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Development and Application of Thermally Functionalized Structural Materials for Heat Spreading in Handheld Devices

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Development and Application of Thermally Functionalized Structural Materials for Heat Spreading in Handheld Devices

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Abstract

Recent developments for clad metals enable thermal functionalization of structural components in consumer and handheld devices. By selectively replacing under-utilized structural space with highly conductive materials, thermal heat spreading performance in these devices can be substantially improved. A new composite Stainless Steel-Aluminum material system will be presented to serve both structural and heat spreading purposes, utilizing high stiffness stainless steel skins clad over a low density, highly conductive aluminum core. This configuration melds the best properties of each material, creating a fully formable composite structure with excellent mechanical and bulk thermal transport properties. It will be shown that using these conventional materials, the bulk thermal transport in the aluminum core can provide improved heat spreading compared to common micron-scale carbon film based materials, while maintaining stiffness and without taking up z-height.

Keywords

Heat Spreader, Clad Composite, Handheld Devices, Structural Materials, Thermal Management

1. Introduction

The ever-growing functionality of handheld devices is driving up the demand for power consumption, and in turn placing a heightened importance on managing the resulting heat generation. Device surface temperatures are often a limiting factor on the allowable power used in handheld devices, with maximum surface temperature for comfortable skin contact of around 41°C. This is commonly referred to as the *Ergonomic Temperature Limit*, and is an important value to consider when designing a mobile device or touch screen [1].

Unlike "conventional" electronic devices, which often have active cooling systems such as fans to mechanically remove heat from the device, passive cooling is a requirement for handheld devices. Thus, for a handheld to dissipate heat, it is limited by the natural radiation and convection of heat from its surfaces. Still, consumers demand that phones and tablets offer the same computing capabilities as a desktop system. Thus, to maximize the amount of energy a handheld device can use, it is important to fully exploit the heat transfer away from each surface [2]. To achieve this maximum heat transfer, an ideal device would have perfectly isothermal surfaces at the ergonomic temperature limit of 41°C. Any local hot spot, perhaps generated by the CPU or Li-Ion Battery, leads to inefficiencies in heat transport and directly limits the maximum allowable power in the device. Wagner *et. al.* found that common commercially available tablets are only 35-45% efficient at dissipating energy due to inhomogeneous surface temperatures [3]. Thus, improving the ability of phones and tablets to passively spread heat across the exterior surfaces will not only provide more comfort to the user holding a device, but just as important – it will directly enable more computing power.

To eliminate hot spots and improve energy dissipation in devices, there has recently been a large emphasis on specialty heat spreading materials added into device designs. A common class of heat spreading materials is based on oriented graphite films which have been rapidly adopted in consumer devices ranging from smartphones to LED Televisions. These graphite materials offer impressive in-plane thermal conductivity values that are many times larger than conventional metals such as copper (as high as 1700 W/mK), and are add-ons to designs that serve the sole purpose of spreading heat [4,5]. Though specialty graphite heat spreaders have large thermal conductivity values, they still have limitations based on their micron-scale thicknesses, cost and the lack of space available in handhelds for a robust thermal solution.

There is a trade-off in handheld design between adding a dedicated heat spreading solution and keeping devices as thin as possible at the lowest cost. To address this contradiction, Materion has developed a material that may be used to thermally functionalize components already required in handheld devices, allowing them to serve as bulk thermal heat spreaders without taking up valuable internal space. Attractive targets for this functionalization are the structural components that give devices strength and rigidity against bending. A newly developed process enables Aluminum-Stainless Steel composite materials (tradename *e*Stainless) to be manufactured with a valuable combination of stiffness and thermal conductivity. By adding thermal functionality to structural materials, it is possible to enhance thermal heat spreading capacity while reducing system costs and taking up less internal space.

2. Material Development

Structural components forming chassis or case components in handhelds are prime candidates for thermal functionalization. These materials are required to provide strength and rigidity to the device in order to protect the screen and internal components such as the battery and processors, but in the smallest volume and least weight. In essence, structural components are an unfortunate necessity which can get in the way of materials with more value-add.

In most devices, the majority of loading on these components is in bending, and the materials forming beams and panels loaded in bending are not uniformly utilized. The material located near the surfaces of these structures support the vast majority of the load, while material near the neutral axis supports significantly less. This basic concept drives the use of I-Beams in construction and the development of honey-comb cored composite materials, which allow lighter weight structures to support the same loads as solid geometries. Just as in these bulk examples, this concept has significant potential to change the way handheld devices are designed.

Using this approach, a composite material may be designed to take advantage of dissimilar conventional materials with advantageous properties. The under-utilized material near the core of structural components can be put to better use as a heat spreader, with the outer skins of the beam supporting the mechanical loads. An illustration of this configuration is shown in Figure 1.

The primary requirements for such a material are:

Core: High Thermal Conductivity, Low Density & Cost
Outer Skins: High Strength & Stiffness, Low Cost

Additionally, it is important that the composite be fabricated in coil form, using a reel-to-reel process to enable the material to be efficiently stamped and formed into a finished component.

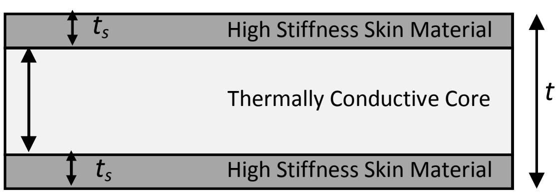

Figure 1. Cross section illustration of a composite sandwich structure with thickness *t*, utilizing specialized high modulus skins over a lightweight, thermally conductive core.

Properties of some potential thermally conductive core materials are shown in Table 1, along with cost and performance metrics. Costs in this analysis are from the London Metals Exchange for copper and aluminum in December 2014, with an approximated graphite sheet price at roughly 50% of that available from several online distributors. Pound-for-pound, high purity aluminum is an attractive material to provide the largest thermal conductivity, *k*, at the lowest cost (*i.e.* lowest cost per watt). This data also demonstrates one disadvantage of graphite based heat spreaders, in which the micron-scale thickness limits the heat spreading effectiveness for the cost of the material.

Many structural components in handhelds are currently manufactured out of stainless steel to make use of its high stiffness and low cost for coils of metal strip relative to other materials commonly considered for lightweight structural designs (Table 2). These same properties make it an attractive

	Market Cost	**Density (kg/m^3)**	**Thermal Conductivity, k (W/m*K)**	**Cost per Volume $\$/m^3$**	**Cost per Watt ($\$ K / W m^2$)**
Copper C10200	\$6.62/kg	8900	400	\$58.9k	147
Aluminum A91100	\$1.98/kg	2710	220	\$5.3k	24
50µm Graphite Sheet (50mmx75mm)	\$1.00/Pc	900	1500	\$5,333k	3556

Table 1. Cost and performance properties of potential materials for the thermally conductive Core. Though Copper and Graphite products have attractive thermal conductivity values, the cost per watt dissipated is a disadvantage. A high purity aluminum alloy such as aluminum A91100 is a much more cost effective material for heat spreading.

option for the skin layers of a thermally functionalized structural composite. Though titanium and magnesium have low densities that make them attractive as lightweight mono-metal structural solutions, 4.5 g/cm^3 and 1.74 g/cm^3 respectively, the proportionally lower elastic moduli and higher costs for these materials are a disadvantage in making a rigid composite material. (Pricing is based on strip metal quotes and includes fabrication costs, as there is no consistent metal market for these metals) Additional disadvantages of magnesium are brittleness, which makes it difficult to stamp and form in low cost processes, as well as a low ignition temperature which requires additional alloying for improved safety in some applications [6].

	Relative Costs	**Elastic Modulus (GPa)**
Stainless Steel	1	193
Titanium	5	116
Magnesium	3	44

Table 2: For low cost, high stiffness skin materials in strip form, stainless steel is a clear choice compared to other materials commonly considered for structural components. (Not considering fabrication costs, which may vary significantly).

The bending modulus, E_b, of a laminated sandwich style material (Fig. 1) is well established, and may be defined as:

$$E_b = \sum_i I_i E_i \Big/ \sum_i I_i \qquad \text{Eq. 1}$$

Where the sum is performed over, *i*, the properties of the core and skin materials where E_i is the elastic modulus of each layer, and I_i is the moment of inertia. The moment of inertia for the core, I_c, is

$$I_c = \frac{bt^3}{12} \quad \text{Eq. 2}$$

and the outer skins I_s, is,

$$I_s = \frac{b}{12}(t^3 - t_c^3) \quad \text{Eq. 3}$$

Where t is the overall thickness of the composite, t_c is the thickness of the core and b is the width of a beam [7].

The average in-plane thermal conductivity values, $\overline{k}$,is simply defined by sum of the thermal conductivity for each material, k_i, multiplied by the volume fraction of each material, f_i [8]

$$\overline{k} = \sum_i k_i f_i \quad \text{Eq. 4}$$

For a stiff, thermally conductive beam it is important for a material to simultaneously have both a large bending modulus, E_b, and Thermal Conductivity, $\overline{k}$. Forming a materials metric by multiplying these materials properties together, Figure 2 demonstrates how the combined thermo-mechanical properties of a stainless-aluminum composite vary with the thickness of the steel skins, t_s, relative to the overall thickness. A maximum combination of conductivity and stiffness occurs at steel layer thickness of roughly 15% of the whole, setting this as a target configuration for a structural heat spreading material.

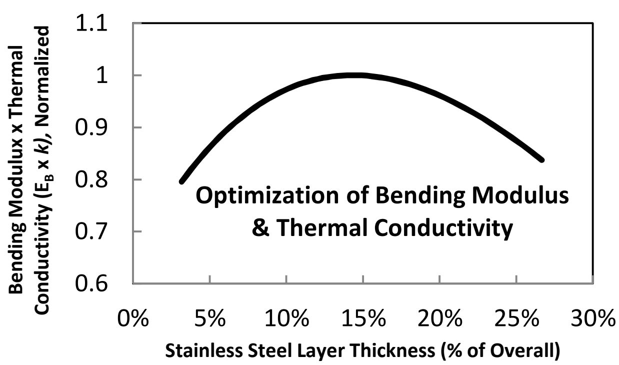

Figure 2. Normalized values of the Bending Modulus multiplied by the Thermal Conductivity value for a composite steel-aluminum sandwich structure, with varying thickness of the steel skin layers. An optimum combination of properties exists at stainless layer thicknesses t_c=0.15t (15%).

With these material design considerations, it is calculated that combining stainless steel and aluminum together in a sandwich structure with a ratio of 15% - 70% - 15% should have an attractive set of properties with nominally 80% the bending stiffness of stainless steel, but with only 53% the density. Furthermore, its average in-plane thermal conductivity is expected to be 10x larger than stainless steel to function as an effective heat spreader – 160 W/m*K. Most analytical work in this manuscript will assume 15% stainless steel skins as a model case.

3. Material Characterization

Stainless-Aluminum Composite materials were produced in a reel-to-reel cladding process with stainless steel skin thicknesses of 0.1t and 0.19t. These were characterized for mechanical and formability, as well as for heat spreading compared to a common graphite solution.

3.1 Mechanical Characterization

The bending modulus of the composite material was measured using DIN EN 12384 on a Zwick automated Spring Bend Limit Tester. Good agreement between the predicted values using Eq. 1 (Table 3)and the measured values indicate that calculated materials properties may be used with good confidence to extrapolate performance to other configurations.

The hardness of each layer of the composite was measured preparing polished cross sections with diamond pyramid Vickers hardness testing.

The formability of the composite was measured per ASTM B820 using a v-block and inspecting for cracking under 50x magnification. Formability of less than 1 r/t was achieved.

Thermal conductivity values were calculated using the approach of Salazar, with Eq. 4 [8].

	10% Steel-Aluminum Composite	19% Steel-Aluminum Composite
Thickness (mm)	0.20	0.25
Bending Modulus (GPa) Actual/Calculated	145/135	166/167
Thermal Conductivity (W/m K)	179	143
Steel Hardness (HV)	185-195	155-175
Density (g/cm^3)	3.79	4.71
Formability (r/t)	< 1	< 1

Table 3: Summary of calculated and measured structural and thermal properties of two clad Aluminum-Steel composite configurations.

3.2 Heat Spreading

The comparative ability of various materials to spread heat was analyzed by placing coupon samples horizontally on a 60°C hot spot generated by a constant temperature heat plate (Figure 3) and recording the temperature distribution over time with a FLIR camera.

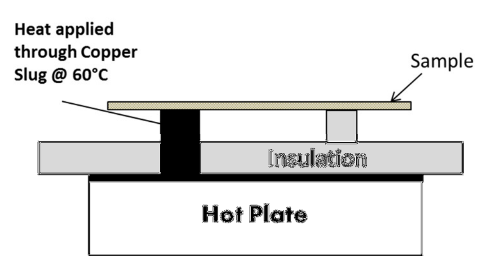

Figure 3. Schematic of the heat spreading test setup, with a constant temperature hot plate, which heated the copper slug to 60°C prior to testing. Plan-view thermal images were taken from a FLIR camera mounted above the horizontal sample.

To compare the thermal heat spreading performance of the stainless-aluminum composite with the common approach of using thin layers of graphite, PGS Thermal Graphite Sheets were used with a graphite thickness of 25µm and an adhesive layer of 18µm. The graphite sheets, which have a reported thermal conductivity of 1600 W/m*K, were applied with the included adhesive as a blanket over-layer on top of a 0.51mm thick stainless steel. Three of the samples tested are shown in Table 3.

	Total Thickness (mm)
Stainless Steel	0.51
0.5mm Stainless Steel + Graphite Sheet	0.55
Aluminum-Steel Composite (10%)	0.55

Table 3. List of samples compared for thermal-heat spreading performance.

The ambient and initial sample temperatures were 22°C. The hot spot surface temperature sample was stabilized at 60°C prior to the test (Fig 4a), after which samples were placed horizontally across the copper hot spot and a piece of supporting insulation. Other than the copper hot spot, the remainder of the hot plate surface was covered with 12mm thick insulation (Fig 3). Test samples were suspended 10mm over the insulation, allowing convective heat transfer from top and bottom surfaces.

A FLIR Thermal Imaging Camera Model EX320 was used to collect temperature profiles as a function of time. For consistent sample-to-sample results, all test coupons were painted matte black prior to testing. The camera emissivity was set to 0.98. Screen captures after 2 minutes of heat spreading are shown in Figure 4C-D. Compared to stainless steel (Fig 4b), both the graphite sample (Fig 4C) and the stainless-aluminum composite (Fig 4D) reduced the hot spot temperature by 10 and 12°C, respectively. The surface of the stainless-aluminum composite was much more isothermal.

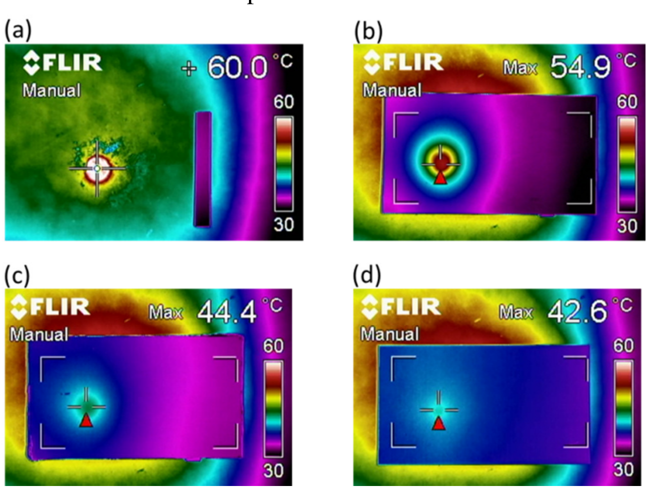

Figure 4. Thermal gradients after 2 minutes for the 0.5mm coupon samples. (a) Hot spot at 60°C before test (b) Stainless Steel (c) Stainless Steel + 25µm Graphite Film (d) Stainless-Aluminum Composite with 10% steel skins.

4. Discussion

In Figure 4, the heat spreading capability was compared between an 0.51mm steel sample with 25µm graphite heat spreader, and the new stainless-aluminum composite of the same 0.55mm overall thickness. The stainless-aluminum composite is shown more effectively spread heat than the 25µm graphite heat spreader. This is not only due to the hotspot temperature being lower by approximately 2°C, but because the surface of the composite material has shallower temperature gradients and is more isothermal across the surface. Over the surface of the test coupon, the stainless + graphite sample had a roughly 12°C temperature gradient along its length, compared to approximately 6°C for the stainless-aluminum composite. This equal temperature utilization of the surface area in the composite structure will more effectively dissipate heat to the ambient, which in a consumer device means more power may be consumed without violating the ergonomic temperature limit.

With heat spreading in thin, wide aspect ratios panels, the geometry of thermal transport is necessarily planar with minimal temperature gradient expected through the thickness of the sample. In the case of thin film heat spreaders, this 2-dimensional heat flow allows the substrate layer (in the present case, stainless steel) to act as a thermal mass which limits the speed of heat conduction (heat cannot flow through the film without first warming the steel substrate layer).

For non steady-state heat transfer, the kinetics of heat spreading factors in the heat capacity of the material, and is proportional to the *Thermal Diffusivity,* α

$$\alpha = \frac{k}{\rho C_p} \qquad \text{Eq. 5}$$

Where ρ is the density and C_p is the heat capacity. For parallel path conductance, values in this equation may be treated as weighted average values for composite systems using the approach of Eq. 4 [8].

In Table 4, thermal diffusivity values are compared for the Stainless-Aluminum composite, compared with 0.3mm and 0.5mm stainless steel with the same 25 µm, 1600 W/m K, graphite used in the heat spreading test (Figure 4).

	Heat Capacity, C_p (J/kg)	**Thermal Conductivity, k (W/m K)**	**Thermal Diffusivity, α (mm^2/s)**
15% Aluminum Stainless	678	160	55
0.5mm Steel + 25µm Graphite	500	83	24
0.3mm Steel + 25µm Graphite	500	121	38

Table 4: Summary of thermal diffusivity values for a Stainless-Aluminum composite with 15% steel on both sides of the Al91100 core, compared to two thicknesses of stainless steel with a blanket layer 25µm graphite sheet.

The thermal diffusivity values in Table 4 help make clear the performance of the stainless-aluminum composite in Figure 4. Due to the limited thickness of the graphite heat spreader (Fig 4c), the ability of the film to dissipate heat in the composite system is limited by the thermal mass of the stainless steel. In contrast, the thermal diffusivity of the aluminum-stainless composite is roughly two times larger.

In addition to thermal diffusivity (or thermal conductivity), for structural components it is also important that materials have large stiffness. In Figure 5, the thermal diffusivity and effective bending moduli are plotted against each other for various material systems that are of interest to handheld devices. The ideal thermally-functionalized structural material would have both large thermal diffusivity and a large bending modulus, placing it in the upper right hand corner of this chart. Materials with attractive thermal properties, such as magnesium and aluminum 6061, tend to have very low stiffness properties. On the other hand, good structural materials such as 316 stainless steel have very poor thermal properties. To consider steel with a graphite heat spreader, the average thermal diffusivity is plotted against a calculated bending modulus value that assumed the graphite provides no support to bending loads.

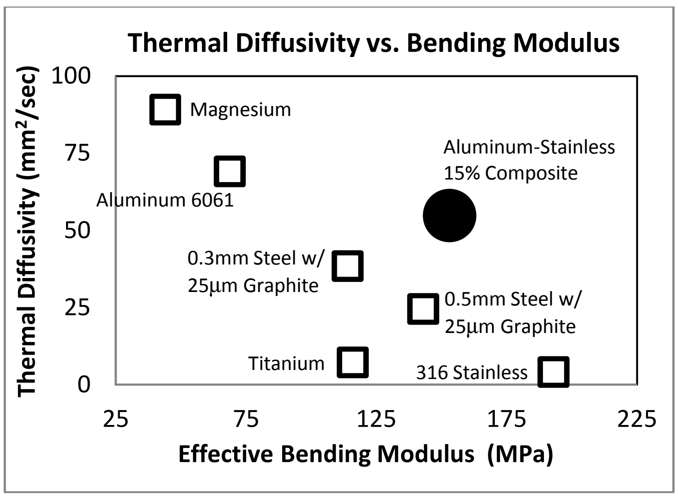

Figure 5: Average Thermal Diffusivity plotted vs. the Average Bending Modulus for materials of interest in handheld devices. An ideal thermally conductive structural material would be in the upper right of the chart, with the Aluminum-Stainless composite with 15% steel skins outperforming commonly used material systems.

With the assumption that graphite films do not support bending loads, the average bending modulus of Steel + graphite systems are typically lower than the aluminum-stainless composite. In device design, this offers the potential to reduce the overall thickness of components without sacrificing stiffness, and while enhancing thermal conductivity.

5.0 Summary & Conclusions

A new composite material of stainless steel and high purity aluminum was developed to serve both structural and thermal heat spreading purposes. The material is produced in a high volume reel-to-reel process capable of producing fully formable product with annealed temper properties. This allows the composite material to be used in high volume automated stamping and forming operations for low cost production of components.

The new clad Stainless-Aluminum composite has roughly 10x the thermal conductivity of stainless steel, but maintains 80% of the bending modulus. For use as a structural component, the broad area footprint of the composite material will increase the distance over which heat may be transported, but without taking up added internal volume. Additionally, average thermal diffusivity values for the composite are higher than the same thickness of stainless steel with common graphite heat spreaders.

Based on widely available conventional metals, and manufactured in large volumes, the stainless-sluminum composite is a cost effective alternative to specialty graphite materials when used as a structural component. Through using otherwise under-utilized volume in structural materials to spread heat through devices, thermal performance of devices may be improved, while potentially freeing up internal space for functional components.

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