 0.02-0.1 e L:10 D: 0.5-30 | 0-1 wt 0-50 | 0.31-1.74 |
| Chun *et al.* (2013) | Polystyrene+ polyisopropene | MWCNTs Ag particles Ionic liquid treatment | D: 0.01 D: 0.035 | 1 wt 51 wt 2.6 wt | 8.7 |
| Fukushima *et al.* (2013) | Epoxy | AlN layer | L:10000 (square); T: 400 | 53-68 vol | 2.50-7.13 |
| Lee *et al.* (2013) | Epoxy | AlN particles | D: 0.040 and 0.2 | 0-20 wt | 0.85-2.22 |
| Zhou *et al.* (2014) | Epoxy | AlN (modified with PI) | D: 1 | 10-40 wt | 1.32 - 2.03 |

Table 2 cont. Characteristics of polymeric composites investigated in recent experimental works.

| Reference | Matrix | Reinforcement | Filler dimensions (µm) | Filler content (%) | Thermal conductivity (W/m.K) |
|---|---|---|---|---|---|
| Chiu *et al.* (2014) | Silicone | Si/AlN particles | D: 5 | 56 wt | 0.36-0.83 |
| Chung and Lin (2016) | Epoxy | BN particles (silane treatment) | D: 3.6; 10.6 | 10-80 vol | 0.41-7.47 |
| Li *et al.* (2016) | Epoxy | Flake Graphite silica coating | D: 38 | 0-50 wt | 0.19-3.56 |
| Moreira *et al.* (2016) | Polyester Epoxy | $Al_2O_3$ particles | D: 0.027-0.2 | 0-10 vol | 0.16-0.31 0.2-0.39 |
| Kim and Kim (2016) | Epoxy | BN particles with $Fe_3O_4$ on the surface | - | 0-40 vol[1] | 0.2-5.4 |

[1] Varying the proportion of the fillers in the hybrid composite; MWCNTs: Multi-walled carbon nanotubes; D: diameter, L: length, T: thickness

In general, the increase of the relative amount of reinforcement provides higher thermal conductivities, behavior reported in the experimental works presented in Tab. 2. However, Yang and Gu (2010), reported a reduction in thermal conductivity for filler volume fractions higher than 20% in epoxy/multi-walled carbon nanotubes (MWCNTs) composites. This phenomenon is probably associated with the difficulty of mixing large amounts of nanofillers, forming large agglomerates that may contain bubbles or air voids that lead to lower thermal conductivities. Yang and Gu (2010) have solved this issue with the addition of silicon carbide spherical nanoparticles modified with silane coupling agent to the epoxy/MWCNTs composite, which reduced the viscosity of the composite (pre-curing) and favored the breaking of large agglomerates.

In general, the more conductive the reinforcing material is, smaller is the required volumetric fraction to achieve a significant increase in the thermal conductivity of the composite. However, it is possible to find in the literature experimental results that do not agree with this tendency, as reported by Weidenfeller *et al.* (2004), Lee and Yu (2005) and Kong *et al.* (2014).

Weidenfeller *et al.* (2004) obtained thermal conductivities varying from 0.79 to 2.32 W/m.K for 15 to 35% volume fraction of Cu, and from 1.48 to 2.50 for 15-30% of talc in PP matrix composites. Although the thermal conductivity of copper is forty times higher than that of talc, PP/talc composite was more thermally conductive, possibly due to an alignment of the talc fibers in the polymeric matrix during the injection molding, resulting in higher interconnectivity filler-matrix. Lee and Yu (2005) reported that for volumetric fractions of reinforcement varying from 0 to 20%, the thermal conductivity of an epoxy/boron nitride composite was higher than that of epoxy/diamond composite, even though the thermal conductivity of boron nitride is 300 W/m.K, about 6.5 times lower than diamond's.

An interesting effect was reported by Kong *et al.* (2014) in their experimental work with PDMS/graphite nanoplatelets-MWCNTs hybrid composite. The authors evaluated the thermal conductivity for a fixed weight fraction of reinforcement (4 wt%) and a variable proportion of graphite nanoplatelets and MWCNTs. The measured conductivity was higher than the value for 4 wt% of graphite nanoplatelets. Contrarily to expected, the addition of MWCNTs, a less conductive reinforcement than graphite nanoplatelets, increased the conductivity of the composite, due to the formation of an interconnected hybrid network between both fillers, facilitating the heat conduction, as illustrated in Fig. 1.
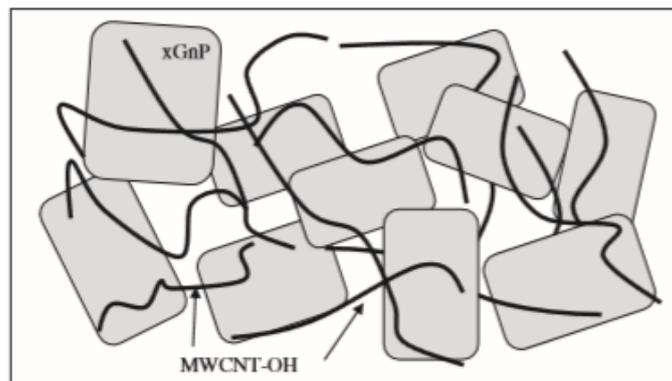


Figure 1. Illustration of interconnected hybrid network between graphite nanoplatelets (xGnPs) and multiwalled carbon nanotubes functionalized with hydroxyl groups (MWCNTs-OH). (Kong *et al.,* 2014)

The effect of surface treatment was evaluated by Chiu *et al.* (2014). The authors measured the thermal conductivity of silicone rubber filled with silicon/aluminum nitride hybrid fillers fabricated in air, argon, $N_2$ and $NH_3$ atmospheres. The highest thermal conductivity was obtained for argon atmosphere, because of the formation of SiC in the surface of the reinforcement particles, which provided a high aspect ratio, touching each other easily inside the matrix and creating a thermally conductive network. Recently, Chung and Lin (2016) reported that surface treatment of boron nitride (BN) particles with 3-glycidoxypropyltrimethoxysilane (GPTMS) increased the thermal conductivity of epoxy/BN composites by 7.7%−35.4%. This was explained by the fact that the surface treatment enhances the bond between filler particles and matrix molecules through GPTMS bridges, thus reducing voids that actuate as thermal barriers.

The addition of coated reinforcements to a polymeric matrix in order to enhance the thermal conductivity was reported by Cui *et al.* (2011) and Zhou *et al.* (2014). Cui *et al.* (2011) obtained a 14% increase in the thermal conductivity of an epoxy/MWCNT composite (1 wt%) by the addition of $SiO_2$-coating for the carbon nanotubes surface. Silica coating not only provided a better interaction between matrix and filler, facilitating heat conduction, but also acted as electrical insulation, reducing the electric conductivity. The same phenomenon was reported by Zhou *et al.* (2014), by the addition of polyimide during the surface treatment of aluminum nitride for epoxy/aluminum nitride composites.

Sun *et al.* (2011), Chung and Lin (2016) and Moreira *et al.* (2016) evaluated the influence of the size effect of fillers on the thermal conductivity of micro and nanocomposites, reporting that larger particles provided higher conductivities. According to Sun *et al.* (2011) and Chung and Lin (2016) particles with larger sizes show fewer contact points and a smaller contact area with the matrix which reduces the interfacial thermal resistance.

A different effect was reported by Lee *et al.* (2013), in which the addition of nanoscale AlN particles enhanced the thermal conductivity of an epoxy/AlN composite. For a fixed weight fraction of 15% of AlN, the thermal conductivity raised from 1.25 to 2.2 W/mK with the variation of the ratio between nanoscale AlN (40 nm) and microscale AlN (20 μm) from 0 to 0.333. This effect is probably related to the formation of thermal conductive pathways by the addition of smaller size particles, improving the heat transport between larger particles. Zha *et al.* (2012) also reported this effect by the addition of nano-sized $Al_2O_3$ and micro-sized $Si_3N_4$ in a silicone matrix.

For electronics cooling applications with high heat fluxes to be dissipated, the thermal conductivity variation of the composite as a function of the temperature must be taken into account. Moreira *et al.* (2011b), Shahil and Baladin (2011), Chen *et al.* (2012) and Chun *et al.* (2013) reported different behaviors of the temperature dependence of the thermal conductivity. Moreira *et al.* (2011b) observed that for temperatures varying from 0 to 50ºC, the thermal conductivity of polyester-based composites remains almost constant. For the epoxy/graphene composites manufactured by Shahil and Baladin (2011), the thermal conductivity was reduced with the increase of temperature, in the range of 20-115ºC. This effect was more accentuated for higher filler loadings due to the increase of the amount of crystalline regions in the composite, which are temperature dependent.

An opposite effect was reported by Chun *et al.* (2013) in which the thermal conductivity of the fabricated hybrid polystyrene-polyisopropene/MWCNTs-Ag composite increased from 5.75 to 8.7 W/mK with the temperature increasing from -190 to 45ºC. In the experimental results obtained by Chen *et al.* (2012), the thermal conductivity of a PMMA/$Al_2O_3$ composite also increased with the temperature, but this effect was only present in the range of 3-150 K. After that, the conductivity remained almost constant with the temperature increase.

Dispersion and alignment are dependent of the processing method and play a key role in the thermal conductivity of composites. Moreira *et al.* (2011a) evaluated the influence of four different dispersion methods (manual, ball mill, magnetic stirrer and mechanical stirrer) in the thermal conductivity of polyester/$Al_2O_3$ and polyester/$Fe_2O_3$ composites, finding that ball milling and magnetic stirrer provided higher values of this property.

Alignment of fillers inside the polymeric matrix provides higher thermal conductivity in the direction of this alignment. This effect can be used to enhance the thermal conductivity of a heat sink in the direction of the heat flux, dissipating high heat fluxes without raising the temperatures above acceptable operation values. Kim and Kim (2016) vertically aligned boron nitride particles coated with iron oxide ($Fe_3O_4$) in an epoxy matrix in the direction of heat transfer through a magnetic field. For a 30% volumetric fraction of BN, the thermal conductivity increased to 3,445 W/mK due to the particle alignment, which is 96% higher than that observed for the composite with dispersed particles (1,765 W/mK).

## 4. POLYMERIC AND POLYMER-MATRIX COMPOSITES HEAT SINKS

Although the experimental values of thermal conductivity of polymeric composites found in literature are still relatively far from the thermal conductivity of metallic materials, a great enhancement in this property can be achieved using low volume fractions of highly conductive fillers. This has been a fundamental advance to enable the use of plastic materials in electronics cooling applications.

According to Danes *et al.* (2003), thermal conductivities in the range of 1.3-2 W/mK and 2-4 W/mK are adequate for mechanical and electronic applications, respectively. Huang *et al.* (2012) and Zhuang *et al.* (2016) confirmed this statement based on numerical simulations. Therefore, it is not necessary to obtain thermal conductivities for composites

in the same order of values of metallic materials. As presented in Tab. 2, composites with thermal conductivity in the range suitable for applications in electronics have already been manufactured.

Table 3 presents a summary of recent works related to polymeric and polymer matrix composites heat sinks available in the literature. It is possible to notice a shortage of works related to heat sinks based on microchannels, with only three experimental studies, and one of them also used metallic materials and manufactured a hybrid heat sink. However, a significant amount of works related to finned heat sinks in natural or forced convection, was found.

Polymers used in the manufacture of the analyzed heat sinks varied, and it is not possible to identify a trend in the use of a specific material. Epoxy, p-phenylene polysulfide (PPS), parylene, polyamide (PA), Polydimethyl siloxane (PDMS) and polyimide (PI) were the polymers used in the analyzed works, while the fillers varied between copper powder, carbon nanotubes, graphene and graphite. None of the works used ceramic fillers, which is probably due to their low thermal conductivity, making necessary the addition of a large amount of reinforcement, altering the characteristics of the polymer matrix.

Table 3. Summary of polymeric heat sinks used in electronics cooling applications.

| Reference | Heat sink | Material | Analysis | Dimensions | Operational conditions | Comments |
|---|---|---|---|---|---|---|
| Chen *et al.* (2003) | Rectangular fins | Epoxy/ graphite (376 W/mK in-plane, 7 W/mK out-of-plane) | Numerical | Base area: 100 cm² Base th: 8 mm 25 fins Fin sp: 3.125 mm Fin th: 1 mm Fin lg: 42 mm | Power: 200 W Air mass flow: 10-60 cm³/min | TR: 0.097-0.27 K/W BT: 54.27ºC |
| Marotta *et al.* (2003) | Rectangular fins | Epoxy/ graphite (370 W/mK in-plane, 7.5 W/mK out-of plane) | Numerical Experimental | Base area: 122.53 cm² 78 fins Fin sp: 0.76 mm Fin th: 0.64 mm Fin lg: 45-50 mm Fin wt: 113 mm | Power: 640 W Air mass flow: 70-135 cm³/min | TR: 0,03-0.042 K/W Pressure drop: 0.077-0.354 kPa |
| Lee *et al.* (2004) and Kang *et al.* (2005) | Rectangular microchannels | PDMS (0.18 W/mK) | Experimental Numerical | Base area: 56 mm² 5-25 channels Wall th: 80-250 μm Channels sp: 250-1250 μm Channels hg: 200 μm Channels wt: 170-1000 μm | Power: 2-8 W Water flow rate: 0.07-0.25 cm³/s | BT: 40-140ºC Pressure drop: 0.5 - 10kPa TR: 7-50 K/W |
| Bahadur and Bar-Cohen (2005) | Pin fins | Commercial enhanced PPS - CoolPoly (20 W/mK) | Numerical Experimental | Base area: 31.36 cm² Base th: 3 mm 41 fins Fin diam: 0.398 cm (base), 0.29 cm (top) Fin lg: 1.8 cm | Power: 1-7 W | BT: 35-95ºC HTC: 24-29 W/m²K |
| Barba *et al.* (2005) | Circular microchannels | PA (0.25W/mK) | Numerical | 74 channels ID: 200 μm Wall th: 90 μm Channels lg: 55 mm Heated lg: 25 mm | Power: 0.58-8.79 W Nitrogen mass flow rate: 40-315 mg/s Helium mass flow rate: 6-77 mg/s Inlet temperature: 33ºC | TR: 4-21 K/W (helium), 5-30 K/W (nitrogen BT: 35-240ºC (helium) BT: 38-120ºC (nitrogen) |

Table 3 cont. Summary of polymeric heat sinks used in electronics cooling applications.

| Reference | Heat sink | Material | Analysis | Dimensions | Operational conditions | Comments |
|---|---|---|---|---|---|---|
| Koşar (2010) | Rectangular microchannels | Polyimide | Numerical | Channel hg: 200 µm Channel wt: 200 µm Channel lg: 5 cm Base th: 100-1000 µm | Heat flux: 50-250 kW/m² Water Re: 50-1600 Inlet temperature: 27ºC | Wall temperature: 67-122ºC |
| Icoz et al. (2010) | Rectangular fins | Commercial enhanced PPS - CoolPoly (20 W/mK) | Experimental Numerical | Base area: 0,015 cm² 25 fins Fin wt: 50 mm Fin lg: 30 mm Fin th: 2 mm | Power: 30 W | TR: 1.72 W/K Efficiency: 0.87 |
| Heinle and Drummer (2010) | Rectangular fins | PA/Cu powder, 10-40% vol (1.1-4.5 W/mK) | Experimental | Base area: 16 cm² 3 fins Fin th: 2.5 mm | Power: 3-7 W Air velocity: 1-5 m/s | HTC: 7-29 W/m²K BT: 45-140ºC (40% vol Cu) |
| Koyuncuoğlu et al. (2010) | Rectangular microchannels (forced convection) | Parylene Copper | Experimental | 10 channels; Channels wt: 100 and 200 µm Channels hg: 20 µm; Channel lg: 1 cm (heated); | Heat flux: 0.5 – 12.5 W/cm²; Water flow rate: 100-300 µl/min; Inlet temperature: 26.4ºC | BT: 29.8 – 55.1 ºC |
| Kozola et al. (2010) | Circular microchannels (forced convection) | Epoxy | Experimental | 10 and 24 channels; Channels diam: 200 and 410 µm; Channels sp: 800 and 1600 µm (center to center); Channels lg: 18,4 mm | Water flow rate: 1 – 10 ml/min; Inlet temperature: 20ºC | BT: 80ºC; Mean steady-state temperature: 30 – 48ºC |
| Huang et al. (2012) | Rectangular fins (radially positioned) | Polymer not informed (1 W/mK) | Numerical | Fin th: 1.1-4.5 mm Fin sp: 1-2 mm Fin surface emissivity: 0.2 | Power: 7 W | BT: 91.4-97.5ºC |
| Zhuang et al.(2016) | Rectangular fins | - | Numerical | Base area: 49 cm² Base th: 1 mm Fin lg: 0.1-0.5 mm Fin th: 0.1-0.5 mm Fin sp: 0.1-0.5 mm | | BT: 45.6-60.8 ºC TR: 4.15-7.2 K/W |
| Cho et al. (2016) | Rectangular fins (radially positioned) | PA/Graphene, 0-5%wt (0.27-5.5 W/mK) | Experimental | - | Power: 10 W | BT: 81ºC (for 5%wt of graphene) |

sp: spacing (between fins or channels); th: thickness; lg: length; wt: width; diam: diameter; hg: height TR: Thermal resistance; BT: Base temperature; HTC: heat transfer coefficient

In general, the thermal conductivity of the materials used in the heat sinks presented in Tab. 3 are in the same order of magnitude as those of Tab. 2, except the epoxy/graphite composites simulated by Chen et al. (2003) and used by Marotta et al. (2003). Chen et al. (2003) studied the influence of the anisotropy of this composite material on the thermal behavior of a rectangular fin heat sink in air forced convection. Figure 2 shows the temperature variation along the heat sink for two different orientations of the plane of high thermal conductivity of the composite. The high temperatures at the bottom of the heat sink observed in Fig. 2a are due to the reduced thermal conductivity in the direction of the heat flux (Z).

Bahadur and Bar-Cohen (2006) have also evaluated the influence of the thermal conductivity anisotropy in heat conduction. They performed computational simulations of a cylindrical pin fin manufactured with a highly conductive

material in the axial direction. According to Bahadur and Bar-Cohen (2006), the obtained temperature profiles diverge from an isotropic material with the increase of the radial Biot number and become similar for higher fin aspect ratio and thermal conductivity ratio (radial/axial). Therefore, the use of non-isotropic materials can be a viable alternative it's the direction with higher thermal conductivity coincides with the direction of the heat flux.
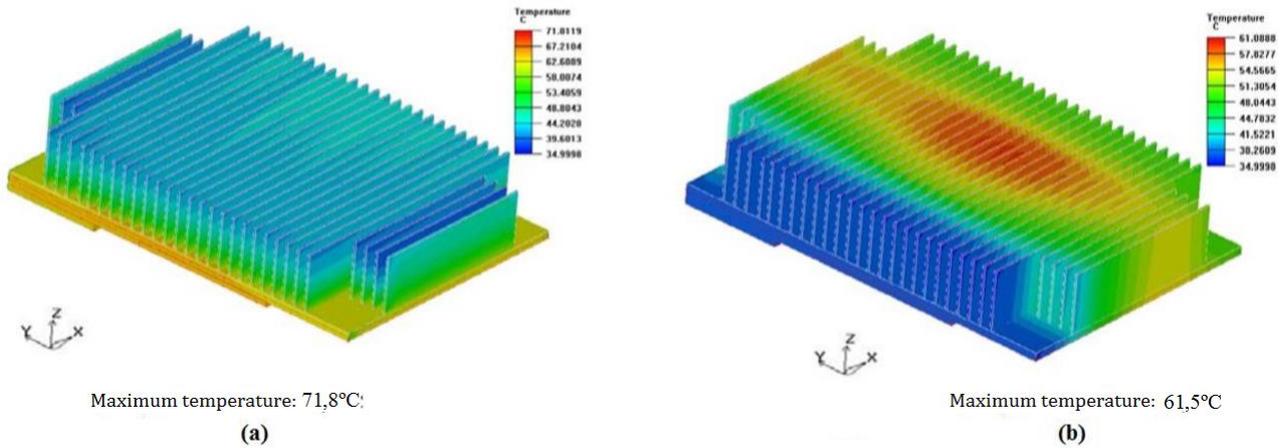


Maximum temperature: 71,8°C;

(a)

Maximum temperature: 61,5°C

(b)

Figure 2. Temperature variation along an anisotropic material heat sink (Q = 30 W). (a) Plane of high conductivity X-Y; (b) Plane of high conductivity Y-Z (Chen *et al*., 2003)

Marotta *et al*. (2003) performed an experimental analysis of an epoxy/graphite rectangular finned heat sink in forced air convection. For a heating power of 640 W and 0.64 mm fins thickness, the minimum thermal resistance measured by the authors for 135 m³/min of air flow rate was 0.03 K/W, smaller value than that achieved with an identical heat sink made of aluminum and practically the same obtained with copper, but with a reduction of 21 to 25% of mass.

Heinle and Drummer (2010) evaluated the influence of the amount of copper reinforcement on the temperature distribution of a Polyamide 6 (PA6) polymer matrix heat sink in air natural convection with a 3 W heat transfer rate. The temperature at the base of the heat sink reduced from 100°C to 75°C with increasing the volumetric fraction of copper from 10% to 40%, as captured in the images of Fig. 3.
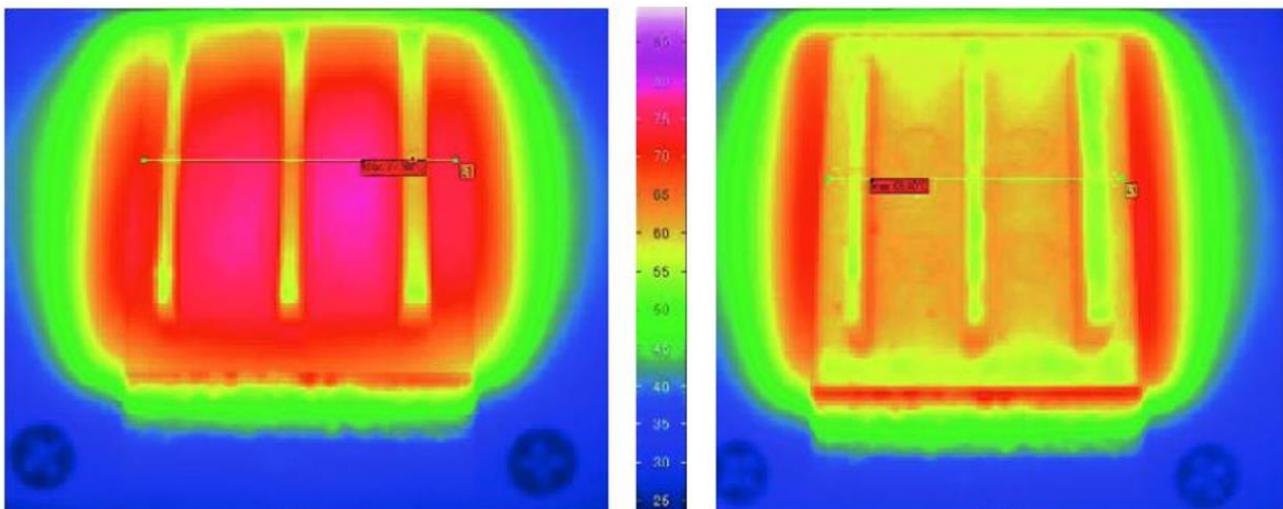


Figure 3. Temperature distribution using thermal camera (Q = 3W, natural convection), (a): PA6 heat sink with 10% vol copper, (b) PA6 DC with 40% vol copper. (Heinle and Drummer, 2010).

Huang *et al.* (2012) and Cho *et al.* (2016) evaluated the thermal performance of rectangular finned heat sinks in a Light Emitting Diode (LED) cooling application. The extrusion process facility of polymers allowed Huang *et al.* (2012) to manufacture more fins, distributed through all the heat sink extension. Figure 4 compares two heat sinks fabricated with aluminum and polymeric material, it is possible to note that the polymer heat sink provides a higher heat transfer area.
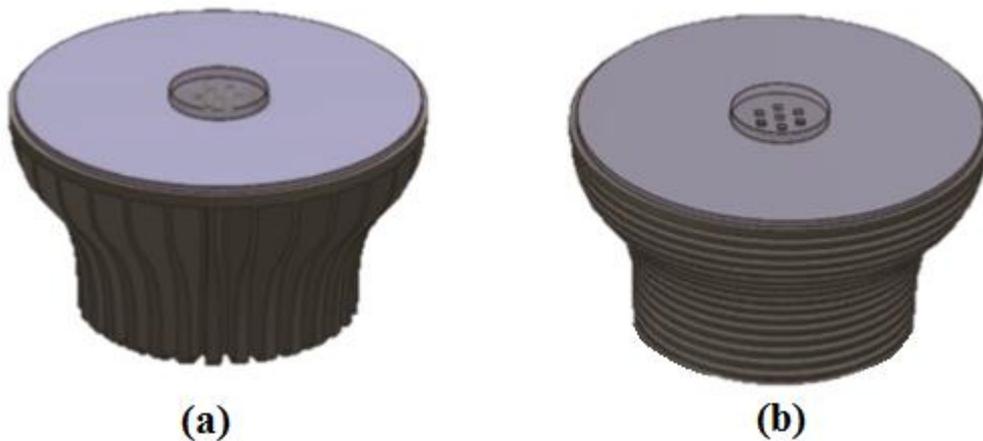
Figure 4. Heat sink geometries proposed by Huang *et al.* (2012). (a) Aluminum (b) Polymer

Cho *et al.* (2016) experimentally evaluated the performance of a PA/graphene oxide heat sink with 3 and 5% weight fractions of filler. Considering 7000 hours of use of a LED lamp, its light intensity reduced only 5% when cooled by a composite heat sink with 5% of graphene oxide and 32% when cooled by a pristine PA heat sink, indicating the influence of heat sink thermal conductivity in the lamp life cycle.

A comparative study of the thermal performance of four rectangular finned heat sinks manufactured with different materials (aluminum, enhanced PPS, carbon foam and pyrolytic graphite) was conducted by Icoz *et al.* (2010). For a heat flow of 30W applied in the base of the heat sinks, enhanced PPS presented a thermal resistance of 1.72 K/W, corresponding to a value about 43% higher than other evaluated materials. In addition, the efficiency of PPS fins was 86.7%, while the same parameter of all other studied materials was above 95%. Icoz *et al.* (2010) suggested that the use of plastic materials in heat sinks is only suitable in reduced heat flux applications, thus allowing satisfactory thermal performance with lower cost and weight reduction.

Barba *et al*. (2005) developed a three-dimensional model for thermal performance and pressure drop evaluation of a PA heat sink with circular channels for nitrogen or helium flow. These authors evaluated the reduction of heat sink thermal resistance with the increase of gas mass flow rate. For helium mass flow rate varying from 40 to 315 mg/s, the thermal resistance of the heat sink was reduced from 21 to 4 K/W and for nitrogen mass flow rate in the range of 6-77 mg/s, the thermal resistance varied from 30 to 5 K/W. These high values of thermal resistance obtained by Barba *et al*. (2005) are a consequence of the use of pristine polyamide, which has a thermal conductivity of only 0.25 W/m.K.

Koşar *et al*. (2010) evaluated the influence of the base thickness (substrate) and its thermal conductivity (Fig. 5) on the performance of microchannels-based heat sinks. These authors emphasize the importance of using low-thickness substrates in polymeric heat sinks in order to reduce the thermal conductivity and consequently the base temperature.
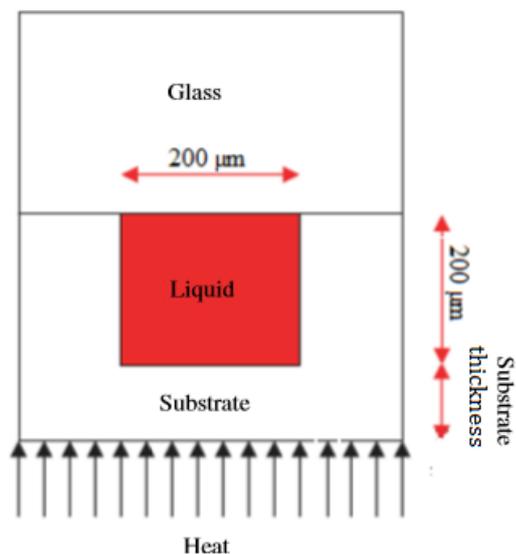


Figure 5. Cross section of a microchannel heat sink. (Koşar, 2010).

Chen *et al.* (2003) and Zhuang *et al.* (2016) proposed hybrid heat sinks designs composed by thermally conductive bases and polymeric fins. According to Chen *et al.* (2003), for heat fluxes concentrated in a specific region of the heat sink base (hot spot), this configuration allows to obtain similar performance to metallic materials. Zhuang *et al.* (2016) reported that as the fin thermal conductivity varied from 1 to 20 W/mK, the base temperature decreased by 0.05 °C, indicating reduced influence of this property in the performance of heat sinks with metallic bases.

Lee *et al*. (2004) and Kang *et al*. (2005) experimentally evaluated a rectangular microchannels (200 μm in height and variable width) heat sink manufactured with polydimethyl siloxane. Considering channel widths between 170 μm and 1 mm, the thermal resistance of the equipment can be reduced from 50 K/W to 7 K/W in applications using water as cooling fluid. For a heat transfer rate of 8 W and minimum channel width (170 μm), the surface temperature of the heat sink varied from 95 ° C to 145 ° C with pressure drop between 0.5 kPa and 10 kPa for water flow rates of 0.07 - 0.25 cm³/s. Figure 6 presents one of the heat sinks evaluated and the respective mold used in its manufacture.
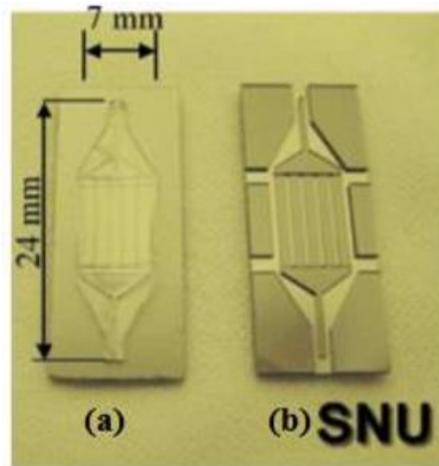


Figure 6. (a) Polymeric microchannels heat sink, (b) Mold used in manufacturing. (Lee *et al*., 2004).

Kozola *et al.* (2010) manufactured circular microchannels in two-dimensional and three-dimensional arrangements (Fig. 7) for water and polyalphaolefin (PAO) flows in a rectangular epoxy block and evaluated their performance in cooling a surface at constant temperature of 80 °C. The increase in coolant flow rate reduced the mean temperature between the channels and temperature stabilization was verified at a distance of approximately 4.9 mm from the heated base for a water flow rate of 10 ml/min. In addition, the authors also reported better fluid distribution along the channels for a three-dimensional arrangement.
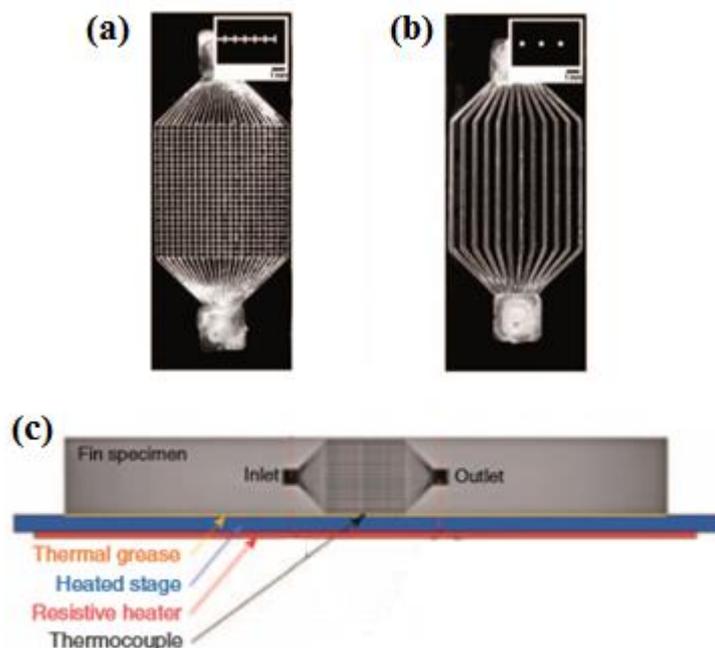


Figure 7. (a) 3D network geometry, (b) 2D network geometry, (c) Test section arrangement (Kozola *et al.*, 2010).

Koyuncuoğlu *et al.* (2010) performed an experimental analysis of a microchannels-based heat sink with parylene insulation and copper fins (Fig. 8) compatible with a complementary metal oxide semiconductor (CMOS). The use of polymeric material in the fabrication of the heat sink base ensured electrical insulation and the reduced thickness of the parylene layer (0.2 μm) avoided increasing thermal conduction resistance. For water flow rates varying from 100 to 300 μl/min with a 26.4 °C inlet temperature, the average heat flux dissipated by the proposed heat sink varied from 0.5 to 12.5 W/cm² with an average base temperature of 29.8-55.1 °C. The authors also evaluated the performance of one single microchannel fabricated with the same materials and reported dissipated heat fluxes of 113-126.7 W/cm² with base temperatures of 90.1-141.5 °C.
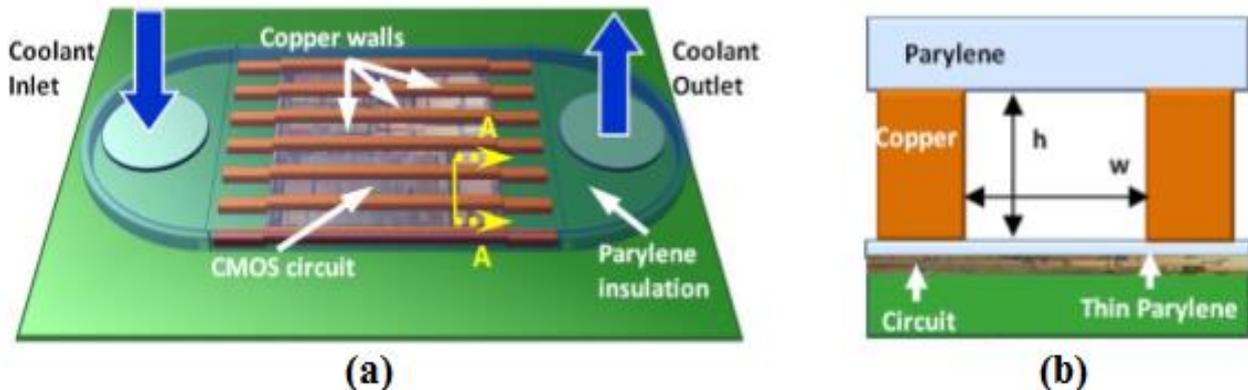


Figure 8. (a)Schematic view of the microchannel heat sink device evaluated by Koyuncuoglu *et al.* (2010), (b) Cross-section A-A.

In addition to the works presented in Tab. 3, some patents related to polymeric heat sinks were found. Krassowski and Chen (2006) proposed a heat sink with fins made of polymer matrix composite positioned on a highly conductive and anisotropic (eg graphite) base with the thermally conductive plane parallel to the plane of the base. Lin (2007) proposed the development of a hybrid heat sink with a polymeric base, eg. silicone, PVC, PP, PE, containing ends of carbon nanotube fins inserted in it, shown in Fig. 9. In this case, the base presents reduced conductivity, whereas the fins formed by carbon nanotubes are highly conductive, which apparently does not represent an advantage over the heat transfer, however, it reduces the electrical conduction, avoiding interference in electronic components, as reported by Koyuncuoglu *et al.* (2010). Other designs are presented by Sagal *et al.* (2001), McCullough (2002) and Tankala *et al.* (2011).
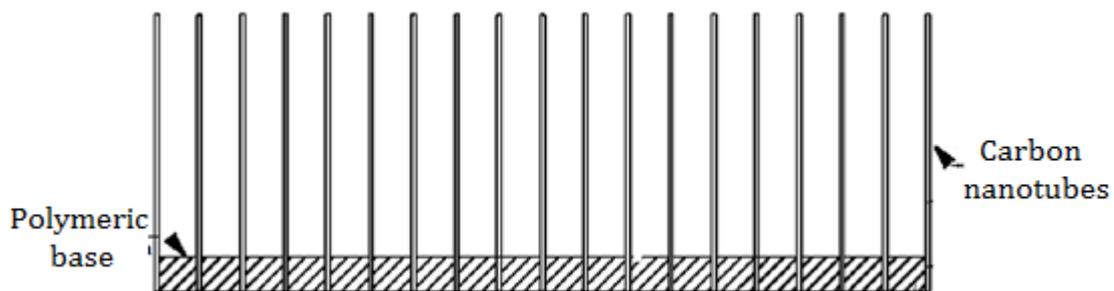


Figure 9: Schematic drawing of a heat sink with a polymeric base and carbon nanotube fins (Krassowski and Chen, 2006).

Different processes were employed in the manufacture of polymeric heat sinks. Injection process was employed by McCullough (2002) and Heinle and Drummer (2010), who also used extrusion process to produce the composite. Kozola *et al.* (2010) opted for the use of a direct write assembly method using a fugitive organic ink (Fig. 10) in the manufacture of microchannels inside an epoxy block.

Marotta *et al.* (2003) manufactured their heat sinks using pre-cast graphite and epoxy fins, positioned with the aid of spacers. Lee *et al.* (2004) and Kang *et al.* (2005) used molds (Fig.6b) to manufacture their microchannels-based heat sinks. The molten polymer added to the mold cavities was pressed and cured to acquire the desired geometry.
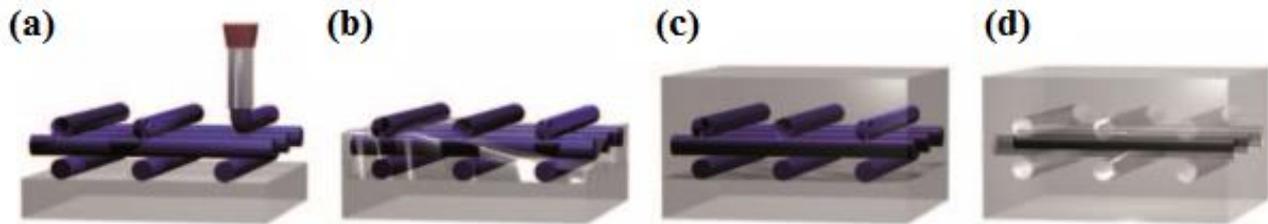
Figure 10. Schematic representation of the direct write fabrication procedure: (a) ink deposition on cured substrate, (b) epoxy infiltration of completed network, (c) cured specimen, (d) specimen after evacuation of fugitive ink (Kozola *et al.*, 2010).

Among the analyzed heat sinks, the reduction of the thicknesses of fins, channel walls and basis was adopted as alternative to overcome the limitation imposed by low values of thermal conductivity. Fin thicknesses presented in Tab. 3 are in the order of 1 mm, depending on the thermal conductivity of the material. However, for pristine polymers heat sinks, as presented by Lee *et al.* (2004) and Kang *et al.* (2005), PDMS microchannels walls with thickness in the order of 80-250 μm were manufactured to decrease thermal resistance.

According to the literature reviewed, base temperatures of the experimentally evaluated heat sinks remained below 140 °C, avoiding thermal degradation. In general, experimental dissipated heat flows remained around 10W, however higher values like 30W and 640W were also found, the latter referring to the anisotropic epoxy/graphite heat sink manufactured by Marotta *et al.* (2003), with high thermal conductivity in the direction of heat transfer. Therefore, the material selection according to the application is fundamental in order to ensure safe operation. For low heat flux applications such as LED, CMOS and low power electronics cooling, polymeric heat sinks are already a low cost alternative, however, it is possible to extend their use through highly conductive composites and the fabrication of complex geometries that enhance the heat transfer. In addition, it should be remarked that conversely to what is found for metallic microchannels-based heat sinks, no work was found employing the use of halogenated refrigerants or convective boiling heat transfer, which could result in further enhancement of the cooling capacity of such devices, thus suggesting these as possible topics for future studies.

## 6. CONCLUSIONS

This paper presented a review of the advantages of polymeric materials in comparison to metallic ones, as well as experimental results obtained for thermal conductivities of thermally conductive composites and the factors that influence this property. Based on this review, recent successful applications of polymeric heat sinks have been summarized, highlighting the materials used in their manufacture as well as limitations identified by the authors and possible solutions to overcome them.

As reported in this paper, thermal conductivities achieved for polymeric matrix composites are not in the range of metallic materials, but are sufficient to guarantee a satisfactory thermal performance in low heat fluxes applications, providing weight and cost reduction, and avoiding electrical interference. Carbon reinforcements, as carbon nanotubes, considerably increase the thermal conductivity of polymeric composites due to their high aspect ratio, good matrix-filler interaction and high intrinsic thermal conductivity, and may be promising fillers to plastic heat sinks for electronics cooling applications.

Reducing fins, walls and base thicknesses also were identified as alternatives to overcome the issue of reduced thermal conductivity of polymers. Ease of manufacture of these materials has enabled this approach. New designs using non-isotropic materials also have been proposed, but still insufficiently experimentally evaluated. Promising experimental results for polymeric microchannel-based heat sinks were presented by Lee *et al.* (2004) and Kozola *et al.* (2010). Furthermore Koyuncuoğlu *et al.* (2010) verified experimentally the performance of hybrid microchannel-based heat sinks composed by a combination of polymers and metallic materials indicating that this may be a viable alternative.

Therefore, for low heat flux applications, polymeric heat sinks are already cost-effective alternatives, with the possibility of expanding operational limits through the use of thermally conductive composites and geometries that intensify heat transfer. There is still a shortage of experimental works related to polymeric microchannel-based heat sinks in the literature, indicating a possible line of research to be explored in the next years, especially through the use of convective boiling and halogenated refrigerants, which can greatly improve their performance.

## 7. ACKNOWLEDGMENTS

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