Material Selection for Heat Sinks in HPC Microchip-Based Circuitries

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Authors' contributions

This work was carried out in collaboration between all authors. Author KJA designed the study, performed the CES EduPack analysis, wrote the protocol, and wrote the first draft of the manuscript. Author FOO managed literature searches and analyzed mathematical theory. Authors DAI and OSA managed the analyses of the study and graphical editing. Author ARA interpreted results. All authors read and approved the final manuscript.

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ABSTRACT

Heat sinks are integral components of high-powered computing system (HPC) microchips which are extensively used in modern electronics and power supply circuitries with intelligence and effective control capability. Integrated circuits typically generate large amount of heat sufficient to damage the chip and other sensitive electronic components of the circuitry. Heat sinks are applied to accomplish a continuous cooling of the microchip by conducting thermal energy away from it and dissipating same into the environment. Suitable materials for the heat sink are therefore important for effective protection of the microchip. In this study, material selection for heat sinks applicable in microchip-based circuitries was carried out using the CES EduPack software. Over 3,000

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candidate materials were first screened using design constraints after which shortlisted ones were ranked using design objectives. Appropriate trade-offs were applied to select the final material which was an alloy adjudged most suitable for the defined function, objectives and constraints.

1. BACKGROUND

Electronic components used in modern day electronics are becoming smaller, thinner, faster, lighter and more powerful [1]. This is because high-powered integrated circuit packages (microchips) are produced by integrating larger number of transistors into a single unit [1,2]. The hundreds of millions of transistors working together in a small confined space generate a lot of heat energy which put the system at risk of damage if not controlled [2].

High-powered computing (HPC) systems can be regarded as the most powerful and flexible research instrument today used for fast computation, modelling and analysis among other applications. They are employed to model phenomena in various fields such as quantum chemistry, computational medicine, climatology, high-energy physics to name but few [3].

Performance demands are increasing in data centers and high-performance computing clusters, which nowadays run various applications from document and media processing to scientific computing and complex modelling [4]. As the need for stacking of the components into single chips becomes increasing in HPCs, cooling of these chip increasingly continue to be a challenge for best performance.

It is important to note that temperature has a dramatic effect on the performance and reliability of the electronic devices of the HPC systems. An approximately 10ºC increase in temperature has been observed to reduce the mean time to failure of the low-profile HPC system by a factor of two [5].

However, most HPCs are now purposely designed not to support some features like video, audio, game port, parallel port among others because they create additional heat and waste energy on a server [6]. The use of Heatsink and water-cooled medium has become viable alternative for heat control of the electronic devices in the HPC systems. Design-specific heatsinks of different sizes are typically used on these systems.

Heat sinks have been designed and conventionally used to prevent overheating of the chips and to enhance their efficiency [7]. They find application in heat control of the computer processing unit (CPU) especially in the HPC microchip-based circuitries. They also find important application in high-power semiconductor devices such as power transistors, lasers and light emitting diodes (LEDs) [8]. Several designs utilize light alloys such as aluminium alloy as sinks [9] but other materials including copper, silver and their alloys are also used. Sinks are categorised according to their shape (geometry) [10] Fig. 1. Among the categories are

i. *Extruded type* in which the heated metal is forced through a profile die. It has moderate performance, cost effective, limited dimension and best for most applications.
ii. *Stamped type*- the metal is stamped to form a particular shape and best for low power. It is inexpensive but comes with low performance.
iii. *Bonded type* has the fins bonded to a pre-grooved base with an epoxy usually for large applications but has moderate performance. They comes in large sizes and expensive.
iv. *Folded fin type* has its fins pre-folded and soldered or brazed to the base plate as the case may be. They usually have a very high performance, best for ducted air, expensive and require high heat-flux density.
v. *Skived type*- it has many applications with medium to high performance, usually with thick base, high weight and directional sensitive.
vi. *Swaged type*- the individual fin of this type of sink are placed in a pre-grooved base and a roller swage the sides to the fins. It is applicable in high power areas and usually heavy and bulky.
vii. *Forged type*- formed by compressing heated metal into a desired shape.

viii. *Single fin assembly type-* It is commonly applied in computer systems, cell phones,

Uninterrupted power supply (UPS), DVD players, Heat pipes, Stabilizers etc. An alternative to heat sink is heat pump as found in large scale applications.

Figs. 2 and 3 show a sketch of application of the heat sink and the model function respectively.

The limitation associated with heat sink include the fact that it takes up too much design space in the circuitry and sometimes requires a fan to blow-out the dissipated heat energy by convection.
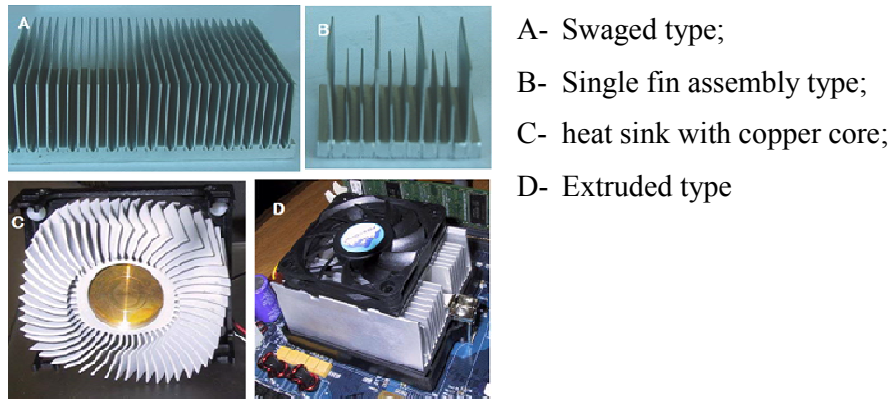
A- Swaged type;

B- Single fin assembly type;

C- heat sink with copper core;

D- Extruded type

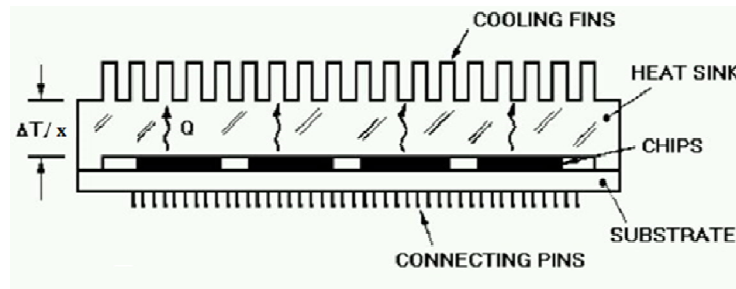**Fig. 1. Cross section of typical heat sinks**
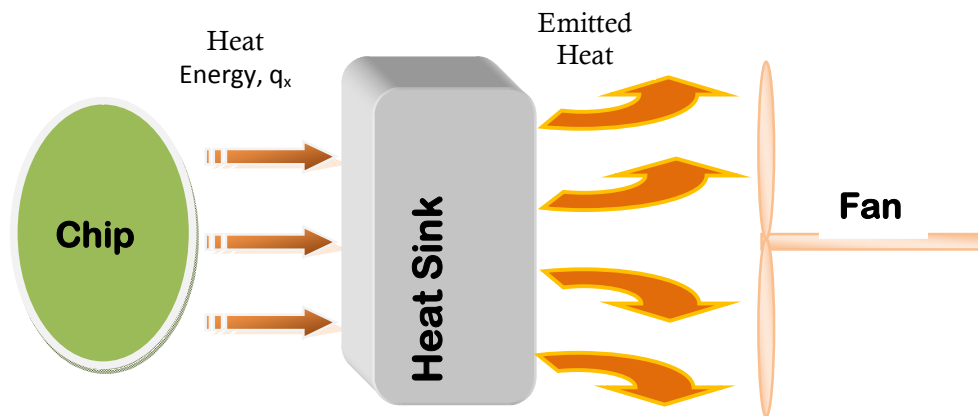
Fig. 2. Heat sink schematic

Fig. 3. Model of a heat sink in a circuit

Microchip is a manufactured component, based on integrated circuit (IC) technology and usually made from silicon material [11]; it is a single unit package with some level of intelligence for both application and control systems.

Major application of chips include: aerospace, medical and biomedical, manufacturing, home appliances, security, automotive, communication, design solutions etc. This is because of their simple, small, fast, light, efficient and cost effective nature [12].

Typical microchip-based systems include the high-powered computing system; chemical, biochemical and several other analysis systems; cell, clinical and other diagnosis systems; target validation systems; power supply systems, lighting system [13,14,15] and countless other systems.

The circuitry advantages associated with the use of microchips are the provision of intelligent system; controllability and processing of integrated circuits in the system; lower cost [16] and high performance. A typical microchip device is shown in Fig. 4.

Its related disadvantages in a circuitry include:

(i) Not flexibility- each chip is produced for a specific purpose. Therefore, the possibility of upgrading the chip is limited which means as the functionality demand increases, a new system is eventually required.
(ii) High power requirement- it requires significant power to operate. The demanding high currents and voltage by the integrated components results in heat generation thus requiring heat sink to keep it from burning-out.

Fig. 4. Typical microchip

The present work reflects on the numerous applications of heat sinks in multifarious microchip-based appliances and therefore applies GRANTA Design (CES EduPack) software to conduct materials selection for it. The CES EduPack is an electronic software developed specifically for materials selection. It has over 3000 materials in its database from which one or more may be selected using inbuilt tools such as SEARCH, BROWSE and GRAPH. The software applies defined constraints (technical or financial) for eliminating materials. The tool applied in this study is GRAPH.

2. METHODOLOGY

2.1 Function and Mathematical Model

The specific function of a heat sink is to effectively absorb and dissipate heat away from a chip device as quickly as possible in order to restore the chip back to its normal operating temperature. A typical heat sink must have a temperature higher than the surrounding in order to transfer heat either by convection, conduction or radiation. This is reflected by the principle of heat transfer- thermal energy is transferred from a region of higher temperature to a region of lower temperature in a fluid medium [17,18].

For steady state heat transfer and constant temperature with time, the Laplace equation for the one-dimensional heat-flow holds [18].

$$\frac{\partial^2 T}{\partial x^2} = 0 \qquad (1)$$

The nature of heat conduction through a body is similar to the ohm's law for electrical conduction. That is, the heat flow rate passing through a thermal resistor is proportional to the temperature difference T_1 and T_2 Fig. 5.
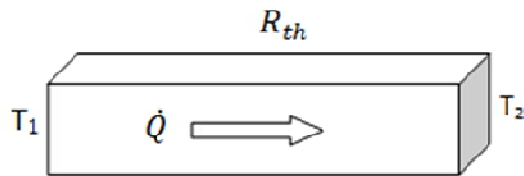

Fig. 5. Heat flow rate through a thermal resistor body

Heat flux rate heat flow rate

$$\dot{Q} = \frac{d\theta}{dt} = mc\frac{dT}{dt} = KA\Delta T \qquad (2)$$

Where = thermal conductivity
= mass of the body
= specific heat capacity

From eqn. (2), the heat flux density becomes

$$\dot{q} = K\Delta T \qquad (3)$$

For a conduction medium,

$$\vec{q} = -K\nabla T = \frac{Q}{A} \qquad (4)$$

In a perpendicular heat flow in a planar geometry of thickness L, the thermal conductivity is given as

$$K = -\left(\frac{Q}{A}\right) \div \left(\frac{dT}{dx}\right) \qquad (5)$$

From eqn (6) the resulting Fourier equation for heat flow is derived

$$K = \left(\frac{Q}{A}\right)\left(\frac{L}{\Delta T}\right) \qquad (6)$$

Where:

$$Q = KA\frac{\Delta T}{L} = KA\frac{(T_1 - T_2)}{L} \qquad (7)$$

Where:

$Q = $ Rate of heat transfer by conduction
$A = $ Area of contact between the chip and heat sink
$L = $ Thickness of the sink

The schematic diagram of steady state heat transfer across the one-dimensional conductor is shown in Fig. 6.
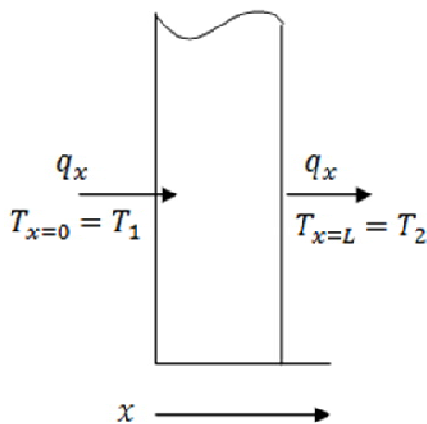

Fig. 6. Steady state 1-D heat conduction

It is assumed that the chip operates continuously and thermal conductivity is constant.

Since the rate of heat transfer is directly proportional to the area of contact therefore, a large chip will require a large heat sink. Assuming the total area of chip contact is

$$CA$$

Therefore, the mass of the sink is given as:

$$m = CA.L.\rho \qquad (8)$$

Where:

$\rho = $ Density of material of which the sink is made

L is thickness of the sink

Combining equations (7) and (8) by division, the resulting equation gives the power drained per unit weight of sink as:

$$\frac{Q}{m} = \frac{\Delta T}{CL^2}\left(\frac{K}{\rho}\right) \qquad (9)$$

The thermal expansion limits the temperature difference (; a very high temperature will cause differential strain between chip and sink which will damage the chip. The expansion difference is given by:

$$\Delta\varepsilon = \Delta\alpha.\Delta T \qquad (10)$$

Where:

$\Delta\alpha = $ Difference in thermal coefficient between sink and chip

But the expansion difference must be kept below the critical value as expressed below.

$$\Delta\varepsilon \leq \Delta\varepsilon^* \qquad (11)$$

Combining equations (10) and (11) into equation (9), the temperature difference term is eliminated:

$$\frac{Q}{m} = \frac{\Delta\varepsilon^*}{CL^2}\left(\frac{K}{\rho\Delta\alpha}\right) \qquad (12)$$

Let the material index be given as M_1.

$$\frac{Q}{m} = \frac{\Delta\varepsilon^*}{CL^2}\left(\frac{K}{\rho\Delta\alpha}\right) = \frac{\Delta\varepsilon^*}{CL^2}M_1$$

$$M_1 = \left(\frac{K}{\rho\Delta\alpha}\right) \qquad (13)$$

The material index is therefore a function of the difference in thermal coefficient, material density and the thermal conductivity of the material under consideration.

2.2 Constraints and Objective

As in every problem of selection, objectives represent what the design is required to maximize, maintain or minimize while constraints represent essential non-negotiable conditions to be met in the design [19]. The design objectives are high thermal conductivity, light weight (low density) and low thermal expansion coefficient. In a specialized high-tech design as a portable heat sink for a microchip in an integrated circuit, cost is not imposed as a constraint. The design will be constrained by a restriction in ($\leq$ 1e-5 strain/^{o}C) and K/ρ ($\geq$1e-2) being results of preliminary simulations for the design. [1]CES EduPack [20] was applied to select the best material for the heat sink using the Function-Objectives-Constraints approach.

2.3 Screening and Ranking

The logarithmic form of the objective function in eqn 13 can be expressed in the standard equation of a straight line as

$$\log\left(\frac{K}{\rho}\right) = \log(\Delta\alpha) + \log M_1 \qquad (14)$$

Fig. 8 is a plot of eqn 14 in CES EduPack where M1 has a slope of 1. Figs. 8 and 9 show screening using design constraints. Ranking was done in Figs. 10, 11 and 12 to arrange materials

that survived screening in a desired order for the purpose of selecting the best material. Shortlisted candidates were ranked according to performance index Fig. 10, Thermal Expansion Coefficient Fig. 11 and by Conductivity/Density Fig. 12.

3. RESULTS AND DISCUSSION

Results obtained from this study are provided in Figs. 7 - 12 and Table 1. Of the over 3,000 candidate materials in the material space (All Bulk Materials), which were originally considered, 97% were screened off—being materials which fall below the line graph of equation 14 Fig. 8. The screened volume may not be considered critical considering the important role of heat sinks. Further screening was done in Fig. 9 by applying restrictions on thermal expansion coefficient to box out more materials as indicated by line-box M2. All materials which fall outside line-box M2 box were again screened off. All materials which eventually survived the screening process were ranked by Performance index in Fig. 10 with diamond as the best followed by Al-60%C alloy. The performance of Al—60%C only drops below that of diamond by about 10%. Fig. 11 reveals that Al—60%C excels other candidates in terms of thermal expansion coefficient. Table 1 therefore considers the strength of the various candidates and arrive at Al—60%C as the most suitable material as heat sink for microchip-based devices and circuitries.
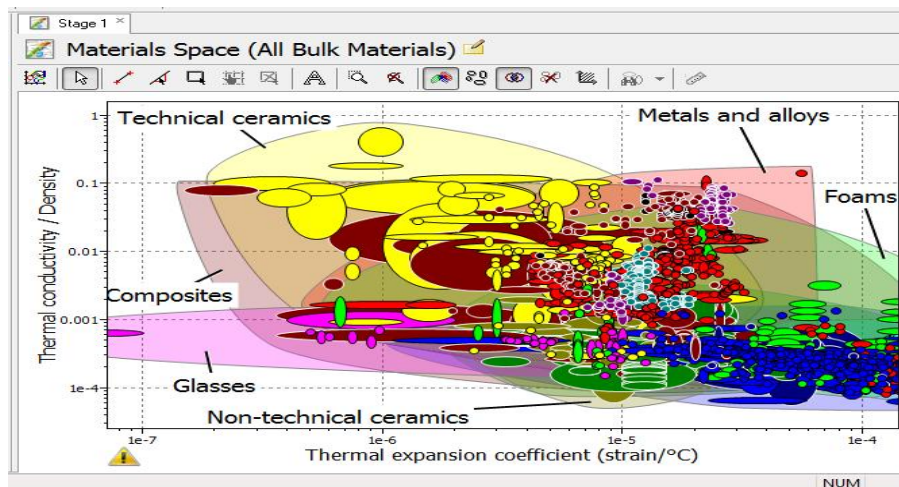

Fig. 7. Over 3000 materials in the sample space (all bulk materials)
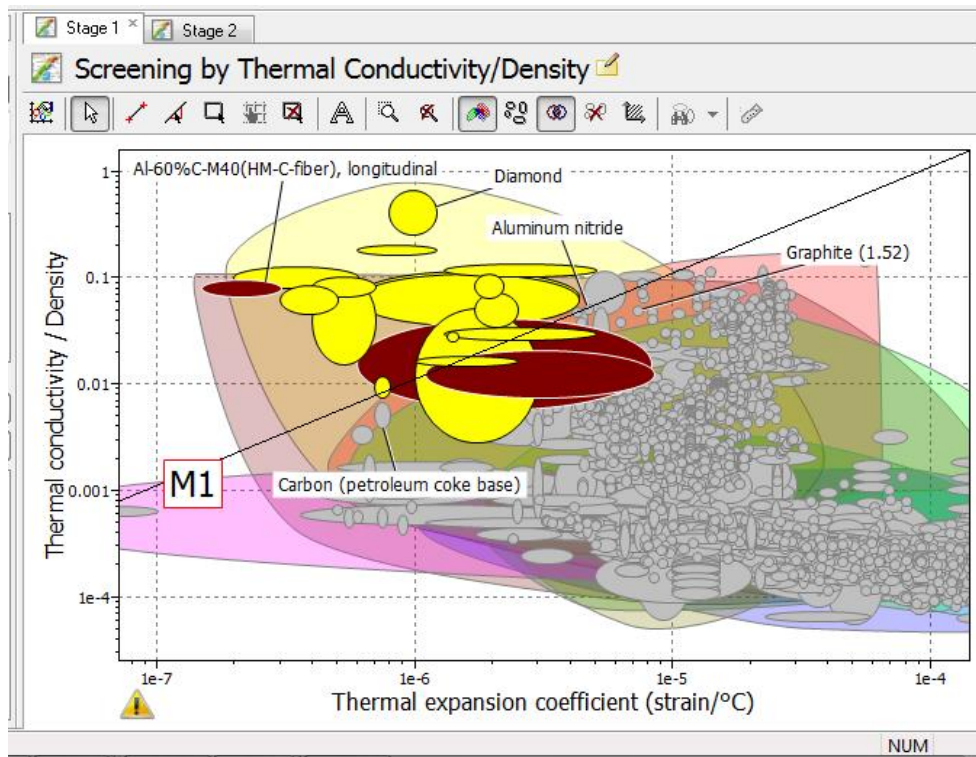
Fig. 8. Screening by thermal conductivity/density
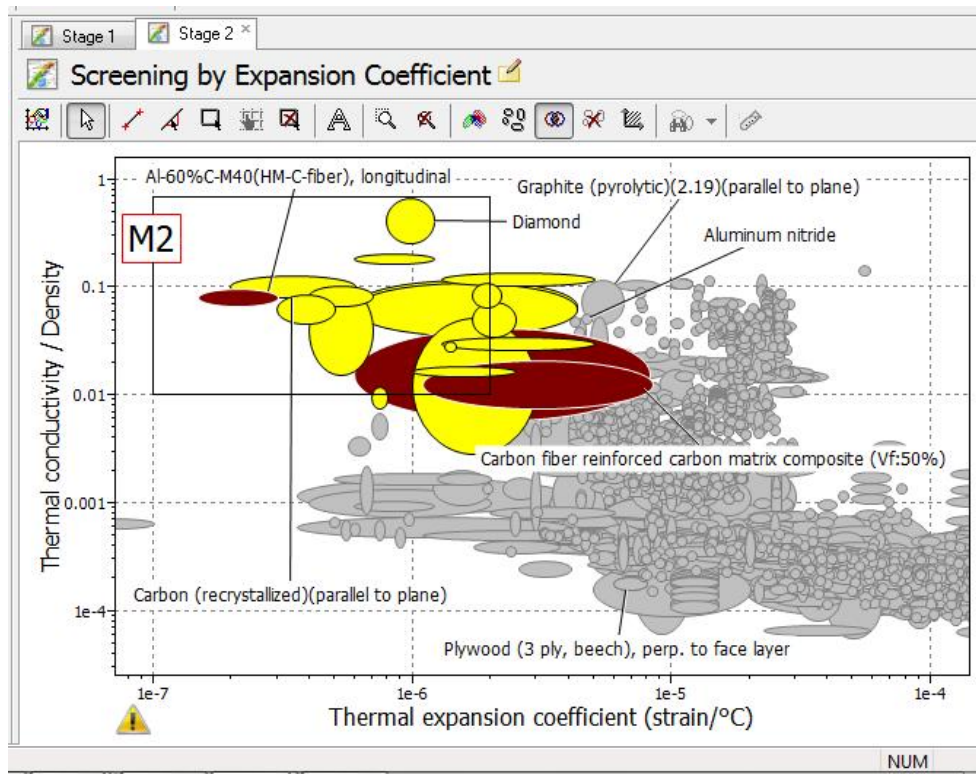
Fig. 9. Screening by expansion coefficient

Fig 10. Ranking by performance index

Fig 11. Ranking by thermal expansion coefficient

Table 1. Selection consideration for shortlisted material candidates (Based on Figs 10, 11 & 12)

Material	Strength	Comment
Diamond	Highest performance index	Enormous hardness makes workability difficult
Al—60%C	Second highest performance index. Excellent workability. Lowest thermal expansion. Excellent thermal conductivity	Properties are most suitable among candidate materials
Carbon fiber	Moderate thermal conductivity	Workability not adequate
Graphite	Lowest thermal conductivity Moderate thermal expansion	Flaky, thermal conductivity inadequate
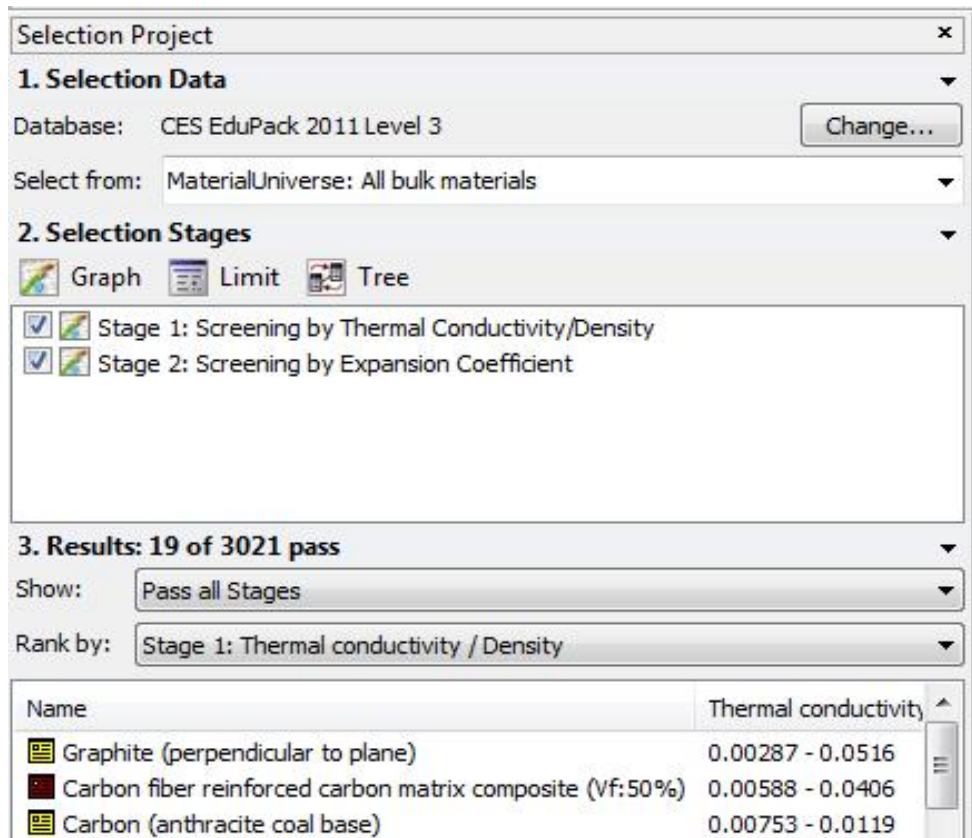
Fig 12. Ranking by Conductivity/Density

In practice, the material constituents of sinks are generally aluminium alloy provided with fins [9]. The fins are designed to maximize the surface area in contact with the cooling medium surrounding it. Traditional heat sinks are composites of two materials where one provides good conductivity and the other limits thermal expansion. The conductivity and heat dissipation could also be enhanced by special structural designs.

4. CONCLUSION

1) This study concludes that Al—60%C is the most suitable choice that satisfies the prescribed objectives and constraints for the selection project.

2) The design was not constrained by cost because it is a highly sensitive application that was intended—heat sinks for HPC integrated circuit microchips.

3) The general properties of aluminium alloys broadly agree with the final material choice

in terms of weight, workability and thermal properties.

4) This study is important for applying property-based criteria in selecting high performance materials for designs with defined function, objectives and constraints.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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