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Thermo-economic optimization for the advanced material selection of fins and heat sinks

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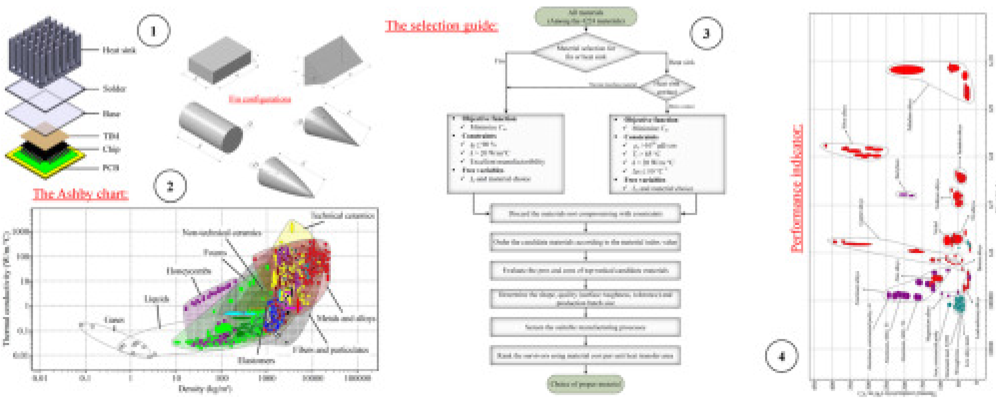
Highlights

- Two material indices are proposed to select fin and heat sink materials.
- Straight fins are ~8 times economically better than pin fins.
- Hot and cold forming processes allow 90.2−98.1% better thermal conductivity to use.
- Hot open die forging gives the best relative cost index among other processes.
- Beryllia alloys and aluminum nitrides are preferable for contact heat sinks.

Abstract

Fins are widely used thermal elements that help transport heat away from a hot surface by increasing the surface area and volume of cooling fluid that flows through them. The functional material selected for these elements is critical for accomplishing efficient heat removal at a low cost. Fin profile, material properties, surface properties, raw material cost, and manufacturing cost are decisive in selecting competitive materials from a holistic perspective. This study has presented two novel material indices for effectively selecting fin and contact heat sink materials. A guiding methodology has been proposed involving both material cost and applicable manufacturing processes for candidate materials. A cost model is proposed to compare manufacturing processes, and production characteristics for varying fin profiles are also investigated. Results show that although die casting is the most economical process among all processes and can produce almost any fin shape, hot forming processes like extrusion and forging allow implementing fin materials with 90.2–98.1% higher thermal conductivity. Beryllia alloys and aluminum nitrides with relatively higher thermal conductivity, ranging between 60–330 W/m·°C, are preferable for contact heat sinks.

Graphical abstract



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Introduction

Finned surfaces promote heat transfer away from a hot surface by enlarging the surface area and the volume of low-temperature fluid that flows through it to achieve this goal. This approach is frequently utilized in engineering to increase heat dissipation in a variety of applications. On the other hand, heat sinks, which are specially designed finned surfaces, are frequently utilized to effectively cool electronic equipment such as power transistors, microchips, or optoelectronic devices. In 2023, the size of the world market for heat sinks reached US$7.37 billion [1]. The market is projected to increase at a compound annual growth rate of 7.5%, reaching a value of US$11.78 billion between 2024 and 2030 [2].

The design of finned surfaces must take into account a number of important parameters to obtain optimal heat transfer performance. To efficiently disperse heat from a surface or electronic components and to guarantee optimum performance and reliability, the proper material must be chosen for fins. Thermal conductivity, mechanical characteristics, cost, and manufacturing feasibility affect the material choice. For this reason, copper is often utilized when weight is not a big consideration, but aluminum is used when weight reduction is required. To choose the best material for your particular fin application, it is crucial to do extensive investigation and testing. Lee [3] classified heat sinks in terms of cooling mechanisms and manufacturing methods. He also stated that higher thermal performance generally comes at a cost—increased manufacturing or material prices, or both. He listed common design constraints and determined a set of constraints such as fin dimensions, shape, patterns, and material which a designer needs to control for optimization to get the maximum possible performance. Under specified design variables and boundary conditions, manufacturing methods and proper material selection become important in the case of obtaining the same overall thermal performance. Heat sinks can be manufactured in a variety of methods. The most popular ones for air-cooling heat sinks are extrusion, stamping, casting, bonding, swaging, folding, forging, skiving, machining, and welding [4]. Culham et al. [5] proposed that a reexamination of the materials and processes used to design heat sinks is necessary in addition to the traditional design requirements brought on by newer heat sink markets. It is a prevalent misconception that heat sink materials should only be chosen for their thermal conductivity, with aluminum and occasionally copper being the most popular choices. But more recently, a variety of manufactured materials have been developed that, despite having thermal conductivities between 25 and 100 W/m·°C, which are much lower than those of aluminum and copper, do have a clear cost and workability benefit [5]. However, noting that fin profiles are often shorter and wider to accommodate the increased thermal resistance when employing lower conductivity materials in heat sink applications. In some cases, a slight increase in the number of fins may be necessary to ensure maximum performance.

Catastrophic solder ruptures are most frequently detected due to interfacial stresses between the different material layers in the base plate and substrate of electronic devices. Khattak and Ali [6] revealed the major causes of failures in electronics. Geffroy et al. [7] proposed a computational approach for the material selection of heat sinks. The coefficient of thermal expansion disparities between the solder junction and base plate are mainly connected to the reliability of electronic devices thus relatively low coefficient of thermal expansion between them has a lower risk of thermal cycling failure. Reddy and Gupta [8] focused on the material selection of microelectronic heat sinks with the Ashby approach. Several material properties were proposed for different mechanical and electrical properties of heat sinks to build the Ashby charts. Exact material indices were not derived. Aluminum-based alloys and metals for microelectronic heat sinks were found to be superior to those of other materials. Ekpu et al. [9] reviewed the thermal management components used as laptop heat sinks and considered four selection criteria of thermal conductivity, coefficient of thermal expansion, density, and cost while choosing a heat sink material. High thermal conductivity, a small coefficient of thermal expansion, low density, and low cost are all characteristics of the ideal heat sink material. According to the four criteria for choosing a laptop heat sink material, AI/SiC was suggested as a close second-best option although aluminum shows better properties. Akinluwade et al. [10] used Granta CES EduPack software to shortlist the material selection for heat sinks applicable in microchip-based circuitries over 3000 screened candidate materials using the same design constraints as given by [9]. They proposed a material index for heat sinks but it was not used directly in the Ashby charts. According to the findings of this study, Al−60%C is the option that best fits the design objectives and constraints but the general properties of aluminum alloys broadly correspond with the final material choice in terms of weight, workability, and thermal properties.

Future demands for heat flux dissipation rate are predicted to increase to 1 kW/cm^2 due to continuous trends of miniaturization and advancements in microelectronics technology. This demand is unmet by air-cooled systems. Liquid-cooled heat sinks are therefore chosen. Kumar et al. [11] presented single-phase flow in microchannels with conjugate heat transfer modeling of an electronic cooling application in COMSOL for different materials of silicon, copper, and aluminum. The increase in temperature of the coolant running through the microchannel which is the greatest in silicon has a direct impact on the microchannel's performance. Kepekci and Asma [12] aimed to identify the best heat sink design and material in terms of thermal performance and cost using COMSOL. They employed 13 different materials and four distinct fin designs, including straight, hexagonal, square, and airfoil. The findings indicated that titanium is the least effective material and silver airfoil fins provided the best cooling performance and cost. However, aluminum and alloys made of aluminum 356 are more effective than other materials as cost factors are considered. On the other hand, Mehmood et al. [13] reported micro-electro-mechanical systems, are the technology behind microscopic devices with combined electronic and mechanical components, including material selection for micro-electronic heat sinks.

In the rapidly developing field of heat transfer enhancement techniques by fins and heat sinks, researchers have extensively explored various fin configurations for various flow problems [[14], [15], [16], [17]] but with limited materials. Despite certain advances, the existing literature reveals the following gaps:

- A comprehensive comparison of different fin configurations and their materials under consistent conditions remains apparently absent.
- The focus on producing various fin configurations without considering manufacturing methods to be used and process cost has overshadowed the broader cost-effectiveness spectrum still in its infancy.
- The growing interest in finned components suggests unknown territory for further detailed research without proposing material indices.

In the context of heat sink and fin design, thermo-economic optimization supports sustainable industrial practices, enhances energy efficiency, and drives cost-effective innovation by combining advanced materials with manufacturing processes. This is directly aligned with the goals of process intensification to make chemical, industrial, and electronic processes more efficient, compact, and environmentally friendly. Modeling and computational-based environments to optimize processes can identify gaps for improving overall process design. From this perspective, a novel approach is proposed to minimize the cost with less resource consumption of fins and heat sinks (by reducing the weight) while achieving optimal performance goals in terms of thermal conductivity and manufacturability. This study has also filled the gaps in the literature as follows:

- A new approach is proposed for the advanced selection of fin materials among 4223 candidate materials based on the manufacturing methods among 146 candidate processes and 5 commonly preferred fin profiles.
- Two novel material indices have been derived for the first time to wisely decide the materials of fins and contact heat sinks used in heat dissipation applications for process intensification.
- A cost-efficient advanced material selection is presented by coupling the heat transfer and economic analyses for optimizing fin properties and applicable manufacturing processes.

Section snippets

Materials and method

Choosing a material is a phase in the design of any physical object. In the context of product design, minimizing costs while meeting product performance objectives is the main goal of material selection [18]. The process of carefully choosing the best material for a certain application begins with the characteristics and costs of potential materials. Material selection is frequently aided by the use of a material index associated with the required material properties.

A designer must have a …

Results and discussion

For fin and heat sink production, various manufacturing methods are available in the market for different material types. Extrusion, stamping, casting, bonding, swaging, folding, forging, skiving, and machining processes are the used production methods but extrusion, die casting, forging and skiving are the most widely used ones in the commercial market. Fig. 4 demonstrates the total number of candidate materials for these processes under the constraints defined in Fig. 2.

Table 2 shows the …

Conclusion

This study has proposed adaptable, compatible, and flexible guidance for the material selection of fins and heat sinks and also presented two material indices aiming to optimize contradictions among thermal conductivity and other requirements to wisely select their materials. Moreover, various fin profiles and manufacturing methods are investigated for low-cost thermo-economy. The core findings of this study can be listed as:

- The material index is not the function of a fin profile. Although …

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CRediT authorship contribution statement

Hulusi Delibaş: Visualization, Software, Investigation, Formal analysis, Data curation. **İbrahim Halil Yılmaz:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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