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MATERIAL DEPENDENCE OF TEMPERATURE DISTRIBUTION IN MULTI-LAYER MULTI-METAL COOKWARE

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Abstract

Laminated structure is becoming more popular in cookware markets; however, there seems to be a lack of enough scientific studies to evaluate its pros and cons, and to show that how it functions. A numerical model using a finite element method with temperature-dependent material properties has been performed to investigate material and layer dependence of temperature distribution in multi-layer multi-metal plate exposed to irregular heating. Behavior of two parameters including mean temperature value and uniformity on the inner surface of plate under variations of thermal properties and geometrical conditions have been studied. The results indicate that conductive metals used as first layer in bi-layer plates have better thermal performance than those used in the second layer. In addition, since cookware manufacturers increasingly prefer to use all-clad aluminium plate, recently, this structure is analysed in the present study as well. The results show all-clad copper and aluminum plate possesses lower temperature gradient compared with single layer aluminum and all-clad aluminum core plates.

Keywords*:* Laminated plate, Multi-metal plate, Conduction, Temperature distribution, Cookware.

1. Introduction

Almost 90% of indoor energy is used for cooking applications in under developed nations [1]. Traditional fuels are widely consumed by rural households as a means

Nomenclatures

[B]	Derivative of [N], $=\frac{\partial[N]}{\partial x}$
DT	Temperature gradient (T_{max}-T_{min}), K
d	Layer thickness, mm
{f}	Force matrix
{g}	Gradient matrix
h	Convection coefficient, W/m^2K
[K]	Element stiffness matrix
k	Conduction coefficient, W/m K
N	Shape function
Q	Constant heat source
q	Heat flux, W/m^2
Tmean	Average temperature, K

Greek Symbols

Δr	Length of heat source, cm
∇	$\left(\frac{\partial}{\partial x},\frac{\partial}{\partial y}\right)$

Abbreviations

ANN	Artificial Neural Network
APDL	ANSYS Parametric Design Language
CrNi	Chromium nickel
SSt	Stainless steel
TD	Temperature Distribution
Ti	Titanium

Subscripts

c	Conduction
h	Convection
P	Plate

to satisfy their indoor energy demands [2]. Wood is the primary fuel used for cooking in rural areas of developing nations [3]. As a result, each year, a large amount of deforestation takes place for cooking purposes [4]. Concequently, efficient and properly designed cookware can be effectively utilized to decrease household energy consumption. A design should be developed for getting the most heat into the cookware to increase efficiency and economize the energy use.

Meanwhile, in modern societies, the consumer demands cookware of high quality, performance and good looks. The cookware industry's response to market needs was a widespread selection of pots and pans [5]. However, little research has been published to quantify cookware performance. A pan made from a single material when heated by an open flame, develops hot spots that can locally burn its contents. That is because the saucepan is thin, and heat is transmitted through the thickness more quickly than it can be spread transversely to bring the entire inner pan-surface to a uniform temperature. Saucepans are usually made of cast iron, duralumin (a range of aluminum-copper alloys) or copper and have isotropic thermal conductivities, whereas what we clearly want is a thermal conductivity that is higher in the transverse direction than in the through-thickness direction [6].

It is difficult for a single material to meet a wide variety of demands such as superior thermal and chemical properties [7, 8]. Different metals need to be bonded together to satisfy the mentioned demands. A multi-layer structure has positive influence on improving the quality of temperature distribution (TD) including uniformity and temperature magnitude [9]. Consequently, the thermal efficiency is increased by getting the most heat into the pot's content, and it can reduce the energy consumption. Using multi-layer plate causes regular TD on the top surface while the bottom surface heats irregularly [10-12].

There are a few technical papers which report on experimental or numerical methods which were used to study cookware performance. Sabilvo et al. [5] used a finite element method to simulate conduction heat transfer through the pot. They also studied the effect of conductivity on cooking quality. An analytical model has been used to simulate convection heat transfer from the burning head to the dish by Jugjai and Rungsimuntuchart [13]. They achieved a high efficiency by using the swirling central flame. Lucky and Hossain [14] conducted an experimental research on Bangladeshi cookstoves and they also compared the thermal performance of a pan with a pot (the latter has taller wall). Oyedepo [15] recommended that pan size should be matched to the size of the burner on the stove top. Karunanithy and Shafer [16], recently used an experimental method to study the heat transfer behavior of different pans on various cooktops. According to their research, natural gas, electric stove, and induction cooktops provided efficiencies of 28, 39 and 70%, respectively.

Jeddi et al. [17] used finite element method to model heat transfer from burners to pan. Ayata et al. [18] used ANN to predict the temperature distributions in different alloys of copper and aluminium layered base of a chromium nickel saucepan. They found that copper has better performance than aluminum as the bottom layer and the optimum thickness of bottom layer was determined as 8 mm for copper. Sedighi and Dardashti [12] used a finite element analysis software, ANSYS, to model transient conduction heat transfer in a pan to calculate the heat transfer and temperature distribution on inner surface of the pan . In addition, they exposed cookware to a flame jet and studied its thermal behavior under thermal conductivity variations [19]. Cadavid et al. [20] calculated thermal efficiency of a pot exposed to an electric coil by using ANSYS FLUENT. The numerical and experimental research demonsarated that increasing the pot diameter directly increases the cooking efficiency, whereas heat losses increase with increasing the pot height.

In the current work, a numerical simulation of the system has been carried out using the finite element method to study the dependence of heat transfer and temperature distribution on multi-metal and multi-layer structures. Moreover, temperature-dependent thermal properties of materials have been considered.

2. Materials and Methods

Since we want to model irregular heating, the annular part of the circular surface of the bottom side of the pan illustrated in Fig. 1 as Δr, was constrained by a constant temperature of 773 (K). There is a geometrical symmetry, so the system can be modeled by a rectangular plane having a length equal to the radius of the pan, and a thin and long rectangle as the wall of the pan. Because of the symmetry, the temperature gradient at the center of the plate along the z-axis have zero value. Hence, there is no heat flux at the center of the plate along the z-axis. The side of the pan has convection heat transfer with air at ambient temperature. The thickness of the plate is 10 mm.

In the first part, the analysis has been extended to 49 metals used in 2-ply plates. When the same metal is used in both layers, it is considered as single layer plate. The thicknesses of first (*d1*) and second (*d2*) layers are 7.5 and 2.5 mm, respectively.

The ambient temperature and the coefficient of heat transfer have been assumed as 293 K and 17 W/ (m^2.K), respectively. In addition, the pan is filled with water and the convective heat transfer coefficient of 50 W/ (m^2.k) [18] has been assumed. Three nodes have been selected on non-heated surface for calculating the temperature distribution including T_1(0,0.1); T_2(4,0.1); T_3(10,0.1), where coordinates are given in cm. ANSYS Parametric Design Language (APDL) is used to perfom finite element model.

Forty nine metals have been applied for each layer in various cases. Two loops were defined to change the 49 metals through two layers. Overall, 2401 models were analysed. The properties of all metals are according to Incropera [21]. It should be noted that only thermal properties of metals have been applied, so the authors did not consider the chemical and mechanical properties. Therefore, when the results suggest one metal, it means only a thermal-property standpoint has been considered. The current research can be treated as a basis for future research which should use present results with other chemical and mechanical considerations required by the applications.

In another section, we have applied the metals used in the cookware industry in one to four layer structures. The thickness of each layer is illustrated in the Fig. 1. Copper (Cu), aluminum (Al), chromium nickel (CrNi), titanium (Ti) and stainless steel (SSt) have been used as the layers.

3. Governing Equations and Numerical Method

In the finite element method, a given computational domain is subdivided as a collection of a number of finite elements, subdomains of variable size and shape, which are interconnected at a discrete number of nodes. The solution of the partial differential equation is approximated in each element by a low-order polynomial in such a way that it is defined uniquely in terms of the solution at the nodes. The global solution can then be written as series of low-order piecewise polynomials with the coefficients of series equal to the approximate solution at the nodes [22].

The problem can be addressed by solving the steady state two-dimensional energy equation in a fixed solid domain in the absence of any heat generation inside the material.

$$\nabla.(k\nabla T) = 0 \tag{1}$$

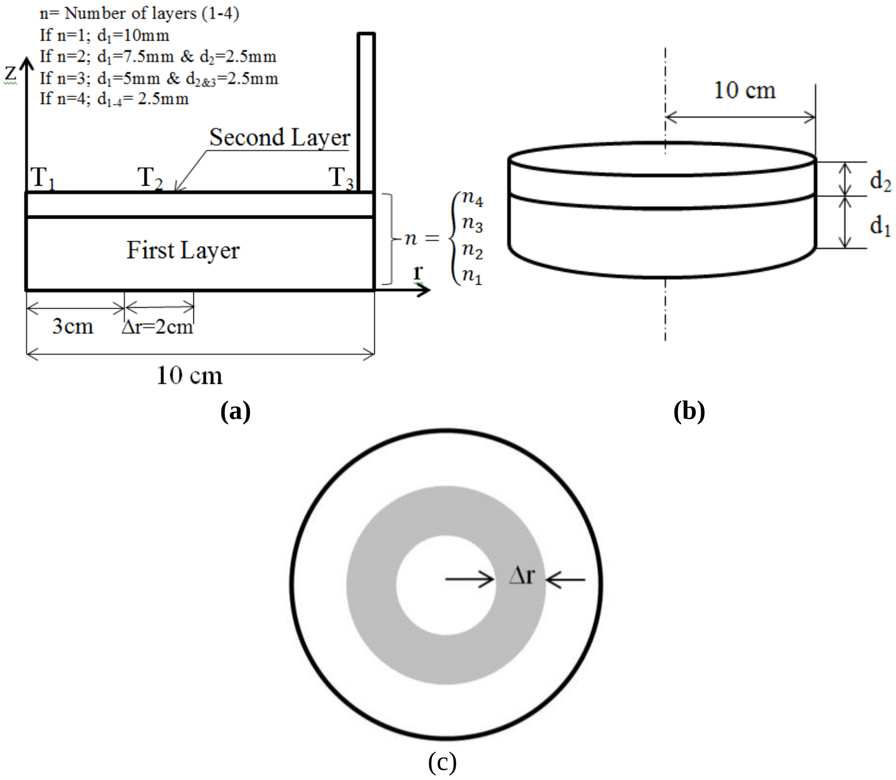

Fig. 1. Schematic of section of a circular multi-layer plate:
(a) 2D, (b) 3D and (c) the annular part of bottom side of the pan.

The finite element method for two-dimensional heat analysis is governed by [23, 24]:

$$\{g\} = \begin{Bmatrix} \dfrac{\partial T}{\partial x} \\ \dfrac{\partial T}{\partial y} \end{Bmatrix} = \begin{bmatrix} \dfrac{\partial N_i}{\partial x} & \dfrac{\partial N_j}{\partial x} & \dfrac{\partial N_m}{\partial x} \\ \dfrac{\partial N_i}{\partial y} & \dfrac{\partial N_j}{\partial y} & \dfrac{\partial N_m}{\partial y} \end{bmatrix} \begin{Bmatrix} t_i \\ t_j \\ t_m \end{Bmatrix} \tag{2}$$

$$[B] = \frac{\partial}{\partial x}[N] = \frac{1}{|x|}\begin{bmatrix} \beta_i \beta_j \beta_m \\ \gamma_i \gamma_j \gamma_m \end{bmatrix} \tag{3}$$

where analogous to strain matrix is $\{g\}=[B]\{t\}$. $[B]$ is derivative of $[N]$. Heat flux and temperature gradient are written as:

$$\begin{Bmatrix} q_x \\ q_y \end{Bmatrix} = -\begin{bmatrix} \mathrm{K}_{xx} & 0 \\ 0 & \mathrm{K}_{yy} \end{bmatrix}\{g\} = -[D]\{g\} \tag{4}$$

$$[k]=\iiint_V [B]^T[D][B]dV+\iint_S h[N]^T[N]dS \tag{5}$$

where the heat source is constant, we have:

$$\{f_Q\}=Q\iiint_V [V]^T dV=\frac{QV}{3}\begin{Bmatrix}1\\1\\1\end{Bmatrix} \tag{6}$$

$$\{f\}=[k]\{t\} \tag{7}$$

Stiffness matrix is the general term for a matrix of known coefficients being multiplied by unknown degrees of freedom, i.e., temperature, etc. Thus, the element conduction matrix is often referred to as the stiffness matrix.

$$\{F\}=[K]\{t\} \tag{8}$$

Heat flux boundary conditions are already accounted for in derivation. It is then substituted into above equation and solved for the nodal temperature and element temperature gradient [23,24].

4. Results

The numerical results of material and layer number dependencies of heat transfer are persented here. Results clearly show that the temperature distribution varies through different conductivities and structures (single and multi-layer) used.

4.1. Material dependence of temperature distribution (multi-metal bi-layer plate)

In this part, 49 metals listed in the appendix, were used in each layer. Figure 2 shows the mean temperature and temperature gradient on the non-heated surface of 2-ply multi-metal plates. The maximum mean temperature belongs to silver/nichrome (P40_31) which is as high as 760 (K). As shown in Fig.2, the mean temperature on the top surface increases with using conductive metals in the first layer. The first 10 are silver, copper, gold, aluminum, cartridge brass, magnesium, iridium, tungsten and rhodium.

The difference of maximum and minimum temperatures on the non-heated surface of bi-layer multi-metal plates is demonstrated in Fig. 2 as well. The lower the temperature differencs (*DT*) is, the more evenly distributed the heat becomes. The result suggests the use of conductive metals in the first layer to minimize the *DT* parameter. In other words, the plates in which their first layers are conductive metals, have lower temperature gradient than the plates in which their first layers are low-conduction metals. Therefore, silver, copper, gold and aluminum, which are ranked in order of *DT* from the lowest to the largest, are recommended to be used in the first layer.

The minimum temperature difference (the most uniformed one) is related to the 2-ply silver/bismuth plate by 28 K. Boron, inconel X-750, constantan, nichrome, titanium, stainless steels, zirconium, germanium and lead also provide a low temperature differenceas second layer.

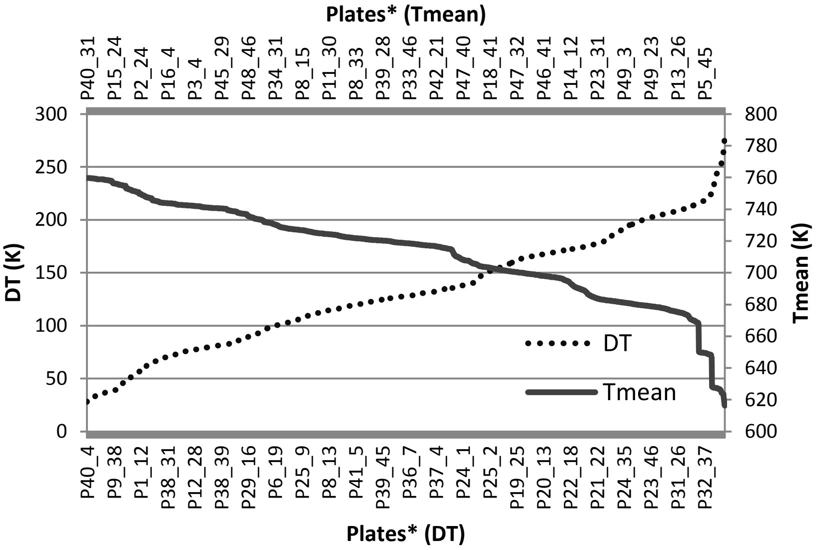

Fig. 2. Mean temperature and temperature gradient on non-heated surface of 2-ply multi-metal plates.

*The order of numbers shows the metals of first and second layers respectively as shown in the appendix.

Figure 3 shows the local temperature distribution of cooking surface of 2-ply silver/nichrome and single layer silver plates. There is a relatively cool zone along side of the plate caused by air convection heat transfer. The *T1* and *T2* nodes which are near the heat source in single layer silver plate (silver/silver) have a higher temperature than *T1* and *T2* in 2-ply silver/nichrome plate, while the *T3* located at the edge of the plate is lower than silver/nichrome specimen, as shown in Fig. 3. This behavior of silver/nichrome provides lower temperature gradient on the surface. That is because the plate is thin, and heat is transmitted through the thickness more quickly than it can be spread transversely to bring the entire inner pan-surface to a uniform temperature. In silver/nichrome plate, two metals with two different thermal conductivities are bonded with each other so that one metal layer possessing a lower coefficient of thermal conductivity than the other metal layer of composite. That is why the heat saturates in that layer prior to being transferred to the second layer.

The local temperature distribution of silver, copper, aluminum, iron and stainless steel are compared as shown in Fig. 4. This figure demonstrates the mean thermal conductivity of each metal in its legend. Thermal conductivity of the plate was the most influential factor on the surface temperature distribution. It was particularly notable in the side of the plate but became less significant near the heat source and center of the plate.

The conductive metals have higher temperatures on the inner surface. Note that the hot ring was considered as a constant temperature annular surface. Therefore, it is predictable that high conduction metals lead to higher uniformity, consequently, temperature throughout the plate becomes close to the heat source temperature. Ayata et al. calculated the temperature distribution in copper and aluminum layered base of a chromium nickel saucepan. They found that copper provides greater temperature distribution than aluminum [18]. In addition Jeddi et al. [17], Hanani et al. [25] and Sedighi et al. [19] reported that thermal performance of cookware increases with increasing the thermal conductivity.

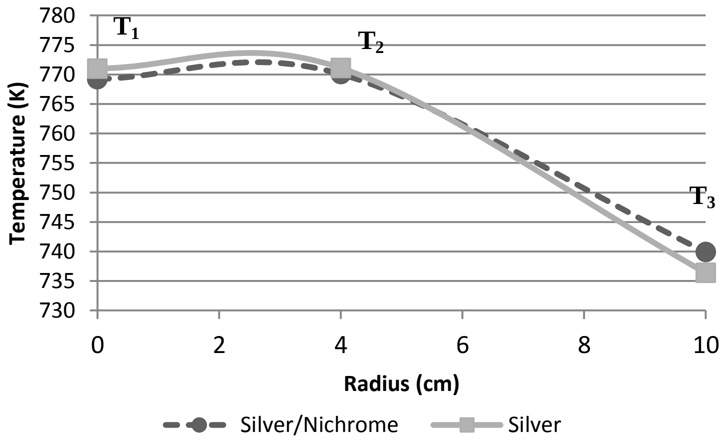

Fig. 3. Local non-heated surface temperature distribution along the radial direction of silver/nichrome and silver plates.

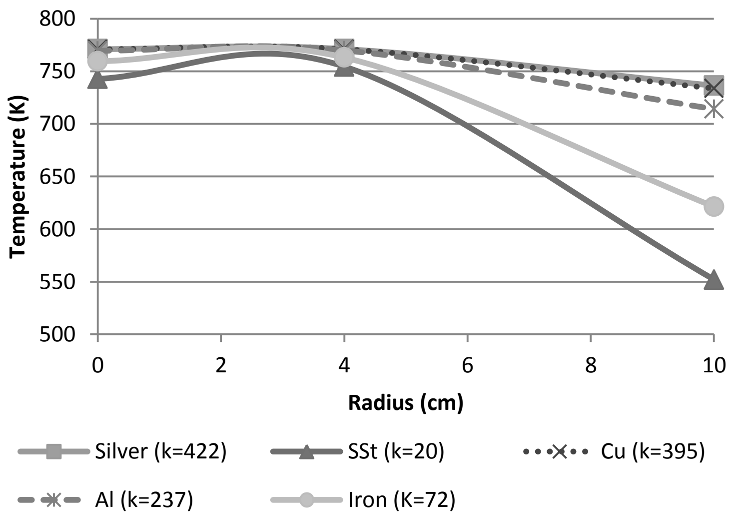

Fig. 4. Local non-heated surface temperature distribution along the radial direction of the plates.

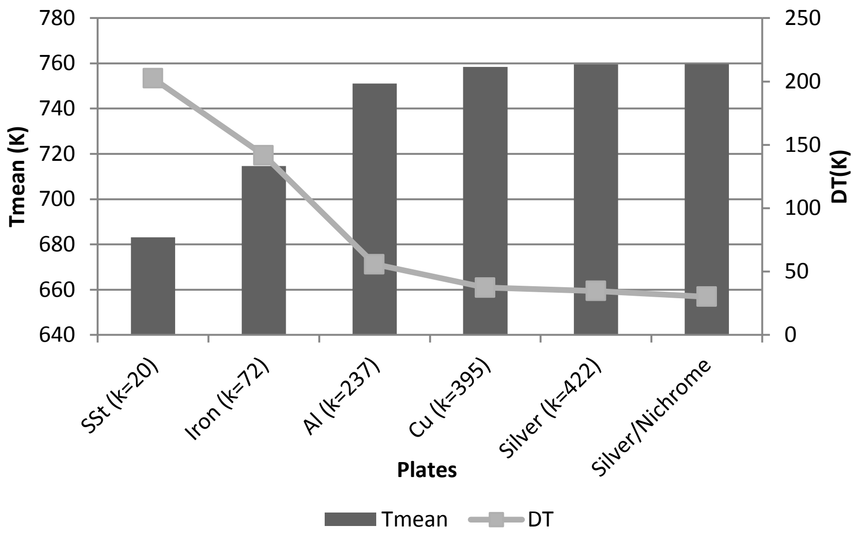

Fig. 5. Mean temperature and temperature gradient on non-heated surface of different materials.

When thermal conductivity of the plate increases to higher values, its positive influence on the temperature distribution diminishes. It was observed from Fig. 5 that with regards to the mean temperature and temperature gradient on the non-heated surface, there is a sharp rise in mean temperature and uniformity from conductivity coefficient of 20 (SSt) to 237 (Al), then it increases slightly. In addition, the figure clearly shows that silver/nichrome has lower temperature gradient on the surface than single layer silver plate, however it shows the same mean temperature.

4.2. Layer number dependence of temperature distribution (multi-layer plate)

In this part, aluminum, copper and stainless steel are used together in a multi-layer structure including one to four layers. Recently, in the industry there is an increasing preference to bond stainless steel, as a non-reactive metal, around a core made out of a conductive material, such as aluminum or copper for manufacturing pots. This structure is called “all-clad”. Furthermore, cookware manufacturers prefer to use aluminum rather than copper due to its lower price. The temperature difference in single layer and multi-layer cookwares, including two, three and four layers, which are made of aluminum, copper and stainless steel are compared in Fig. 6. The 2-ply plate including copper and stainless steel with thicknesses of 7.5mm and 2.5mm respectively, provides the highest temperature uniformity on the cooking surface. As shown in Fig. 6, all-clad copper and aluminum plate has lower temperature gradient than single layer aluminum and all-clad aluminum core plates. Also the maximum temperature gradient belongs to single layer stainless steel due to its low heat conduction.

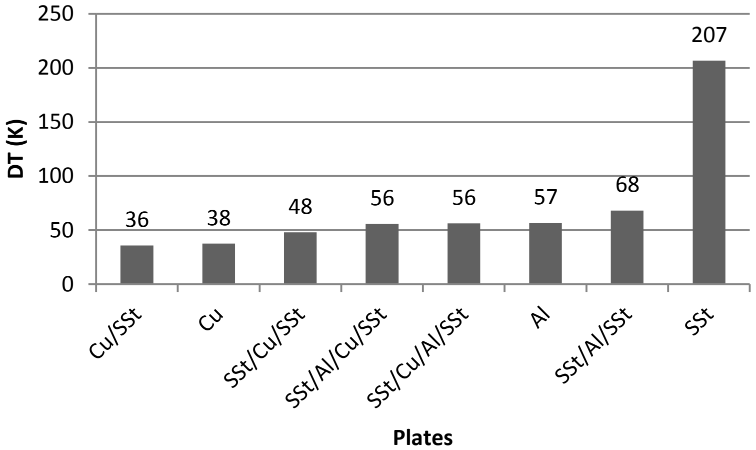

Fig. 6. Temperature gradients on cooking surface of single and multi-layer plates consisting aluminum, copper and stainless steel.

5. Conclusions

Finite element method was employed to study the influence of different materials and multi-layer structures used to manufacture cookware, on heat transfer and temperature distribution. Comparison of temperature distribution, subdivided to temperature gradient and mean temperature, was made through multi-layer multi-metal plates, which have different thermal conductivities and were heated non-uniformly under steady state conditions. Temperature dependent thermal properties of the materials are used.

Forty nine metals in 2-ply plates were applied so as to compare temperature distributions on non-heated surface of the plates to determine which combination of metals provides more uniform temperature distribution. Results clearly suggested that when the first layer exposed to the heat source, is a conductive metal, it provides a higher mean temperature and uniformity on the non-heated surface, whereas low conduction metals as first layer, show poor thermal performance. Nonetheless, low-conduction metals as second layer have an acceptable behavior regarding the mean temperature and temperature gradient. This result can be useful in designing cookware as there is a need to bond multi-metals together with different thermal properties to meet a wide variety of demands. In this study only thermal properties of metals are considered, while chemical and mechanical properties are not considered. Bi-layer plates including silver/inconel X-750, silver/nichrome, silver/stainless steel, silver/constantan and silver/titanium, ranked in order, have satisfactory behavior with respect to the two parameters of Tmean and DT. Moreover, copper, gold and aluminum as first layer satisfy the two factors. In addition, bismuth, inconel X-750, constantan and titanium in first layer have poor performance due to their poor conduction.

The analysis has been extended by changing the number of layers. Copper, aluminium and stainless steel applied widely in cookware industry, were used together to form single and multi-layer cookware including two, three and four layers in order to find temperature distribution on cooking surface of the plates. Results clearly showed all-clad copper and aluminum plates create lower temperature gradient compared with single layer aluminum and all-clad aluminum core plates. Also single layer stainless steel is not suitable to use due to its poor heat conduction.

Much work remains to be done for further improving thermal performance of the multi-layer multi-metal plates. Chemical and mechanical properties of the used metals have not been considered in current modeling procedure which should be taken into account in future research.

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Appendix

Metals	Code	Metals	Code	Metals	Code
Aluminum (Pure)	1	Carbon steels	18	Inconel X-750	32
Al 2024-T6	2	Carbon–silicon	19	Niobium	33
Beryllium	3	Carbon–manganese– silicon	20	Palladium	34
Bismuth	4	Chromium (low) steels		Platinum	35
Boron	5	(0.18% C, 0.65% Cr, 0.23% Mo, 0.6% Si)	21	Alloy 60Pt–40Rh	36
Cadmium	6	(0.16% C, 1% Cr, 0.54% Mo, 0.39% Si)	22	Rhenium	37
Chromium	7			Rhodium	38
Cobalt	8	Stainless steels		Silicon	39
Copper	9	AISI 302	23	Silver	40
Commercial bronze	10	AISI 304	24	Tantalum	41
Phosphor gear bronze	11	AISI 316	25	Thorium	42
Cartridge brass	12	AISI 347	26	Tin	43
Constantan	13	Lead	27	Titanium	44
Germanium	14	Magnesium	28	Tungsten	45
Gold	15	Molybdenum	29	Uranium	46
Iridium	16	Nickel	30	Vanadium	47
Iron (Pure)	17	Nichrome	31	Zinc	48
				Zirconium	49