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A REVIEW OF THERMAL AND MECHANICAL ANALYSIS IN SINGLE AND BI-LAYER PLATE

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Abstract. This paper reviews several aspects of thermal and mechanical properties of cookware appliance. Numerical results of temperature distribution (TD), heat retaining, thermal stress and body deformation are summarized. Finite Element Method, ANSYS program, is employed. We described different thermal and mechanical results of Al/Cr-Ni, Al/SSt, Al/Ti, Cu/Cr-Ni, Cu/SSt, Cu/Ti, gray cast iron (GCI), carbon steel (CSt), iron. The laminated plate provides improved thermal and chemical properties in comparison with single layer. From this analysis the result suggests that Cu/SSt bi-metal structure provides the best application as cookware.

1. Introduction

Temperature and its distribution (TD) on the surface that contacts food are important parameters in improving cookware performance. Cookware functions best when there is thermal conductivity to spread and retain heat and has a strong, corrosion resistant, non-reactive food preparation surface. It is achieved by the lamination (or bonding) of dissimilar metals [1]. By bonding composite metal cookware that having at least one metal layer possessing a lower coefficient of thermal conductivity than the other metal layers of composite so as to cause the heat to saturate in that layer prior to being transferred to cook. In this manner, hot spot in cook surface are eliminated so as improve the performance of the appliance [2]. There is another consideration that we need to make sure that the materials we use in our cookware do not react to food and adversely affects the taste of our food [3]. By combining metals of higher thermal conductivity, such as aluminium (Al), copper (Cu) with metals of lesser conductivity but higher inertness such as various alloys of stainless steel (SSt) or titanium (Ti), achieved the best [1]. Ti and SSt have excellent corrosion and chemical resistance and Al and Cu enhance the thermal performance of cookware; enabling both a faster heating of foodstuff and a more uniform TD [4].

On the other hand cast iron has a large heat capacity as compared with the other metals. Even after you remove your cast Iron from the heat source, the heavy metal of pan keeps the food warm. Also It is easy to use and care for wide range of cooking. These attributes make it such a good cookware [5]. Rena L. Hecht, et al., 1996 [6]; W. L. Guesser, et al., 2005 [7] performed experimental study on thermal properties of gray iron and GCI.

Although laminated plate provides improved application quality of utensil, it accommodates some disadvantage such as body deformation. The reason is materials with different coefficients of thermal expansion and stiffness are bonded together to form laminated plate [8]. There is interfacial stress in bi-metal structure. Valuable insight in to thermally-induced in heterogeneous structures, including interfacial stress have widely provided by many paper such as [9, 10].

Notes that since mid-1960 many investigators applied numerical, mainly finite element, methods to analysed bimetal structures, subjected to thermal loading [9]. There are many papers, used FEM to calculate thermal buckling of laminated plate subjected to uniform or non-uniform temperature [11-15].

Reference [16] has studied on bi-layer cookware including different metals. It demonstrated bi-layer consist of copper and stainless steel provides more uniform TD and maximum temperature degree and also have better heat retaining ability than other applied metals such as Al/SSt and etc. It got the GCI as a basis for assessing of heat storage of other metals. Stainless steel and titanium provide almost equivalently TD over the surface of pan that is exposed to food [17].

Reference [19] predicted the TD on layered metal plates using artificial neural networks. It has optimized thickness and material of the bottom layer containing different alloys of aluminium or copper. It showed that the optimum thicknesses of copper and aluminium are 8 mm and 6–7 mm respectively.

A numerical model for thermal stress analysis of multi-layered cookware under isothermal loading is proposed in [18].

In this paper we have reviewed several aspects of cookware, focusing on research done before. Numerical results of TD, heat retaining, thermals stress and body deformation are summarized.

Table 1. Symbols and thicknesses of metals

Metals	Symbols	Thicknesses
bi-layer		
Copper	Cu	8 mm
Aluminium	Al	6.5 mm
Titanium	Ti	2 mm
Chromium- nickel	Cr-Ni	2 mm
Stainless steel	SSt	2 mm
single layer		
Grey cast iron	GCI	10 mm
Carbon steel	CSt	10 mm
Iron	-	10 mm

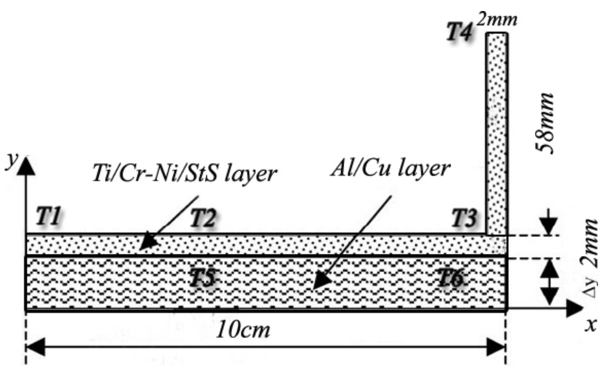

Fig. 1. 2D bi-layer model in numerical analysis and positions of different selected nodes, named T1-T6.

2. Boundary and geometry conditions

Annular part of the circular surface of bottom side pan, which illustrated in Fig. 1 as Δr is constrained, by constant temperature about 773 K. There is a geometrical symmetry so the system can be modeled by rectangle plane with length of the pan radius and a thin and long rectangle as wall of pan. Because of the symmetry, the temperature gradients at the centre of plate along the y-axis have zero value. Hence there is no heat flux at the centre of plate along the y-axis. Side of pan has convection heat transfer with air in ambient temperature. Thickness of layers have been taken according to Table I Δr is 2 cm. The ambient temperature and the coefficient of heat transfer have been assumed as 293 K and 17 W/ (m² K), respectively. In addition, it is also assumed that the pan is filled up by water with boiling temperature, and the coefficient of heat transfer between the pan and the water is 50 W/ (m² K).

In another part is modelled bi-metal pan for studying on body deformation in steady state. At first the model is in ambient temperature degree. Then we assumed that all over the pan is heated and reached to uniform elevated temperature degree, 600 K. It is axisymmetric geometry so displacement and the temperature gradients at the centre of plate is zero. In this part we took the bottom layer and top layer thicknesses, 8 mm and 2 mm respectively for all metals. All materials properties are shown in Table 2.

Table 2. Mechanical and thermal Properties of metals [6, 20, 21].

Symbol	Density, kg/m^3	Conductivity, W/m K Specific heat, J/ kg K	Conductivity, W/m K Specific heat, J/ kg K	Poisson's ratio	Elasticity, GPa	Thermal expansion, $10^{-6}/\,^{o}C$,
		T = 400 K	T = 600 K			
Cu	8933	393 397	379 417	0.355	1.17	16.92
Al	2700	240 949	231 1033	0.334	6.96	23.58
SSt	8055	17.3 512	20 559	0.305	1.93	17.28
Cr-Ni	8400	14 480	16 525	0.29	1.86	13.4
Ti	4500	20.4 551	19.4 591	0.32	1.13	9.54
CSt	7854	56.7 487	48 559	0.295	1.9	10.8
Iron	7870	69.5 490	54.7 574	0.29	2.11	11.8
		T = 293 K	T = 773 K			
GCI	7340	55 490	31 675	0.21	0.69	12.1

3. Results

A. TD of single layer in comparison with bi-layer structure. In this part the TD of Cu is compared with Cu/SSt. These used results are published in [16]. It's obviously when the model reached to steady state, the maximum temperature on upside surface of Cu pan is higher than Cu/SSt, its 771.618 K and 769.66 K respectively. But the difference between maximum and minimum temperature on food preparation surface of Cu and Cu/SSt pan in steady state is 32 and 25 degrees respectively. It showed that TD in Cu/SSt multi-layer pan is more uniform than Cu single layer pan. In Fig. 2 the differences between maximum and minimum temperature during analysis time are illustrated. It is observed that this difference for Cu in beginning of analysis is about 80 degrees greater than Cu/SSt and it is decreased to 7 degrees in steady state. Figure 2 represents that MLP provides more uniform TD upside surface of multi-layer pan than single layer.

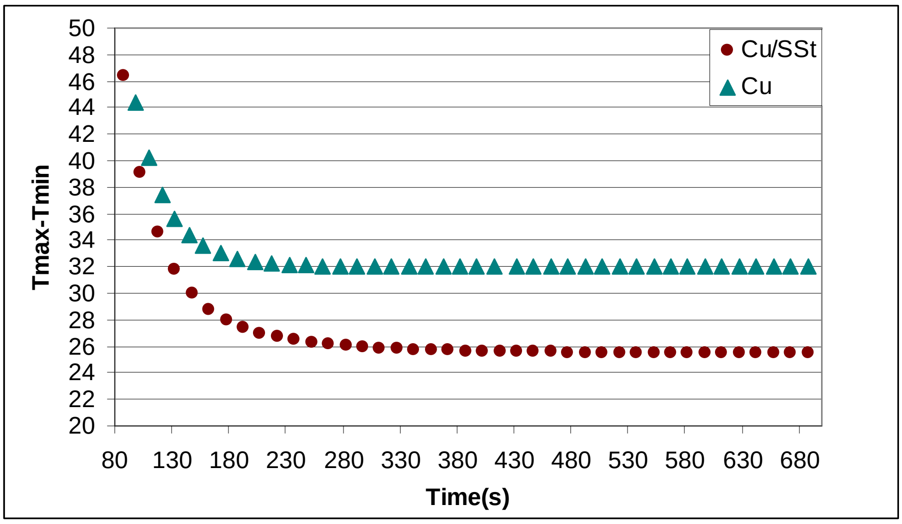

Fig. 2. Time variation of differences between maximum and minimum temperature on food preparation surface of Cu and Cu/SSt pan.

B. TD in different materials. Reference [16] has analysed the TD of combinations of metals in bi-layer structure consist of Cu/SSt, Cu/Cr-Ni, Al/SSt and Al/Cr-Ni. In addition it analysed GCI in single layer structure as compared with bi-layer. It is predictable that minimum temperature observed at edge of wall. There is highly temperature gradient so it represented high convection heat transfer side of pan. We have the regular and uniform TD in all MLP as compared with single layer and between these MLP, Cu/SSt combination has maximum temperature profile. The minimum temperature in Cu/SSt is greater than minimum temperature of other combinations and it's about 451.1 K illustrated in Fig. 3.

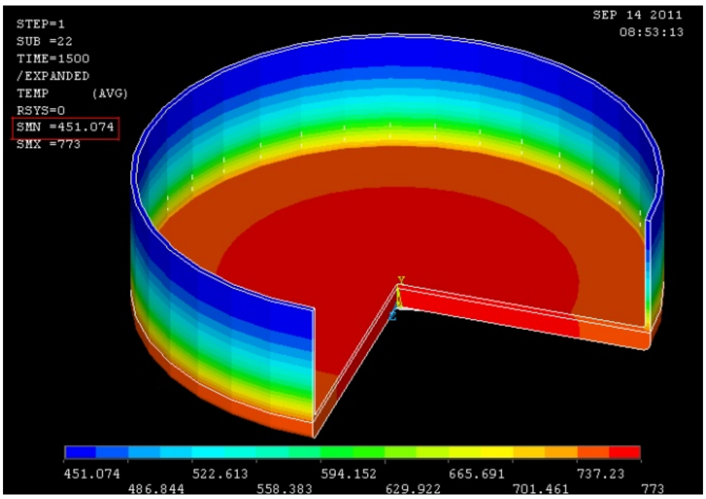

Fig. 3. 3D TD of Cu/SSt bi-metal pan at steady state.

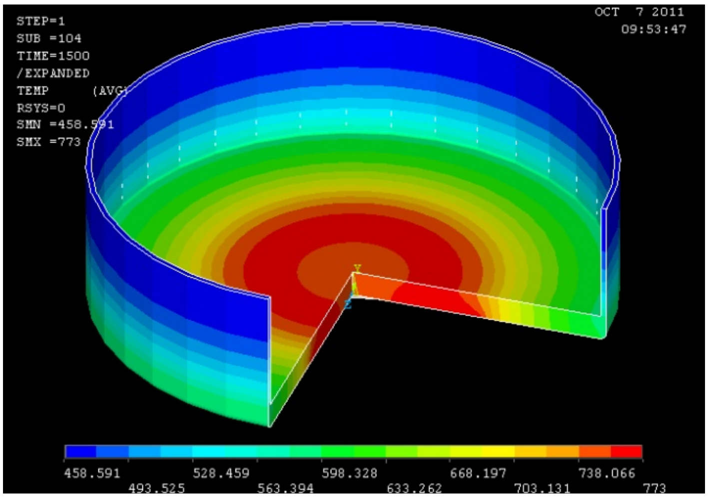

Fig. 4. 3D TD of single layer GCI pan at steady state.

Transient response of T4 node with all combinations is compared. Temperature variations of T4 node in all combinations during first 100 seconds are the same approximately. After this time we observed some differences between bi-layer pan containing SSt and bi-layer pan including Cr-Ni layer obviously. Insofar as after 500 seconds it is apparent about 17 degree differences between them as shown in Fig. 5 [16].

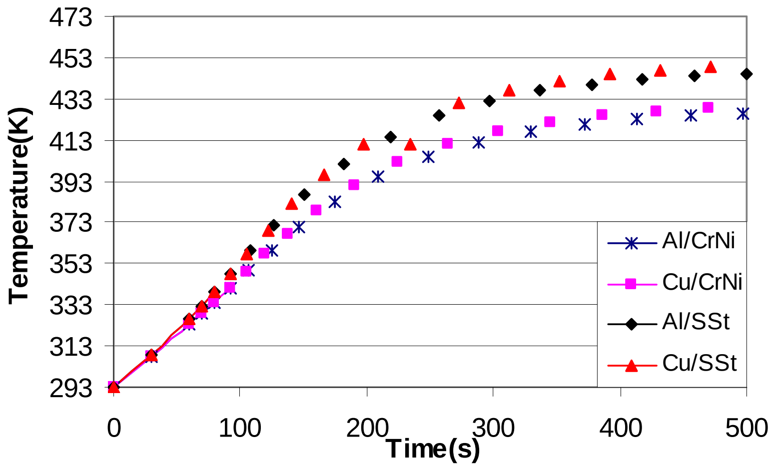

Fig. 5. Temperature variation comparison of T4 node for all combination of bi-layer pans.

C. TD comparison of different metals on food preparation surface of pan. Numerical solution by [17] show that the maximum temperature and most uniform TD occurred in Cu/Ti and Cu/SSt bi-layer structure whereas GCI provides irregular TD as shown in Fig. 6. Figure 6 shows the steady state results of TD on food preparation surface of pan for all metals. It is clearly illustrated that TD in single layer such as GCI is not regular and uniform so it’s derived that single layer cases are not suitable for pan.

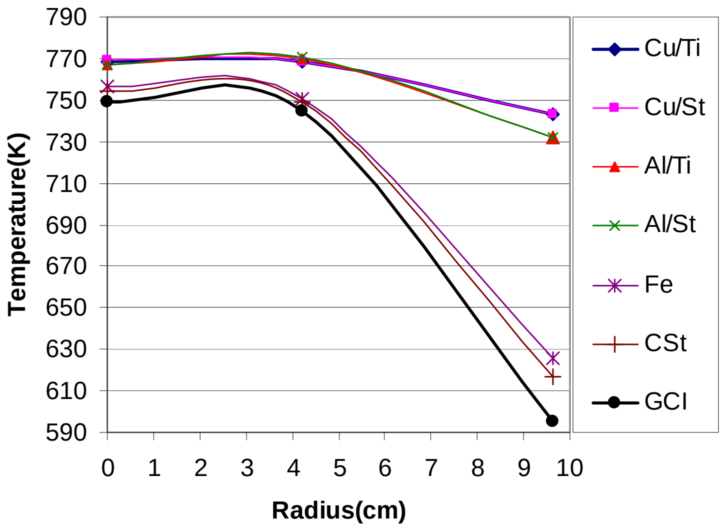

Fig. 6. TD on food preparation surface of pan for all metals in steady state.

D. Heat retaining. After the model reached to steady state, the boundary conditions of pan are changed to analysing the heat retaining of the model. Hence the heated pan is modeled to transfer the heat just with air at ambient temperature for cooling [16].

The T5 node of model with all applied metals is compared as shown in Figs. 7, 8. These results are published by [16]. It represents the heat storing differences of studied cases clearly. It shows that the pans consist of Cu can store the heat better than others even GCI. But the cookware containing Al cannot retain the heat well in compare with Cu and GCI. In the other hand SSt has better heat retaining characteristics than Ti in second layer and almost is same with Cr-Ni. Consequently bi-metal structures containing Cu/SSt and Cu/Cr-Ni have the best heat storage ability among others. The GCI has the almost equivalently behavior compared to other single layer such as Iron and CSt. You see that temperature of T4 node first increase and then it decrease because T4 node has minimum temperature in compared with all over the pan so there is a heat flux from high to low temperature degree. In the other hand conduction coefficient of metals is very greater than convection coefficient of air.

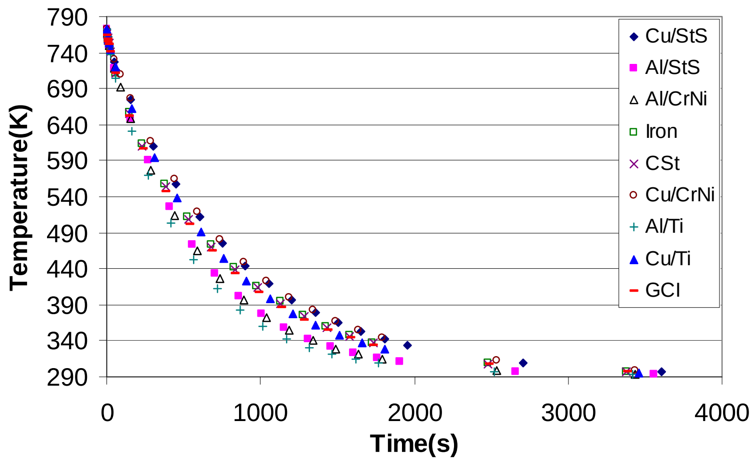

Fig. 7. Temperature variation comparison of T5 node for all metals in cooling step.

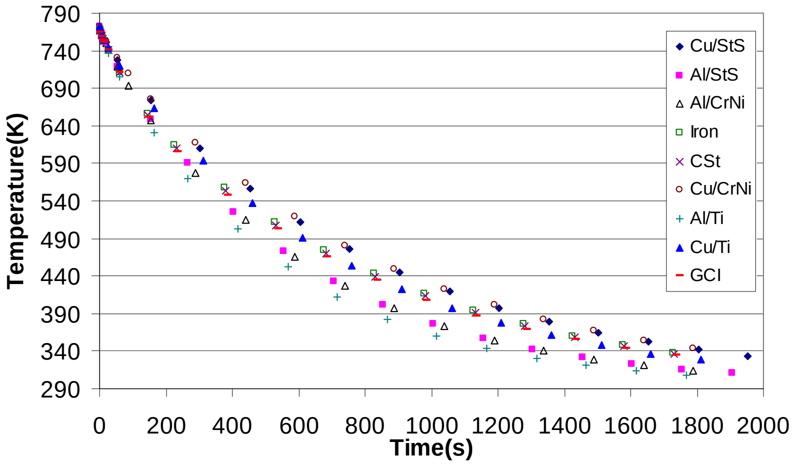

Fig. 8. Temperature variation comparison of T5 node for all metals in cooling step.

E. Thermal stress and body deformation. The numerical solution of thermal stress is carried out for Cu/Ti, Cu/SSt, Al/Ti, Al/SSt, Cu/CrNi, Al/CrNi, CSt, GCI and iron illustrated in Figs. 9-14. In this part we used some results of [18].

Al/CrNi has the maximum deformation due to maximum thermal stress. It is 2.9 mm. The results are shown in Table 3. It is demonstrated that the Al has the maximum deformation in bottom layer and CrNi accompanied by Al causes greater deformation in top layer between Ti and SSt. In the other hand Ti in combination by Cu has higher body deformation in top layer between CrNi and SSt. The reason is that Cu/Ti has greater stress than Cu/CrNi. In addition SSt has the minimum deformation among applied metals in second layer in combination by both Al and Cu. Cu causes minimum deformation compared with Al. It is clear because the thermal expansion of Al is greater than Cu. Consequently Cu/SSt has minimum body deformation. Base on Table 3 deformation in Cu/SSt pan is almost close to single layer. Figures 9-14 show deformed shape with undeformed model of pan. The deformation of body in Cu/SSt is different than others. As the thermal expansion of SSt is greater than Cu, the body deformation is convex. In other combinations the deformation of body is concave because thermal expansion of Cu and Al that used in bottom layer are greater than the metals of second layer.

Table 3. The calculated deformation of all metals.

Metals	Von Mises stress, MPa	Deformation, mm
Al/CrNi	704	2.9
Al/Ti	569	2.07
Cu/Ti	294	0.961
Al/SSt	461	0.859
Cu/CrNi	227	0.706
Cu/SSt	24.4	0.609
Iron		0.5
GCI		0.424
CSt		0.387

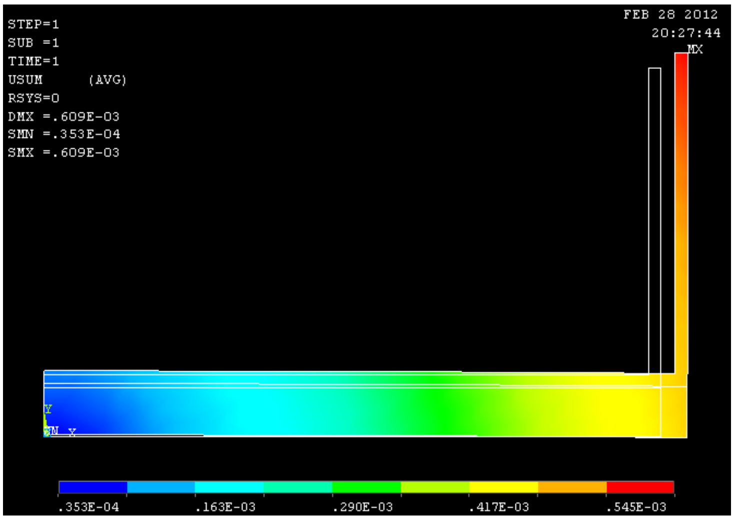

Fig. 9. Deformed shape with undeformed model of Cu/SSt pan.

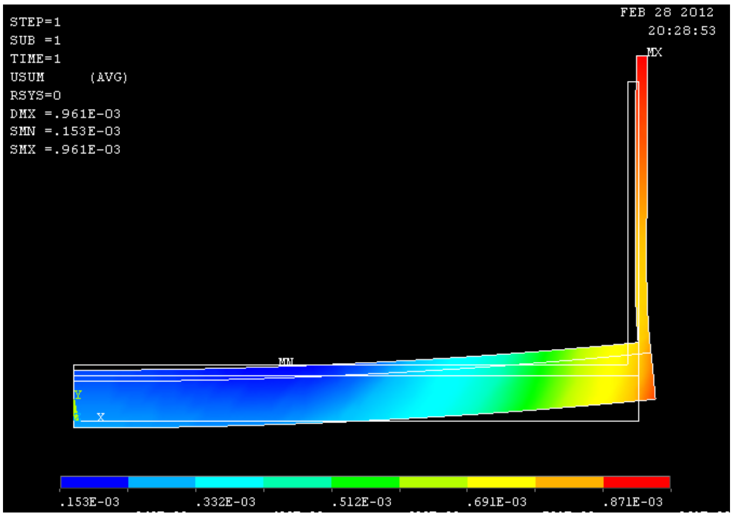

Fig. 10. Deformed shape with undeformed model of Cu/Ti pan.

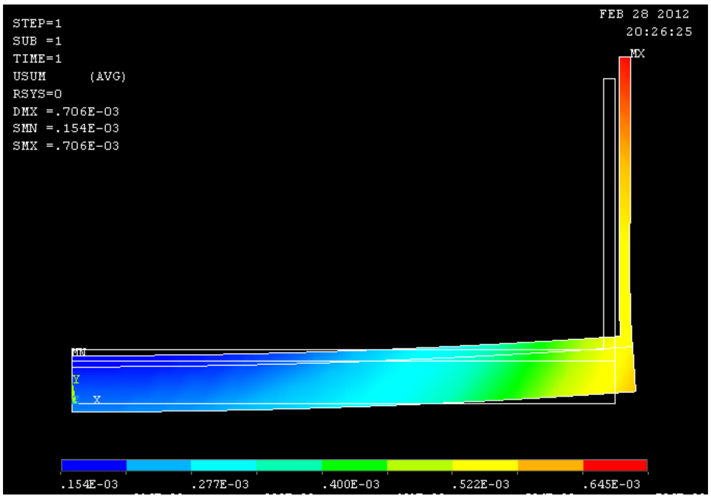

Fig. 11. Deformed shape with undeformed model of Cu/CrNi.

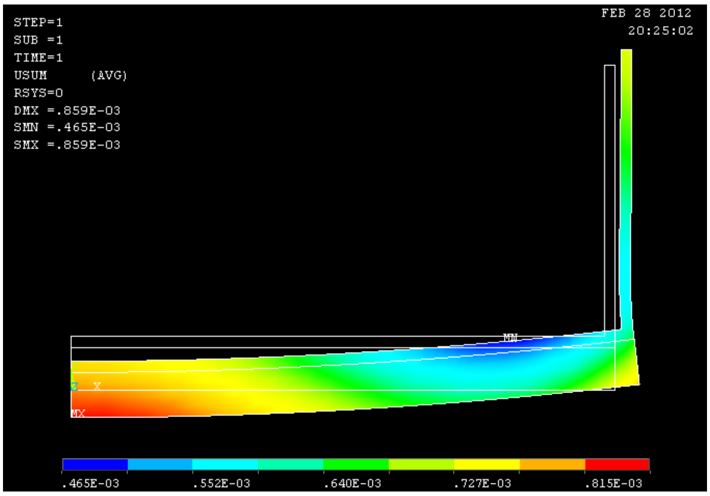

Fig. 12. Deformed shape with undeformed model of Al/SSt pan.

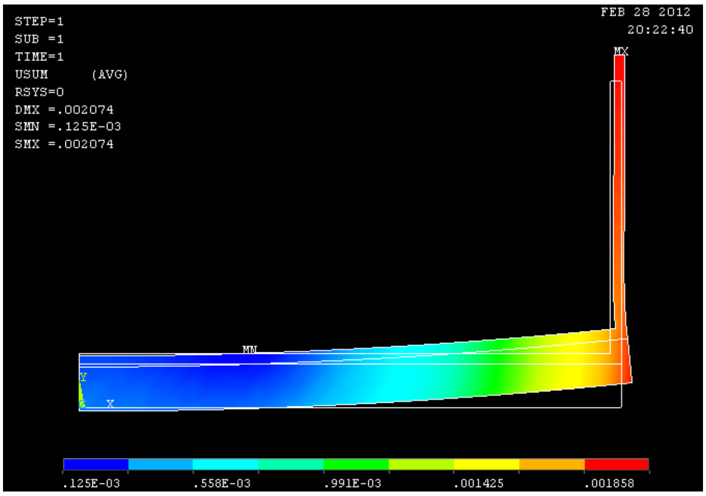

Fig. 13. Deformed shape with undeformed model of Al/Ti pan.

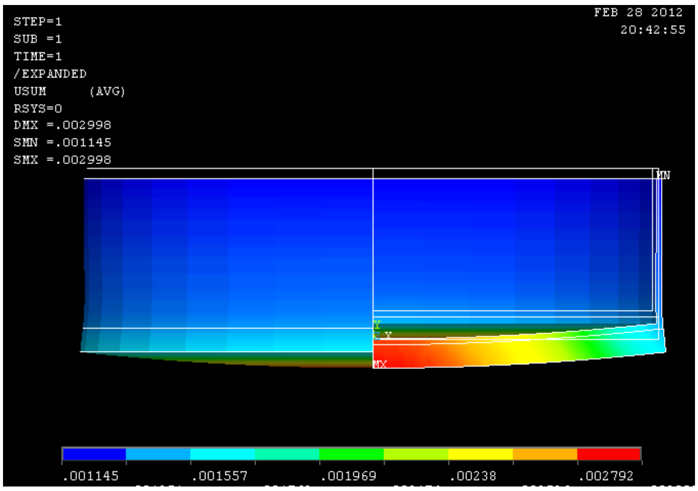

Fig. 14. Deformed shape with undeformed model of Al/CrNi pan.

4. Conclusions

The laminated plate remains applicable case of problems having both practical and academic interest.

The work summarized thermal and mechanical analysis of bi-metal cookware. TD, temperature degree is analyzed upside surface of pan. Cu/SSt MLP provides highest temperature degree and most uniform TD food preparation surface of pan. In the other parts, heat retaining and body deformation are discussed too. Cu/SSt and Cu/CrNi have the highest heat storage in compared with others such as Cu/Ti, Al/SSt .in addition we analysed the thermal stresses which deform the body of pan. Al/CrNi has the maximum deformation whereas we can meet minimum deformation in Cu/SSt among bi-metal structure. From the results the advantage of laminated plate in manufacturing the pan deduced as reliable results. In addition thermal, mechanical, and chemical behaviours of Cu/SSt MLP make it completely excellent structure for cookware production.

References

[1] William A. Groll // *US Patent*, Pub No US2010/0108690A1.
[2] William A. Groll // *US Patent*, Pub No 2004/0058188A1.
[3] Peter Barham, *The Science of Cooking (*Springer-Verlag, Berlin-Heidelberg-New York, 2001).
[4] Stanley Kin Sui Cheng // *US Patent*, Pub No US 2006/0283844A1.
[5] Tracy Barr, *Cast Iron Cooking for Dummies* (John Wiley & Sons, Indiana, 2011).
[6] Rena L. Hecht, Ralph B. Dinwiddie, Wallace D. Porter, Hsin Wang // *SAE Technical Paper* 962126 (1996), doi:10.4271/962126.
[7] W.L. Guesser, I. Masiero, E. Melleras, C.S. Cabezas // *Revista Matéria* **10** (2) (2005) 265.
[8] Yujun Wen, Cemal Basaran // *Mechanics of Materials* **36** (2004) 369.
[9] E. Suhir // *J. Appl. Mech.* **56** (1989) 595.
[10] J.W. Eischen, J.S. Everett // *Journal of Electronic Packaging* **111** (1989) 282.
[11] Chen Lien-Wen, Chen Lei-Yi // *Computers & Structures* **34**(1) (1990) 71.
[12] Ahmed K. Noor, Jeanne M. Peters // *Finite Element Analysis and Design* **15**(4) (1994) 343.
[13] K. Chandrashekhara // *Finite Element Analysis and Design* **12**(1) (1992) 51.
[14] M.R. Prabhu, R. Dhanaraj // *Computers & Structure* **53** (1994) 1193.
[15] Maloy K. Singha, L.S. Ramachandra, J.N. Bandyopadhyay // *Composite Structure* **54** (2001) 453.
[16] Mohammadreza Sedighi, Behnam Nilforooshan Dardashti *// International Journal of Science and Engineering Investigations* **1** (1) (2012) 97.
[17] Behnam Nilforooshan Dardashti, Mohammad Reza Sedighi // *Applied Mechanics and Materials* **148-149** (2012) 227.
[18] M.R. Sedighi, B. Nilforooshan Dardashti // *Advances in Natural and Applied Sciences* (2012), submitted.
[19] Tahir Ayata, Abdullah Çavuşogˇlu, Erol Arcaklıogˇlu // *Energy Conversion and Management* **47** (2006) 2361.
[20] Frank P. Incropera , David P. DeWitt, Theodore L. Bergman, Adrienne S. Lavine, *Fundamentals of Heat and Mass Transfer* (John Wiley & Sons, Hoboken, New Jersey, 2006).
[21] Ferdinand P. Beer, E. Russell Johnston, John T. Dewolf, David F. Mazurek, *Mechanics of Materials* (McGraw-Hill, New York, 2008).