Low Cost, High Performance, High Volume Heatsinks

Kurtis Keller
Computer Science – Microelectronics Systems Laboratory
University of North Carolina at Chapel Hill, USA

ABSTRACT

Higher-powered electronics are being integrated into automobiles rapidly. With these electronics comes a problem of how to cool this equipment economically. Heatsink costs have not benefited nor adapted to the high volume nature of automotive electronics. Specially shaped heatsinks are much more efficient for a given size than aluminum extrusion-based ones, most prevalent used in automobiles. However, machining costs precede specially shaped heatsink use in most automotive applications.

High purity extruded aluminum has always been a good heatsink material for electronic components. Casting aluminum to create more efficient and useful shapes has a severe penalty in thermal conductivity due to the impurities necessary for casting. Porosity is another significant factor lowering the thermal conductivity in both die and hand cast aluminum. I will show a new heatsink design and material process that allows porosity free, low cost heatsinks to be diecast into complicated 3D shapes. A cost and performance analysis comparing different high volume heatsink manufacturing methods, die cost, and per piece cost will be examined between various commercial copper-based, zinc, zinc-aluminum, and aluminum die casting materials. Additionally, I will show where the automotive industry can benefit from these technologies and where they may not be as appropriate.

Introduction

More emphasis is placed on the introduction and use of computers and electric controls in transportation systems than ever before. With this push have come problems that have not been able to keep up with the demand for answers. One is the cooling of these components and systems cheaply.

One bright star in the automotive world is in stereo systems where a simple extrusion has been an effective mean of radiating the heat from the high power dissipating amplifiers. Besides cooling, it is also a necessary member in the mechanical structure. The transportation industry does not have many other examples of efficient, low cost cooling apparatuses.

Extrusions, when they can be used, are an efficient and economical heatsink, although a rather weak structural item. When extrusions cannot be used, the possibility of finding an efficient, low cost heatsink drops considerably.

3D heatsinks

Cast heatsinks do not have the limitations imposed by extrusions from a 2-D profile nor do they have the backpressure inherent in the saw cut, blunt front end of an extrusion. In forced air systems, the squared shape entrance of a saw cut creates a large pressure build up region creating much of the backpressure by a heatsink. Designing airfoil shaped entrances and exits into the fins of a cast heatsink can eliminate this backpressure. Ripples can also be added to increase surface area or increase local turbulence for higher thermal conductivity where needed.

Assembly cues can be molded directly onto such a heatsink. Items like arrows and alignment pins can be easily placed in the mold. Clips and holders are also are easily molded in the design. In our example (Figure 1), we have included a recess for installing an optional wire tie down, assembly stop and alignment arrow.

Diecastings normally do not require deburring or other secondary processes to clean up machining operations as needed in extruded or machined heatsinks. Drill holes are normally needed for mounting extruded heatsinks; however these can also be integrally molded in cast heatsinks.

Stated before, the real problem is finding an appropriate material for diecasting to meet the needs of the high volume, transportation equipment industry.

Efficient Shapes for Heatsinks

Nearly pure aluminum can be used in an extrusion. It gives a very high thermal conduction coefficient (about 160 - 200 W/m*C^o), has a fine, flat finish, and is rather light. However, it is limited to a 2D shape only and any other items, such as mounting holes, flats, deburring, and necessary plating, are all secondary processes that quickly bring up the costs of such heatsinks. Its relative weakness in its pure, high conduction alloy state restricts its use to all but holding electronic components. Extruded cooling fins are notorious for bending during minor, accidental impacts.

If small amounts of additives are added to aluminum to aid in its extrudability, machineability or strength, its thermal conduction coefficient quickly drops while still retaining other inherent problems associated with 2D extrusions.

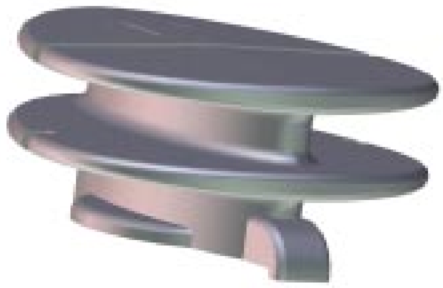

Figure 1 Diecast 3D heatsink

When a specialty shape is required, there are other manufacturing methods available. But these methods are normally limited to low conduction materials. In order to machine or form most high conduction metals, additives are required. However, even small trace impurities drop their conductivity quickly.

Heatsinks formed out of solid blocks are too expensive for medium and high volume heatsink applications. In addition, the materials available that are easily machineable do not have acceptable thermal conduction coefficients (Aluminum 2024, or 6061 for example).

Aluminum cannot be forged like steel eliminating this process; likewise, powdered metal in addition to its extreme porosity problems.

Manufacturing Methods

The transportation industry is always on the forefront in high volume manufacturing processes. A brief summary of heatsink manufacturing methods of how they relate to the automotive industry and their applications follows:

None:
Some component life cycle and temperatures do not require a heatsink. This is the preferred route if possible. The cost and weight saving are obvious.

Extrusion:
Common for audio components and electronic ignition drivers. This is most useful for high powered, high temperature devices such as MOSFETs and voltage regulators. Moderate cost due to secondary processes but cheap tooling. 2D designs only.

Machining:
Expensive to manufacture. Not recommended for high volume markets. However most extrusions require machining as a secondary process for drilling or milling mounting holes or slots.

Imbedded Conduction:
This uses the case or nearby structure to conduct heat. Sometime the actual automotive body may be used for heat dispersion. This can be effective but the labor costs of installation may be higher than a separate heatsink. It has been used effectively for non-temperature sensitive components like ballast resistors.

Stampings:
Good for up to a few Watts of heat dissipation. Good for power drivers and voltage regulators. Lowest cost external heatsink manufacturing process. Used on individual components on circuit boards. Because fin thickness is uniform, not tapered as in extrusions or castings, thermal conduction resistance to fins is higher, limiting it to lower power devices.

Castings:
In volume, lowest cost for high powered or sensitive electronics. Can be structural. High setup costs. Most freedom in shapes; full 3D design capability. Secondary processing normally not necessary.

Material Selections

Highly thermally conductive materials are commonly believed to be only type of material appropriate for heatsinks. This is a misconception. Even with medium powered chips of about 5 watts, the temperature only rises about 4 °C from die to surface of the heatsink θ_{JC} (case being heatsink surface) in our example (figure 2) of a zinc heatsink casting in the ultra dense PXFL computer. The airflow is about 3 m/s with a θ_{JA} of about 54 °C. The perceived problem of resistance of the heatsink material as a major factor in cooling at this power level is actually only about 5% of the total resistance. Most resistance is in the exchanges from fin surfaces to passing air. Much cost savings in the heatsink can be saved by using cheaper materials or manufacturing methods that only affect a few percent of the entire heatsink efficiency.

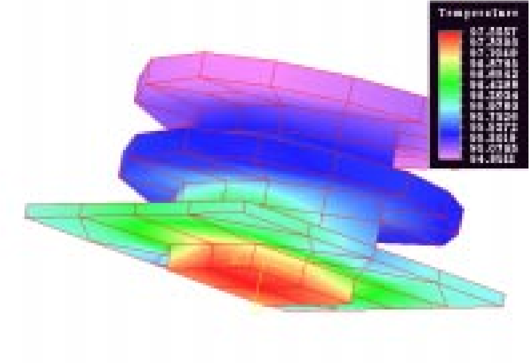

Figure 2 Temperature across heatsink

A machined aluminum heatsink of the same geometry only reduces the die temperature by about 2 more degrees. A cast aluminum one is about the same as the zinc. In the moderate power ranges, the surface area and the heatsink geometry contribute to most of the heatsink efficiency.

The materials for casting will be compared by manufacturing economies to efficient heatsink ability.

Aluminum alloys

Aluminum is the most common material used as a heat sink or conducting material for many good reasons. It has an exceptionally high thermal conductivity. It is easy to form and fairly easy to machine although, not nearly as easy as free machining. Aluminum is also quite light compared to other high thermally conductive materials.

However, secondary processing is required on all aluminum heatsinks used in electrical equipment. This is a plating required for regulatory approval. Raw aluminum oxidizes creating an insulating film that can be easily rubbed down onto the conductive surface. This leaves a danger that rubbing wires can cause shorts.

For casting, aluminum has some other inherent disadvantages. Aluminum has poor diecasting ability when in a pure state. Aluminum must have a couple percent of silicon added to allow it to slip out of a mold easily. This causes the internal structure of aluminum to be non-homogeneous and reduces its thermal conductivity to about 1/3 of pure aluminum. Porosity inside the casting forms results in poor material contact, greatly increasing its thermal resistance.

A process called Hot Isostatic Pressing pours aluminum into a mold and then compacts it under low pressure and cools it slowly that results in a better defined crystal structure and an acceptable thermal conductivity. Unfortunately, this is a very expensive process that does not match to economies of scale, as do other processes in the transportation industry. This labor-intensive process costs 2 to 4 times more than standard diecasting. However, this may be acceptable in systems with strict weight limitations – like avionics.

Extruded aluminum

Aluminum is a prime material for extrusions. It has a low enough temperature to allow steel to be used in the forming process, it is thermally conductive, it is a widely available process, and has a good finish. However, it is notoriously weak and cannot be used where fins are prone to bumping or other high force encounters.

Cast Aluminum

Die casting aluminum parts for transportation systems is extremely common. However, aluminum die cast heatsinks are not used much due to one particular fault: thermal conduction is extremely poor.

Aluminum efficiently conducts heat in a solid structure when pure. When impurities are added, its crystalline structure is broken. Bubbles and small spaces are formed, resulting in internal friction. This can be demonstrated by examining a cut diecast aluminum valve cover.

Reducing Porosity of casting can be accomplished through the process called Hot Isostatic pressing mentioned earlier, but this labor-intensive process is not cost effective for high volume.

Copper Alloys

Brass and bronze are not used as frequently for thermal dissipation. Pure copper has an extremely high thermal conductivity but, even more so than aluminum, the impurities needed to make casting or machining possible drop its conductivity dramatically. Table 1 shows how these impurities affect the thermal conductivity of copper.

The most common copper-based heatsink is a pure slug as a heat spreader on chip carriers. It is normally not economical, due to its high material cost, for larger uses.

	Pure Copper	Aluminum Bronze	Bronze	Red Brass
Conductivity	386 K/(m^{o}C)	83 K/(m^{o}C)	26 K/(m^{o}C)	61 K/(m^{o}C)
Composition	100% Cu	95% Cu, 5% Al	75% Cu, 25% Sn	85% Cu, 9% Sn, 6% Zn

Table 1 Copper Alloy Comparison

Zinc Alloys

Zinc, with its decent thermal conductivity (112 K/(m^{o}C)) compared to pure aluminum (204 K/(m^{o}C) often is overlooked as a heatsink material. In weight-sensitive equipment this oversight may be acceptable but in most other electronic cooling applications, especially medium to high volume, zinc alloys may have many benefits over aluminum. Several zinc alloys have unusual properties that make them rather attractive for diecast heatsinks.

Porosity Free Castings

With alloys added to zinc to help in strength, durability and castability, zinc remains porosity free in the casting process. This results in thermal conductivity loss less than aluminum or copper. In fact, its cast thermal conductivity exceeds that of most cast aluminum and copper alloys.

Low Cost

Zinc, sometime referred to as pot metal, is known as a low cost material for casting. In the electronic manufacturing industry, it is used extensively in high tolerance motor castings, electronic mounts and brackets and even switch housings. Where weight is a premium, aluminum can be used but at a penalty of 2 to 3 times the cost of a zinc alloy die cast. This tradeoff needs to be carefully examined where weight is a major concern. The zinc alloys ZA-8 and ZA-27 have a high percentage of aluminum in them which reduces their density. However, care needs to be used with ZA-27 due to its large coefficient of thermal expansion.

Low Pouring Temperature

Die casting always requires higher initial tooling costs than extruded or machined heatsinks. Aluminum die casts can be quite expensive since the mold must be machined out of steel. Lower melting temperature zinc alloys have the mold made out of easily machined aluminum, saving about 50% on the mold cost. However, if parts quantity is over 120,000, a long life steel mold may still be more appropriate.

Plating free

UL, CSA, DVE requires plating on aluminum but not zinc since it does not create a non-conductive film on its surface. This translates into lower overall costs by eliminating secondary manufacturing steps.

A comparison of different casting materials for same heatsink:

	Zinc Zamak 3	Zinc-Aluminum ZA-8 [b]	Zinc-Aluminum ZA-27 [c]	Aluminum poured 357	Aluminum die cast 380	Brass annealed 360
Tensile Strength (MPa)	2800	3700	4200	2200	3200	3300
Density (g/cm^3)	6.65	6.3	5.0	2.7	2.7	8.3
Melting Point (deg. F)	382 - 387	375 - 403	375 - 480	557 - 590	540 - 590	890 - 900
Coef. of Thermal Expansion (cm/cm ^{o}C)	27.4	23.2	26.0	21.8	21.4	20.5
Thermal Conductivity (W/m ^{o}C)	113	115	125	161	96.2	61
Tooling Cost ($)	$8,000 - $15,000[a]	$8,000 - $15,000[a]	$8,000 - $15,000[a]	$20,000 - $35,000[a]	$20,000 - $35,000[a]	$20,000 - $35,000[a]
Material Cost $ per pound	0.60	0.63	0.72	7.50 -12.00	7.50 - 12.00	10.00
Cost for part run of 10,000 each $	0.40	0.41	0.48	1.40	1.20	1.60

Table 2 Heatsink Casting Materials Comparison

Table Notes:

All prices are averages among several die casters for each process. Stronger weight of averaging on vendors who bid several different processes for same part.

a) Second price is cost for four cavity molds. This would reduce "cost per part" and useful for large lots.
b) ZA-12 (not listed) has a thermal conductivity that is 1.2% greater than ZA-8 and generally is not worth the cost premium for heatsinks.
c) ZA-27 has a 9% greater thermal conduction coefficient than ZA-8. However, its thermal expansion coefficient is quite high and could cause problems when attaching to many chip carriers. It can be effectively used when attachment surface area is small and secured with fasteners like TO-220s.

Summary

As can be seen when selecting a zinc alloy, ZA-8 has a thermal expansion match close to many copper backed chip carrier packages. Even though its thermal conductivity is less than that of ZA-27, or of ZA-12, the problems associated with thermal expansion mismatch can cause stress later.

Note "a" also specifies pricing for four cavity molds. When casting aluminum, a certain amount of cooling time is required to let the core solidify which results in a better thermally conductive heatsink. This cooling period takes a significant amount of time on very expensive die casting machines. Because of this, it is economical to produce multicavity molds even for runs as low as 20,000 parts. The cooling of zinc alloy in the die is relatively quick partly due to its lower melting point creating a smaller temperature differential. This results in a much faster diecasting time, benefiting in reduced costs per part. Single cavity molds are most economical for most zinc alloy castings until casting volumes pass 60,000 or so.

Also from the above compiled chart is the variation of weights in the casting materials. This variation should be noted in the material cost per pound calculations. Zinc, especially ZA-8, is well matched for electronic cooling heatsinks, has high thermal conductivity, has no secondary process requirements, is strong, and economical. However, where light weight is paramount, cast 380 series aluminum may be best. Where very high power densities are required, investigate hot isostatic pressing with 357 or similar series aluminum alloy.

References and Acknowledgements:

Dash, Glen A., Editor, *Compliance Engineering, 1993 Reference Guide*, Boxboro, MA, Compliance Engineering, 1993.

Dow Chemical, “Comparisons of Typical Casting Alloys,” data sheets

Flinn, Richard A. and Paul K. Trojan, *Engineering Materials and Their Applications*, Boston, Houghton Mifflin Company, 1981

Keller, K., “Cast Heatsink Design Advantages,” *Advances in Electronic Packaging* (Proceedings of the 1997 ASME / JSME Conference on Electronic Packaging),

Ozisik, Necati M., *Heat Transfer a Basic Approach*, McGraw-Hill, Inc. 1985.

Tummala, Rao R. and Eugene J. Rymaszewski, Editors, *Microelectronics Packaging Handbook*, New York, Van Nostrand Reinhold, 1989.

Yamaji, Y., Y. Atsumi and Y. Hiruta, “Thermal Characterization of LSI Packages Mounted on PC Boards: Evaluation of the Thermal Effects of PC Boards,” *Advances in Electronic Packaging* (Proceedings of the 1992 ASME / JSME Conference on Electronic Packaging), pp. 199 - 205.

Particular thanks to: Advance Die Casting Company, Aravalda Corp., Dycast Specialties, Dynacast, Formcast Inc., North Carolina State University, UNC Chapel Hill, Hewlett Packard, and Joni Julian.