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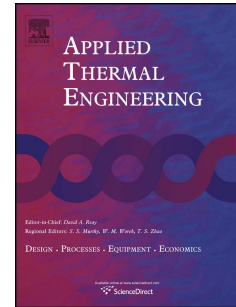
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## Investigation of Thermal Management Materials for Automotive Electronic Control Units

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### Abstract

Today's electronics packages are smaller and more powerful than ever before. This leads to ever increasing thermal challenges for the systems designer. The automotive electronic control unit (ECU) package faces the same challenge of thermal management as the industry in general. This is coupled with the latest European Union legislation (Euro 6 standard) which forced the ECU manufacturers to completely re-design their ECU platform with improved hardware and software capability. This will result in increased power densities and therefore, the ability to dissipate heat will be a key factor. A higher thermal conductivity (TC) material for the ECU housing (than the currently used Aluminium) could improve heat dissipation from the ECU. This paper critically reviews the state-of-the-art in thermal management materials which may be applicable to an automotive ECU. This review shows that of the different materials currently available, the Al/SiC composites in particular have very good potential for automotive ECU application. In terms of metal composites processing, the liquid metal infiltration process is recommended as it has a lower processing cost and it also has the ability to produce near net-shape materials.

**Keywords:** Electronic Control Unit, Thermal Management, Metal Matrix Composites, Thermal Conductive Polymer, Thermal Interface Material

## 1. Introduction

The two important features of modern semiconductor chips are the “ever-increasing power densities” and “decreasing transistor dimensions”. Because of these trends, the challenge of thermal management within the chip and surrounding packaging is greater than ever (e.g., a commercially available power MOSFET (metal-oxide-semiconductor field-effect transistor) with a dimension of 10.4mm×6.73mm×2.36mm has a power dissipation rating of 83W at 25 °C [1]). Thermal management decisions remain a key part of the automotive electronic control unit (ECU) design process, with device performance being significantly affected by temperature. Moreover, the useful lifetime of electronic devices can be decreased significantly because of the large thermal stresses that occur especially at interfaces [2, 3].

In order to reduce the level of pollution caused by road vehicles, the European Union has introduced legislation [4] to put more stringent limits on pollutant emissions, particularly for emissions of nitrogen oxides and particulates (Euro 5 and Euro 6 standards). The Euro 6 standard (which will come into force on 1 September 2014) will require a substantial reduction of emission of hydrocarbon (HC), nitrogen oxides (NO<sub>x</sub>) from all vehicles equipped with a diesel engine. For example, NO<sub>x</sub> emissions from diesel engine vehicles will be limited at 80 mg/km (a 50% reduction when compared to the Euro 5 standard) [5]. The EURO 6 will also limit carbon mono-oxide (CO) at 500 mg/km, combined HC and NO<sub>x</sub> at 170 mg/km and particulates at 5 mg/km [4, 5]. In addition, fuel consumption has to be reduced to meet the growing demand for economical cars and it is also important to reduce environmental pollution caused by CO<sub>2</sub> emissions. In modern automotive engines, the control unit (ECU) plays the crucial role of controlling and integrating different complex actions such as mixture formation, combustion and exhaust gas treatment. Figure 1 shows an

example of a customized automotive ECU sourced from ref. [6]. In order to deliver the performance required for Euro 6 applications and to reduce CO<sub>2</sub> emissions, ECU manufacturers are forced to completely re-design their ECU platform with improved hardware and software capability. It is naturally expected that the new ECU will have a greater functionality and a reduced size and weight, but most importantly increased power density. For example, if the power MOSFET [1], as mentioned earlier, is used in an automotive ECU, then the expected power dissipation density (of that particular area in the ECU) can be calculated as 118.58 W/cm<sup>2</sup>. This is in good agreement with Cola [7], who also agreed that the die-level power dissipation density will exceed 100 W/cm<sup>2</sup> in the next 10 years. Because of the increased power density, the ability to dissipate heat will be an important factor. For this reason ECU designers and manufacturers are evaluating new high thermal conductivity (TC) materials which also exhibit a better coefficient of thermal expansion (CTE) match with chip materials for use in the ECU outer casing (housing and heat spreaders or thermal interface materials).

Thermal management in ECU has long been a challenging issue. In separate studies, Myers [8] and Myers et al [9] reported on the challenges and trends in automotive electronics thermal management. It was pointed out that although the size and cost of automotives ECUs has decreased, the required functionality and operating temperatures have significantly increased. Pumped liquid cooling and the use of advanced thermal materials were among the different cooling technologies suggested by the authors. In another study, Kevorkijan [10] extensively reviewed the prospects of metal matrix composites (MMCs) in automotive industry. The author has found out that although MMCs could offer significant weight reduction and improved mechanical and thermal properties, their advancement are hampered by higher cost over Al alloys, lack of optimum processing techniques and doubts over recyclability. MMCs have also attracted the attention of many other researchers for various

thermal management applications [11, 12, 13]. The use of thermally conductive polymers has also been suggested [14, 15, 16] as alternative to metals and MMC in thermal applications. Although numerous research have been reported on different thermal management issues in electronics, but none of these have explored the thermal management issues in automotive ECUs in details.

The aim of this paper is to outline the results from an investigation of the thermal management materials which may be applicable to an automotive ECU. The study is made up of three main sections. The first section reports on the use of metal matrix composites (MMCs) and thermal conductive polymers as thermal management materials for ECU housings. The second section outlines the different types of thermal interface materials that can be used to fill the gap between the PCB components and the ECU housing. The third and final section presents the recommendation and conclusions from the study.

## **2. Thermal Management Materials for ECU housing**

This section outlines the details of thermal management materials which can be used for ECU housings and is made up of two parts. The first part deals with metal matrix composites and the second part provides brief details on thermal conductive polymers.

### **2.1 Metal Matrix Composites as Thermal Management Materials**

Metal matrix composites (MMCs) are a special group of composites in which one constituent is a metal or alloy and the other constituent is embedded in the metal matrix and serves as reinforcement [17]. The major attractions in manufacturing and utilizing MMC are improved strength to weight and stiffness to weight ratios in a low cost light material [10]. MMCs are

becoming the most promising materials to fulfill the current and future demands in thermal management. This section presents the three most important aspects (also known as “3Ps”) of MMCs: Properties, Processing and Price.

### 2.1.1 Thermal Properties of MMCs

The metal matrix composites, which can be used for thermal management, fall into three main streams: Al-based composites, C-based composites and Cu-based composites. This section discusses the thermal properties of these composites.

#### *Aluminium Based Composites*

It is generally recommended that the thermal management materials used in electronics packaging should have coefficient of thermal expansion (CTE) values between  $4$  and  $7 \times 10^{-6} \text{ K}^{-1}$  to match the CTE of semiconductors. Although the specific thermal conductivity (STC, the TC divided by specific gravity) of Al is higher ( $\sim 54 \text{ W/m.K}$ ) than any other metallic material, the CTE is too high (between  $20$  to  $30 \times 10^{-6} \text{ K}^{-1}$ ) to be useful. SiC additions decrease CTE without significantly degrading STC. In addition to useful CTE and STC, Al/SiC also provides a non-hazardous and cheaper solution than the other metal matrix composite competitor materials. The low material density of Al/SiC ( $3 \text{ gm/cc}$ ) would make it ideal for weight sensitive automotive applications over other thermal management materials (such as CuMo of  $10 \text{ gm/cc}$  and CuW of  $16 \text{ gm/cc}$ ). When packaging structure is considered, Al/SiC has approximately three times the material strength and stiffness compared to the traditional Al-metal [11]. AMETEK is manufacturing AlSiC composites with  $68 \pm 2 \%$  SiC reinforcement by volume to provide a thermal conductivity value of  $220 \text{ W/mK}$ .

Although the price is low and they offer near net-shape fabrication versatility, the thermal conductivities of Al/SiC composites are still relatively low (maximum reported to be 250 W/mK) [12] for many thermal applications. Diamond has the highest potential in this regard (with a thermal conductivity of 600 W/mK), but has so far been limited to niche markets where cost is not of primary concern. Having considered the potential of diamond, Molina et al [13] have investigated the TC of Al-based diamond/SiC hybrid composites. Aluminium matrix composites reinforced with mixtures of diamond and SiC particles of equal size were produced by gas pressure-assisted liquid metal infiltration process. This process [11, 13, 17] uses pressurized gas (in this case Argon gas was introduced up to a pressure of 1 MPa within 1 min) to apply pressure on the metal surface driving the liquid into a preform. More details of liquid metal infiltration process are provided in the “processing of metal matrix composite materials” section of this paper. It was found that replacing SiC gradually by diamond particles (up to 90% volume) results in a steady increase of TC from 220 to 580 W/mK. Because of increasing demand for diamond composites as a high thermal conductivity material PLANSEE, a multinational company with headquarters in Austria, is offering diamond composites (with Al, Ag or Cu matrices) produced by gas pressure infiltration with TC in the range of 400-700 W/mK and suitable CTE of about 6-9 ppm/K.

#### *Carbon/metal Composites*

From the commercial point of view, one of the main advantages of carbon/metal composites is the ease of machinability. However, these materials suffer from low values of TC, especially for through-thickness (z-plane) TC. For example, the maximum through-thickness TC of carbon fibre/Al is reported [18] to be 125 W/mK. As reviewed in ref. [12], several carbon-based reinforcements (graphite particles, carbon fibers or carbon nanotubes) have been mixed with metals through various fabrication techniques (infiltration, drain casting,



etc.) but none of them have been demonstrated to have high enough thermal conductivities for the actual market.

In a recent study, Prieto et al [12] reported a fabrication procedure and thermal properties of different graphite flakes/metal composites and provided a comparison with other carbon based composites. For graphite flake composites, a “separator” phase (either carbon fibers or SiC particles) was used between the aligned graphite flakes to facilitate infiltration of the liquid metal when pressure is applied.

Table 1 presents the results of thermal conductivity and thermal expansion coefficient for the different carbon based composites. Although thermal properties of composites based on graphite particles and carbon fibers are highly isotropic (similar properties in x, y and z planes), they can show respectable values of TC. Based on the thermal properties presented in table 1, the diamond based composite seems to be the suitable choice as this isotropic composite shows a high value of TC (350 W/mK) and reasonably low CTE ( $11 \times 10^{-6} \text{ K}^{-1}$ ). However, the “high cost of diamond” as raw material and “impossibility of machining” for post-processing makes this composite unsuitable for mass commercialization.

The graphite foam based composites could also be a good thermal management material candidate as they show very attractive thermal properties and they are easily machinable. However, these materials are still far from commercialization because of their high cost. As reported in table 1, the thermal properties of graphite flake composites are anisotropic (shows different thermal properties in xy and z planes). This is because the graphite flakes are

oriented on a plane and therefore, shows highest maximum thermal conductivity and lowest CTE in xy-plane. Although anisotropy could be an issue for some applications, it could also be a benefit, allowing designers the ability to make heat preferentially flow in one direction. Therefore, the graphite flakes/metals composites represent another suitable alternative to the commercialized Al/SiC composites, given their superior TC and their cheaper price and ease of machinability.

Amongst other carbon based materials, pyrolytic graphite (PG) and annealed pyrolytic graphite (APG) are reported [19, 20] as two of the highest TC (xy-plane) materials available. PG is manufactured through a pyrolytic reaction in a vacuum at high temperature (at or above 2150 °C) and APG is PG heat-treated at high temperature (at or above 3000 °C) [19]. As reviewed in ref. [19], PG/APG has reported to have TCs (xy-plane) up to ~3500 W/mK at ~120 K. They do however have much lower through thickness (z-plane) TC which reduces the overall equivalent TC of these materials. The k-Core<sup>®</sup> materials, manufactured by k Technology (a division of Thermacore, Inc) [20], uses APG as an insert within an encapsulating structure of conventional thermal management materials (e.g., aluminum and copper alloys, ceramics, and composites). In order to overcome the through thickness TC issue of the APG, thermal vias are incorporated into the encapsulant material. In this way, a copper/APG k-Core<sup>®</sup> material could provide an equivalent TC of up to ~1200 W/mK.

### *Cu-based Composites*

Copper is considered as one of the most important materials for contemporary thermal management. This is due to its high TC value (~ 400 W/mK). However, if weight is taken into consideration, the specific thermal conductivity (thermal conductivity divided by specific gravity) of Cu is only ~45 W/mK. This makes it unsuitable for automotive applications where

weight and cost (Cu is \$6.61/kg versus Al \$2.02/kg, as found in MetalPrices on 11 February 2010) is a significant concern. The use of SiC or diamond particles as reinforcements in copper was shown as quite attractive to meet the increasing demand for high performance thermal management materials [21].

Table 2 presents the thermal properties of Cu-40%SiC composites reported by Schubert et al [21]. As SiC is not stable in contact with copper at elevated temperatures, a vapour deposited molybdenum barrier coating onto SiC was used to control the chemical reaction of Cu and SiC. Mo coating was found to be quite effective in controlling interfacial reaction between SiC and Cu and enabled the production of high thermal conductive Cu/SiC composites (306 W/mK).

Schubert et al [21] also reported on the thermal properties of the fabricated 42% volume diamond reinforced copper composites. In order to improve wetting of liquid Cu with diamond, several pre-alloyed Cu(X) powders (X = B, Cr, Al, Ti, Zr) were used for the diamond reinforcement. It was reported that the thermal conductivity of Cu-diamond could be doubled by using boron or chromium as an alloying element. The preparation of the most promising Cu/diamond composite resulted in a thermal conductivity of about 640 W/mK combined with a CTE of about  $11 \times 10^{-6} \text{ K}^{-1}$ .

### **2.1.2 Processing of Metal Matrix Composite Materials**

As reported by Delannay et al [22] and Kaczmar et al [23], there are two main routes for the processing of metal matrix composite materials. These are casting and powder metallurgy methods; the former is liquid state processing and the latter being the solid state processing. Again in the casting methods, the two most common and popular methods of casting are

liquid-metal-mixing process and liquid-metal-infiltration process. A comparative study of these processes is presented at the end of this section (see figure 2).

#### *Liquid-Metal-Mixing Processes (Stir Casting Process)*

In this process the reinforcement particles or short fibers are blended into a molten or semi-solid metal matrix through a stirring process. Because of the low-cost raw materials as well as the low-cost molten-metal processing route, this process has wide applications in automotive and other industrial and commercial sectors [24]. However, the following limitations of this manufacturing process need to be addressed as well [24, 25]:

- high foundry cost and high-cost of tooling and casting equipment,
- low ductility of the finished product due to agglomeration of reinforced particles in the matrix,
- lack of cast MMC with high-temperature performance,
- lack of design information for use as commodity and engineered materials,
- lack of clear statement of needs for markets and applications.

In order to cope with the issues of low ductility and his cost of traditional stir casting, Babu et al [25] developed a shear-intensive stir casting process called “rheo-process”. This method involves applying very high applied shear stress (up to 50 MPa) during the mixing process and hence, facilitates uniform distribution of the reinforced particles in the liquid metal.

#### *Liquid-Metal-Infiltration Processes*

In this approach of casting [17, 22 – 24] a preheated preform (a shaped porous assembly of reinforcement elements such as fibres, whiskers or particles) is placed in a preheated die immediately before (or immediately after) pouring of the liquid metal. A complete infiltration

of the preform can be achieved within a few seconds (before the beginning of solidification) by applying a rapid pressure using a punch [22]. The success of the casting is very much dependent on the quality of the preform which must have a homogeneous distribution of the reinforcement material with fully open porosity together with sufficient compressive strength to avoid deformation or damage during infiltration [22]. This process can produce essentially net shape materials with a range of reinforcement volume fractions [24]. However, the process is reported to be well suited for making metal composites with more than 50% volume fraction of reinforcement component. This makes the infiltration process very suitable for producing thermal management materials for electronics packaging where high volumes (>50%) of reinforcement are needed to increase thermal conductivity and to optimize CTE to match it with semiconductor materials. The Liquid-Metal-Infiltration process is also reported to be the easiest and cheapest method for processing continuously reinforced composites with Al-based matrices [22]. As with other processes, infiltration process has some limitations [24]:

- high cost of preform and inability to produce a net-shape perform,
- inability to reduce particle size in preforms to a size that would improve properties,
- high cost and limited number of reinforcements available,
- machining is difficult (if not net-shape).

However, with the recent advancement of technologies, the cost of making preforms has been reduced [26] and an increase in productivity with metal infiltration process is also reported [27].

*Power Metallurgy Method (Solid state Processing)*

Powder metallurgy methods involve the mixing of reinforcement into a solid-state metal matrix. The metal matrix powders are blended with reinforcing elements (such as dispersion powders, platelets and fibers) and then cold pressed and/or sintered to form the composite material. The resulting composites are further fabricated (via extrusion, forging or rolling) to make the final product. In addition to traditional powder metallurgy processes (such as sintering and cold pressing), mechanical alloying and spray forming are also widely used [23]. Powder metallurgy is regarded as the only possible route for reinforcing higher melting point alloys (such as Cu-based alloys) with fibres [22]. As for composites processed in the liquid state, the major challenge in the development of composites by powder metallurgy is the control of the interface reaction [21, 22]. Delannay et al [22] suggested the use of suitable “alloying addition” to control the interface adhesion. On a more specific application, Schubert et al [21] demonstrated the use of molybdenum coating and carbide formers to control the interfacial reactions in Cu-SiC and Cu-diamond composites respectively. Powder metallurgy methods produce high-performance metal matrix composites with highly improved materials properties. For that reason, these composites are primarily used in higher-performance applications, especially in the aerospace sector [24]. The limitations of this method are [24]:

- lack of thermally stable matrix alloys to satisfy high temperature applications,
- high cost of matrix and reinforcement powders,
- net-shape processing is not feasible.

### 2.1.3 Evaluation of Composite Price

Use of metal matrix composites could be quite cost-effective when compared to the traditional thermal management materials. Traditional materials such as cast-aluminium usually goes through expensive machining to provide complex shapes and features required for final packaging. As discussed earlier, using molten metal infiltration process, MMCs can however, be fabricated in net-shape. Ceramics Process Systems Corporation's QuickSet<sup>TM</sup>/QuickCast<sup>TM</sup> fabrication process [28] can be noted for instance. This net-shape fabrication process is capable of producing complex geometrical features and hence, obviates the need for costly machining [11].

The cost of a composite material,  $C$  can be estimated by the following formula [10]:

$$C = X_1C_1 + X_2C_2 + C_3 \quad (1)$$

where  $X_1$  is the weight fraction of matrix alloy and  $X_2$  is the weight fraction of the reinforcement in the composite,  $C_1$  is the cost of matrix alloy,  $C_2$  is the cost of reinforcement and  $C_3$  is the production cost.

For a composite prepared using aluminium alloy and SiC particles, the cost of the matrix alloy can be taken as ~1.96 \$/kg (this is the price of aluminium alloy obtained from MetalPrices in January 2010 [29]), the cost of the SiC particles as ~1.40 \$/kg [30], and the production cost as the cost of squeeze casting or gas pressure infiltration which is typically less than 1 \$/kg (for medium size production) [10]. Considering  $X_1 = X_2 = 0.5$ , the final price of the composite would be ~ 2.68 \$/kg which is definitely higher than the cost of non-reinforced aluminium alloy. However, it is worth noting that for squeeze cast components the production cost would be almost the same for non-reinforced and reinforced aluminium alloy, the \$2.68 is therefore comparable with a \$1.96 cost for pure aluminium, which indicates at

least the potential for a cost reduction. One way of reducing the cost of composite would be to find a cheaper production method. Also as the cost of reinforcement particles is less than the aluminium alloy (although this is not always the case), increasing the proportion of reinforcement will reduce the final composite price.

The move towards metal matrix composites should be primarily on a value-added basis, i.e. on the improvement of the cost-to-quality ratio [10]. That is to say, the introduction of a carefully selected reinforcement into a metal matrix should result in a profitable material. This is coupled with the huge market demand for improved material performance (such as high thermal conductivity, improved strength and many more). Although the automotive market has been traditionally interested in low cost materials due to the very low profit margins, there is now a new trend to use materials with increased performance and hence the high market demand of MMCs.

## **2.2 Thermally Conductive Polymers**

Thermally conductive polymers (TCPs) could be used as alternatives to metal and MMCs in heat transfer applications. Conventional plastics are very poor thermal conductors (with a thermal conductivity value of around 0.2 W/mK). But the addition of fillers or additives in plastics makes heat dissipation possible [14, 31, 32]. In thermal applications, conventional plastics will not spread or dissipate heat, resulting in a localized hot spot. Conversely, thermally conductive plastics with uniformly distributed fillers or additives, will spread heat uniformly, giving a more isothermal profile across the part [14]. TCPs typically use ceramic additives, which also makes them electrically insulating. Boron nitride (BN), aluminium nitride (AlN), silicon carbide (SiC), alumina (Al<sub>2</sub>O<sub>3</sub>) and fused silica (SiO<sub>2</sub>) are some of the



common ceramic additives used in TCPs [31, 32]. Lee et al [32] reported TC value of 2.42 W/mK for high-density polyethylene (HDPE) filled with 60% vol. AlN and 3.66 W/mK for 50% vol. BN. Graphite or metal based additives can be added to make the plastics electrically conductive. The conductivity depends on the amount of additive, the higher the amount of additives the higher the conductivity would be and vice versa.

Chander from Technical Insights [15] has identified five main drivers for TCPs. These are:

- a) *Ease of Manufacturing.* TCPs can be easily custom manufactured using simple injection molding which enables them to be used for broader range of applications.
- b) *Miniaturization of electronic components.* Because TCPs are injection moldable they are very suitable to fit in smaller and thinner spaces without compromising on mechanical properties.
- c) *Continued focus on weight reduction.* Use of TCPs could reduce device weight. TCPs made from CoolPoly Polymers are 40 to 50% lighter than aluminium [14].
- d) *Excellent Mechanical Properties.* TCPs possess high flexural, tensile and impact strength.
- e) *Recyclability.* Bio-based polymers can be effectively recycled with no harmful effect on the environment.

Most thermally conductive plastic compounds carry thermal conductivities at least 100 times (around 15 W/mK) that of base plastic. Metals such as stainless steel and titanium have a similar value of thermal conductivity. Highly filled TCPs could even provide a TC value of 100 W/mK [16], but still less than die-cast aluminium which range between 80 – 160 W/mK. Figure 3 presents a comparison of materials for thermal management applications. From the economic point of view TCPs are also substantially more expensive than traditional thermal

management materials. Many thermal conductive polymer compounds cost around 5 to 50 times more than aluminium [14]. Although thermal conductive polymers have higher material cost and lower thermal conductivity, Miller [14] and Ogando [16] argued that for appropriate applications these materials can still compete against metals with much higher thermal conductivities. Their arguments are based on the fact that the total heat transfer from any system comprises of conduction, convection and radiation paths. Heat sink materials, for instance, conduct heat to the surface and then transfer it to the surroundings by convection. If conducting the heat out of the system is not the major issue, a lower conductivity polymer can be used for the heat sink with an improved design to increase the surface area, and hence increase convection heat transfer. A lower manufacturing cost for TCPs compared to die-cast aluminium also means that the overall cost could be lower, for low production volumes.

### **3. Thermal Interface Materials (TIM)**

A thermal interface material (TIM) is normally used to minimize the contact thermal resistance between the heat transfer surface areas of the heat source and the heat exchanger. When these two surfaces are brought together, as much as 99% of the surfaces might not be in physical contact [33]. This is due to the fact that all surfaces are expected to have a certain irregularities, either due to surface roughness (micro-irregularities) or as a result of poor surface flatness (macro-irregularities). Figure 4 shows the schematic presentations of these irregularities. If no interface material is used, the space between the heat source and the base of the heat sink is normally filled with air. As the thermal conductivity of air is very poor (0.026 W/mK), it increases thermal resistance and acts as a thermal barrier and preventing efficient heat transfer across the interface. TIMs are designed to fill in air gaps and irregularities, resulting in dramatically lower thermal resistance and thus better cooling.

These materials should also be electrically insulating to avoid the risk of electrical shorting. Common TIMs include a variety of polymer-based materials with high thermal conductivity particle inclusions (typically with diameters of 2 – 25  $\mu\text{m}$ ) to provide an effective TC value in the order of 2 W/mK [2]. For commercially available TIMs, the thermal impedance (TI) value (which represents temperature drop across the TIM thickness for each watt of heat flow) was found to be in range of 0.018 to 0.581 K  $\text{cm}^2/\text{W}$  (0.0028 to 0.09 K  $\text{in}^2/\text{W}$ ), depending on the material and clamping pressure [34].

As outlined by Xu et al [35], in addition to high thermal conductivity and high electrical resistivity, TIMs should have a low dielectric constant for fast signal propagation and a low CTE for resistance towards thermal fatigue. According to Gwinn and Webb [34], the ideal TIM would have the following characteristics: a) high thermal conductivity, b) easily deformed by small contact pressure to contact all uneven areas of both mating surfaces, including surface pores, c) minimal thickness, d) would not leak out of the interface, e) would maintain performance indefinitely, f) non-toxic, g) manufacturing friendly (easy to apply and remove). However, when it comes to the selection of the right TIM, there are several different test standards used to test and measure thermal properties of TIMs [36] and this makes it difficult to compare materials from different suppliers.

Traditionally thermal interface materials come in two different types: Thermal Grease and Thermal Pads. However, there are other new and emerging technologies in TIMs some of which are already in production. The following section addressed the different types of TIMs.

#### *a) Thermal Grease*

Thermal grease is a form of thick paste composed of a thermally conductive filler dispersed in silicone or a hydrocarbon oil. Thermal grease usually comes in a syringe, a tube, or a small

plastic sachet. Thermal grease is similar in consistency to ordinary toothpaste and is typically gray or white [37].

Depending on the type of filler material used thermal paste materials may be categorised into three groups:

*Metal-based Thermal Pastes.* These materials use metals (such as Ag, Cu or Al) as their base. Although metal based thermal pastes offer better thermal conductivity they suffer from high manufacturing cost. The other big issue is that these pastes are electrically conductive which limits their use in electronics.

*Ceramic-based Thermal Pastes.* Ceramic-based pastes are still widely used because of their good thermal conductivity and low cost. These materials are commonly composed of a ceramic powder suspended in a liquid or gelatinous silicone compound. The most commonly used ceramics are: beryllium oxide, aluminum nitride, aluminum oxide, zinc oxide, and silicon dioxide.

*Carbon-based Thermal Pastes.* Because of being electrically non-conductive, carbon-based TIMs are very suitable for all types of electronics applications. With the use of carbon nano-tubes, carbon fibers, diamond powder these materials are quite promising as the future of high-performance TIM.

One of the big advantages of thermal pastes is their lower cost compared to thermal pads or other thermal interface materials. The other advantage is their ability to fill up gaps properly (for rough or irregular surfaces) and hence to reduce the interface resistance between the mating surfaces. However, handling of these materials tends to be messy and also time consuming.

*b) Thermal Pads*

Thermal pads are usually made from silicone gel technology in combination with a thermal medium (usually ceramic). The silicone gel and ceramics are mixed, cast and cured to a soft, conformable pad with a dough-like texture. In ECU's, thermal pads are typically found between the PCB and the housing base plate. The path of heat removal from an ECU electronic package involves conduction across the interface to the PCB surface and then through a thermal pad, into the case or housing (heat sink) and then convection to the environment.

The Bergquist Company [38], one of the leading thermal interface material producers, is commercializing thermal pads with the brand name of "GAP PAD". In order to suit different application sectors the TC of these pads could vary from 0.6 to 5 W/mK and thickness can also be supplied from 0.254 to 6.35 mm. Thermal pads are also being produced by Chomerics [39] with the THERM-A-GAP brand name. These materials can offer a TC of as high as 6.5 W/mK with TI of 1.9 K-cm<sup>2</sup>/W (0.3 K-in<sup>2</sup>/W) at 345 kPa (50 psi) pressure and 1 mm thickness. Fujiploy, USA [40] has introduced its new silicone based thermal pads SARCON-XRM to provide a remarkable TC value of 17 W/mK and TI of 0.89 K-cm<sup>2</sup>/W (0.14 K-in<sup>2</sup>/W) for the same pressure and thickness.

Because thermal pads are not messy, handling of these materials is much easier than thermal grease. They are less likely to be pumped out of the space between the PCB and baseplate of the ECU. Thermal pads act as a vibration damper and protect the electronic components mounted on the PCB. These materials have an inherent tack that aids placement during assembly [41]. Use of thermal pads could save time by speeding up the assembly process. Thermal pads are also more stable than phase change products (discussed in next section) and have higher operating temperatures. However, it should be noted that thermal pads are designed

to fill gaps and are not recommended for applications where high mounting pressure is applied on the thermal pad [38]. Finally, while thermal grease material is less expensive, thermal gap pads have advantages in function and assembly time, so the overall cost to use thermal gap pads can be lower.

### c) Other Thermal Interface Materials

In addition to the traditionally used thermal grease and thermal pads, there are other technologies in the TIM which also need to be addressed. These include: Phase change materials (PCM), Elastomers and Thermally Conductive Adhesives

*Phase-change Materials.* These materials are usually made of suspended particles of high thermal conductivity, such as fine particles of a metal oxide and a base material [34]. At room temperature, PCMs are solid and easy to handle. At component operating temperature these material change from solid phase to liquid phase. This allows the material to readily conform to both mating surfaces by completely filling up the interfacial air gaps. Among the different PCMs available in the market, worthy of mention are: THERMFLOW categories from Chomerics and the Hi Flow categories from Bergquist. Since metal-to-metal contact is possible after the material undergoes phase-change, Chomerics does not recommend their THERMFLOW products to be used as electrical insulators. The uses of phase change materials are mainly limited to high end applications [42], such as solar power plants, spacecraft thermal systems, thermal comfort in vehicles and so on.

*Thermal conductive Insulators (Elastomers).* These materials are specially suited for electronics application as they are electrically non-conductive. Chomerics's CHO-THEM is a highly thermally conductive elastomer insulator which combine a silicone binder with a boron nitride filler [39]. Bergquist has been manufacturing elastomers for more than 25 years with the brand name Sil Pad [38]. These materials can offer excellent thermal performance without the mess of thermal grease. They are also cleaner to apply.

*Thermal conductive adhesives.* Thermal conductive adhesives are available both in liquid and solid form (double sided adhesive tape). Use of these materials eliminates the need for mechanical attachment (i.e. screws, clips, rivets, fasteners etc). Adhesive tapes supplied by Chomerics (named as THERMATTACH) are offered in custom die-cut configurations to suit a variety of applications. Although these materials have unique properties, they suffer from poor thermal performance [34].

#### **4. Recommendations and Conclusions**

Because of the increased power densities and reduced dimensions, thermal management still remains the key challenge in the ECU mechanical design process. In order to comply with the European Union's pollution control legislation (Euro 6 standard), the ECU manufacturers are also forced to re-design their ECU platform for improved performance. In terms of thermal management, these changes will eventually increase the heat dissipation from the ECU. This paper addressed these issues and explored the option to find out alternative thermal management materials to aid in the ECU design. Based on the findings from an extensive literature review, the following recommendations are suggested:

1. In terms materials for ECU's housing, our investigations showed that the use of metal matrix composite materials can offer significant improvements in thermal performance when compared to the traditional materials currently used in ECU's. Metal matrix composites are also mechanically strong and offer the additional advantage of reduced weight. This report provides an overview of the thermal MMCs including their properties, the processing options and overall costs. Although the use of composite materials as thermal management materials will incur additional costs, it is felt that the improvements in thermal performance that can be achieved will more than help to offset these costs.
2. Our review also shows that of the different metal composites currently available, three particular types are known to offer potential for improved thermal performance, namely: (a). Al-based composites, (b). C-based composites and (c). Cu-based composites. The Al/SiC composites in particular have very good potential for automotive ECU application, as they have higher thermal conductivity than traditional thermal management materials (such as aluminium), and also have lower processing costs than the other composites.
3. In terms of metal composites processing two main methods are available: casting (carried in the liquid state), and powder metallurgy (carried in the solid state). Our investigation of the literatures show the liquid metal infiltration process has good potential as it has a lower processing cost and it also has the ability to produce near net-shape materials (less machining is required after casting). In addition, liquid metal infiltration processing offers other benefits, such as its ability to produce composites with high volume fraction of reinforcement (typically more than 50%).



4. In addition to MMC's, our study showed that the use of thermal conductive polymers can also provide good thermal management performance, but their higher material costs and lower thermal conductivity seems to make them less attractive for ECU application. We would strongly recommend carrying out in-depth modelling and simulation analysis before making any decision to use thermal conductive polymers.
5. Finally, in terms of thermal interface materials between the PCB components and the ECU housing, we would recommend the use of thermal pads as this will help to provide electrical insulation and also offer the desirable function of a vibration damper. Another option for thermal interface materials is the use of elastomers, which can provide the same function as thermal pads.

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**Table 1:** Thermal properties of different C-based composites (re-produced from Prieto et al 2008)

Reinforcement	Reinforcement Vol (%)	Metal	Infiltration Pressure (bar)	TC (W/mK)	CTE ( $10^{-6}K^{-1}$ )
90% Graphite flakes + 10% Carbon fibers	88	Al-12Si	15	xy: 367	z: 24 xy: 3.0
90% Graphite flakes + 10% Carbon fibers	88	Ag-3Si	15	xy: 548	z: 21 xy: 3.0
60% Graphite flakes + 40% SiC	88	Al-12Si	15	xy: 368	z: 11 xy: 7.0
63% Graphite flakes + 37% SiC	88	Ag-3Si	15	xy: 360	z: 11 xy: 8.0
Diamond	61	Al-12Si	40	xyz: 350	xyz: 11
Graphite particles	67	Al-12Si	40	xyz: 118	xyz: 11
Carbon fibers	55	Al-12Si	40	xyz: 131	xyz: 2.8
Graphite foam	60	Al-12Si	40	z: 140 xy: 330	z: 12 xy: 10
		Ag-3Si	40	z: 220 xy: 387	z: 12 xy: 10



**Table 2:** Thermo-physical properties of different Cu/SiC composites (re-produced from Schubert et al [4])

<b>Material</b>	<b>Thermal diffusivity (mm<sup>2</sup>/sec)</b>	<b>Specific heat (J/gK)</b>	<b>Thermal conductivity at room temperature W/mK</b>	<b>CTE (30 – 100 °C) 10<sup>-6</sup>/K</b>
Cu/SiC	72	0.468	222	14.5
Cu/SiC <sup>Mo</sup>	102	0.466	306	11.2



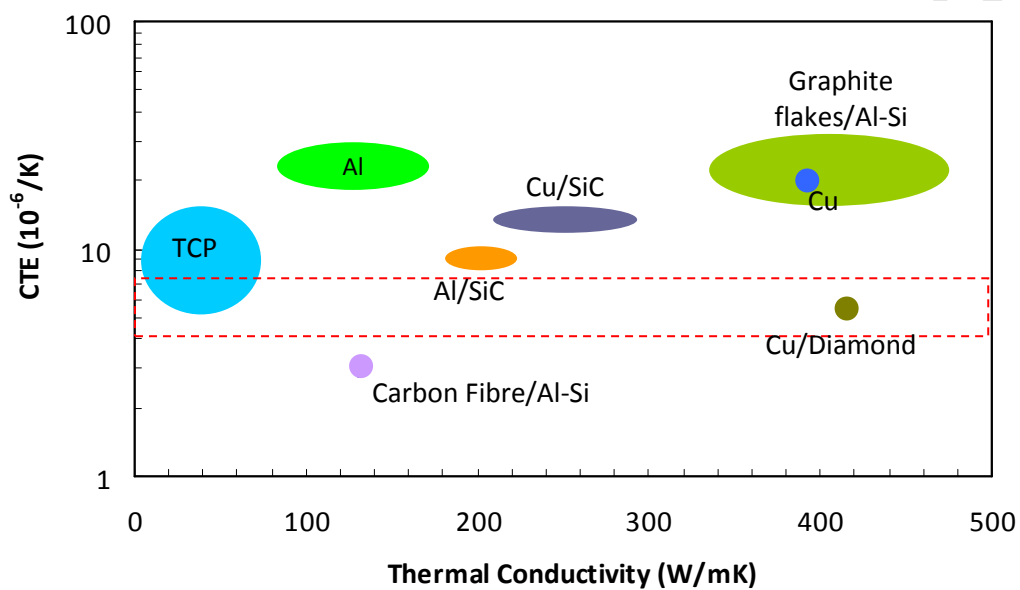
**Figure 1:** A custom made automotive ECU, without top plate (on the left) and assembled view (on the right) [4].

Attributes	Liquid-State Processing (Casting)			Solid-State Processing/ Powder Metallurgy Method
	Aluminium Casting	Liquid-Metal-Mixing	Infiltration	
Material Cost	Medium/ Acceptable	Low/Good	Low/Good	Low/Good
Performance – Thermal Conductivity	Extreme/Bad	Medium/ Acceptable	Low/Good	Medium/ Acceptable
Performance - CTE	Extreme/Bad	Medium/ Acceptable	Low/Good	Medium/ Acceptable
Performance – Mechanical Integrity	Medium/ Acceptable	Extreme/Bad	Low/Good	Extreme/Bad
Pre-processing Cost	Low/Good	Medium/ Acceptable	Extreme/Bad	Medium/ Acceptable
Processing Cost	Low/Good	Low/Good	Low/Good	Medium/ Acceptable
Post-processing Cost (Net-shape fabrication, machining)	Low/Good	Extreme/Bad	Low/Good	Extreme/Bad

**Key**

Extreme/Bad	Extreme/Bad
Medium/ Acceptable	Medium/ Acceptable
Low/Good	Low/Good

**Figure 2:** Comparative study of aluminium and metal matrix production processes



**Figure 3:** Thermal conductivity Vs CTE for different metals, metal composites and thermal conductive polymers (TCPs). Red dotted line represents the acceptable CTE band to match with that of semiconductor materials.



**Figure 4:** Examples of surface irregularities between heat source and heat sink base plate: (a) surface roughness, (b) poor surface flatness (reproduced from [31])