

## Enhancing Thermal-Shock Reliability of a Sleeveless Power Inductor Assembly upon Reflow Soldering

Fildzah Fajrina<sup>1, a</sup>, Teddy Sjafrizal<sup>1, b</sup> and Rino Andias Anugraha<sup>1, c</sup>

<sup>1</sup> Industrial Engineering Department, School of Industrial Engineering, Telkom University, Bandung 40257, Indonesia

<sup>a</sup>fildzahfajrina@gmail.com, <sup>b</sup>teddysjafrizal@telkomuniversity.ac.id,  
<sup>c</sup>rinoandias@telkomuniversity.ac.id

**Keywords:** Surface Mount Inductor, Reflow Soldering, Thermal Shock, Taguchi Method, Computational Fluid Dynamic, Finite Element Method.

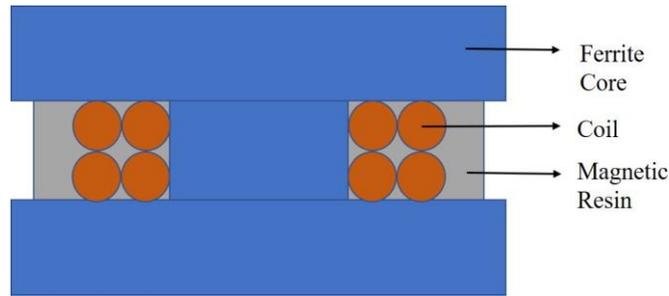
**Abstract.** Employing magnetic resin in between the upper and bottom flange of a drum core is proven design in boosting the performance of a power inductor. The optimum core design and magnetic resin characteristic were investigated to improve the thermal shock reliability of the component upon reflow soldering. Finite element modelling (FEM) was utilised to simulate the response of the assemblies to the variations of the core inner radius ( $r_c$ ), upper flange thickness ( $t$ ) and the coefficient of thermal expansion of magnetic resin ( $CTE_{mr}$ ). The assessment of those designs was conducted at a reflow oven, modelled by the computational fluid dynamic technique (CFD), on sixteen designs generated by the orthogonal array. The results showed that the inner radius of the drum core was the most vital parameter in designing a drum core in preventing core crack upon reflow soldering. The optimum design of the drum core was obtained at 0.5 mm inner radius of drum core, 0.3 mm upper flange thickness and 2.8 ppm/K coefficient thermal expansion of magnetic resin. Those findings may be used as a reference for designing a similar drum core of a power inductor.

### Introduction

Continuously improving the performance of the products and miniaturizing are widely practised by the electronics manufacturers to be sustained in the industry. Eventually, these directions end in a compact design and built-up by the high-efficiency components. This challenge leads to a more complex and difficult process in designing the component and the assembly process. To improve the density of component on a printed circuit board, the surface mount technology (SMT) is preferred than the conventionally through hole technology (THT). By pursuing the SMT design and SMT assembly process, both sides of the PCB can be utilized for placing more electronics components.

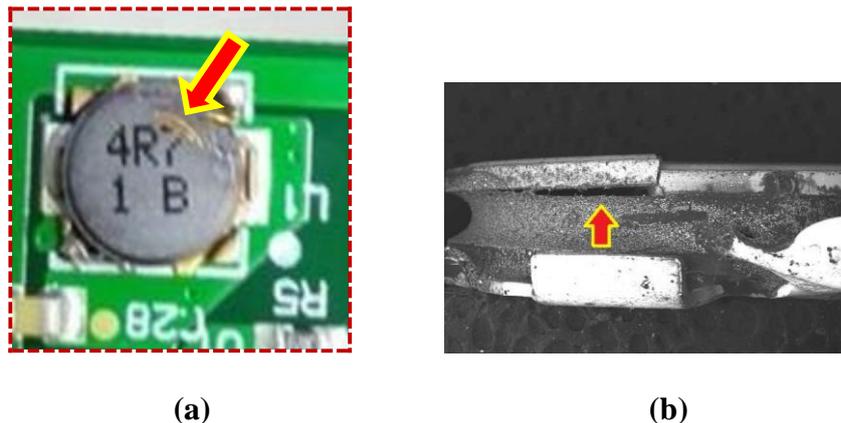
An additional challenge comes from the directive of the European Union Waste Electrical and Electronic Equipment (WEEE) about disallowing an intentional addition of lead (Pb) element into any electronics parts [1]. Due to this regulation, lead-free type solder becomes the default soldering material for the SMT assembly process. Lead-free solder possesses high melting temperature, hence higher reflow soldering temperature is necessary to ensure the formation of reliable solder joints. On the other hand, higher reflow soldering temperature means higher thermal stress to be experienced by the components.

As one of the standard passive component, chip choke coil designer shall cater the possible high thermal stress into the design. Power inductor is frequently found as the components of the mobile-phone, laptop, data storage and many other electronics applications. Current dominant design of power inductor comprises of high-performance ferrite core, coil and magnetic resin (Fig. 1).



**Figure 1.** A power inductor structure

Employing magnetic resin as the filler in the coil window is meant to improve the magnetic path length, thus increasing the inductance of the inductor. However, this design comes with an issue on the built-up thermal stress at the SMT assembly process, due to the difference in the coefficient of thermal expansion (CTE) of the constituents. The high CTE of magnetic resin exerts high stress to the ferrite core, especially on the upper flange. Typically, the surface crack is initiated and appears along the inner radius of the drum core [2]. The temperature change causes thermal stress between the ferrite core and the magnetic resin [3]. The interaction between geometric factors and the temperature change affect the reliability of the electronic package [4]. The condition is getting worse as higher soldering temperature need to be applied to the lead-free SMT process. At extreme case, this condition may result in core cracks (Fig. 2).



**Figure 2.** Core crack failure on a power inductor upon reflow soldering, (a) top view by optical microscope (b) side view by electron microscope.

Knowing the inherent risk of core crack, conducting a simulation study to understand the behaviour of the sleeveless power inductor upon reflow soldering becomes reasonable. To the best of the author's understanding, there is no previous study in addressing a similar issue. This study aims to propose the design specification of power inductor to minimize the thermal stress due to the reflow soldering.

### Procedures

In order to improve the thermal-shock reliability of the sleeveless power inductor during the reflow soldering, three design factors were selected, the inner radius of the drum core, upper flange thickness and the CTE of the magnetic resin. Detailed of the factors and their level is presented in Table 1.

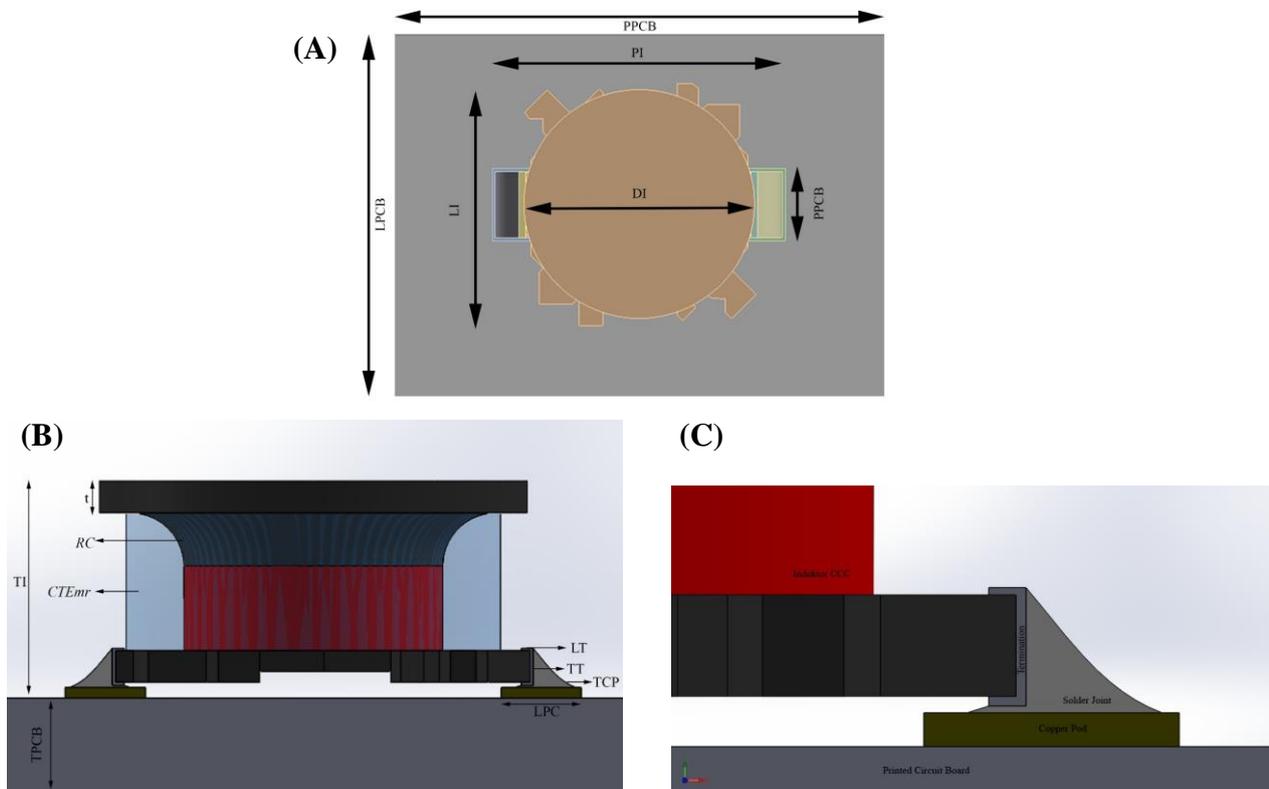
**Table 1.** Control factors and their levels in experiments

Factor	Factor	Unit	Level			
			1	2	3	4
A	Core Inner Radius [2]	mm	0.1	0.3	0.4	0.5
B	Upper flange thickness [4]	mm	0.1	0.2	0.25	0.3
C	Coefficient of Thermal Expansion [2]	$10^{-5}$ ppm/K	2.8	4.1	10	11

To investigate the interaction effect among the factors, an  $L_{16}(4^3)$  orthogonal array was chosen as the experimental design. As many as 16 combinations were analyzed individually by simulating the computational fluid dynamics (CFD) and static structural responses to thermal loads upon reflow soldering in ANSYS 18.1. The sleeveless power inductor was modelled by the SOLIDWORKS. The detailed dimension of the model is presented in Table 2, and the visual description of the model is shown in Fig. 3.

**Table 2.** Detailed dimensions of the modelled power inductor.

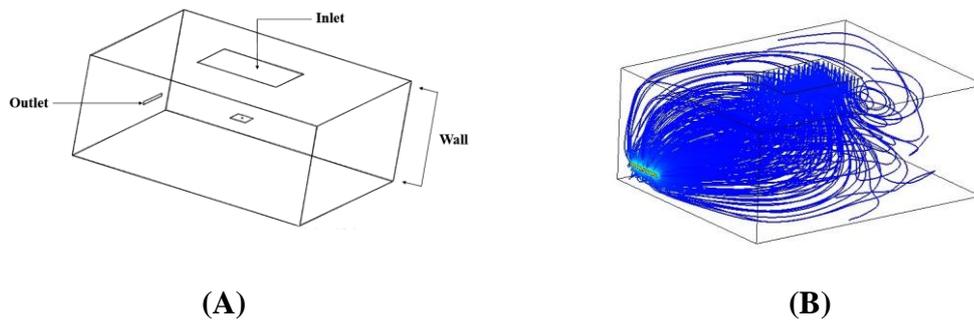
Parameters	Dimensions	Parameters	Dimensions
PCB Length (PPCB)	48 mm	Copper Pad Width (LCP)	1.2 mm
PCB Width (LPCB)	53 mm	Copper Pad Thickness (TCP)	0.1 mm
PCB Thickness (TPCB)	1.6 mm	Termination Width (LT)	0.11 mm
Inductor Length (PI)	3.88 mm	Termination Thickness (TT)	0.35 mm
Inductor Width (LI)	4.84 mm	Upper Flange Thickness (t)	Variable
Inductor Thickness (TI)	1.9 mm	Core Inner Radius ( $r_c$ )	Variable
Inductor Diameter (DI)	4 mm	Coefficient Thermal Expansion	Variable
Copper Pad Length (PCP)	0.75 mm	Magnetic Resin ( $CTE_{mr}$ )	Variable



**Figure 3.** (A) Inductor assembly in top view , (B) Inductor assembly in front view, (C) Detail of components

In setting up the model for a CFD simulation, the mesh size was dense near the drum core into  $1 \times 10^{-4}$  m and a cutcell grid was used to create the volume mesh which has more regular domain cell than tetrahedrons [5]. The total number of nodes was 410061 with 212853 elements. The mesh and time step sizes used in the current study were optimized and finalized for better accuracy and computational time.

The boundary condition was set according to a reflow oven model which consists of inlet, outlet and wall. A pressure boundary was assigned as the inlet and outlet. The optimum inlet velocity for a reflow oven is 0.5 m/s [6]. The turbulence model was set up as the K-epsilon model with enabling thermal effects was used to model the behaviour of the turbulent flow field of the reflow oven. A wall boundary assigned to the inductor assembly and the turbulence model as shown in Fig. 4.



**Figure 4.** (A) Structure of reflow oven, (B) Turbulence model inside reflow oven

Once the CFD model was set up, the thermal stress response was conducted in static structural. All material was modelled as linear elastic and isotropic substance except the PCB which was simulated using orthotropic material as shown in Table 3. The thermal stress as the response of the experimental factors was analysed by applying the Taguchi method to derive the optimum parameter design of the drum core. Finally, as a guideline for minimizing the thermal stress of the ferrite core, the vital parameter for the drum core design was defined by the ANOVA analysis.

**Table 3.** Material properties for the simulation

Material Properties	Ferrite NiZn (Inductor)	Silver (Termination)	M705 (Solder Joint)	Copper Pad	PCB
Density (kg/m <sup>3</sup> )	4800	10490	7500	8390	1700
Young's Modulus (GPa)	140	83	33	129	$E_x = 19680$ $E_y = 8550$ $E_z = 19680$
Poisson's ratio	0.29	0.37	0.36	0.34	$E_x = 0.11$ $E_y = 0.39$ $E_z = 0.11$
CTE (ppm/K)	8	18.9	23.3	7	$E_x = 17.6$ $E_y = 64.1$ $E_z = 17.6$
Specific Heat Capacitance (J/Kg K)	710	235	250	383	920
Thermal Conductivity (W/ m K)	6.3	406	73	398	0.2

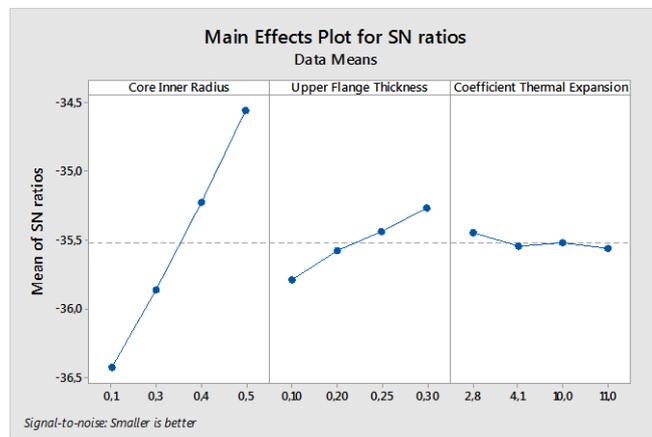
**Result and Discussion**

Table 4 presents the simulated thermal stress as the responses of the selected factors. The identified maximum stress of the model ranged between 50 – 68 MPa. The typical tensile strength of a ferrite core is around 71 MPa [7]. Since the simulated thermal stress almost reaching 71 MPa, the possibility of having micro core crack upon reflow soldering was prominent.

**Table 4.** Orthogonal array L16

Ekspe- riment	Faktor			Response Stress (MPa)	Ekspe- riment	Faktor			Response Stress (MPa)
	A	B	C			A	B	C	
1	0.1	0.1	2.8	68.099	9	0.4	0.1	10	58.470
2	0.1	0.2	4.1	66.564	10	0.4	0.2	11	57.828
3	0.1	0.25	10	65.218	11	0.4	0.25	2.8	57.956
4	0.1	0.3	11	65.371	12	0.4	0.3	4.1	56.531
5	0.3	0.1	4.1	64.501	13	0.5	0.1	11	55.964
6	0.3	0.2	2.8	61.872	14	0.5	0.2	10	54.727
7	0.3	0.25	11	61.271	15	0.5	0.25	4.1	52.859
8	0.3	0.3	10	60.894	16	0.5	0.3	2.8	50.291

Taguchi method recommends analyzing the S/N Ratio to evaluate the quality characteristic of a process. In a recent study, the smaller-the-better quality characteristic was selected to investigate the influence of factors on the simulation results. The simulation results were converted into signal-to-noise ratio (S/N Ratio) using the MINITAB 17 as shown in Fig. 5.



**Figure 5.** Main effect plot for S/N ratios

The highest value of each S/N Ratio for each factor is used to form an optimum combination of level factor. The optimal conditions for the thermal-shock reliability of sleeveless inductor’s reliability at 0.5 mm core inner radius, 0.3 mm upper flange thickness, and 2.8 ppm/K CTE of the magnetic resin. This finding provides a typical design specification for improving the reliability of the drum core by the presence of thermal stress during reflow soldering. In the case of this selection does not suit to the inductor performance, the available factor to be adjusted is the upper flange thickness. Inner radius of drum core size directly affect the stress distribution in inductor, as the inner radius gets smaller, the stress is the less concentrated and the cracking occurs easily [2]. The use of very low CTE of the magnetic resin in inductor would result minimum damage due to the low magnetic resin expansion from inner layer to core[4].

Further, ANOVA test employed to determine the significant factors upon the dependent variabel [8]. There are two types of ANOVA: one-way ANOVA and two-way ANOVA. One-way ANOVA

used to identify each independent variables respect to the dependent variable .Despite of two-way ANOVA used to identify the interaction of two or more independents variabel upon the dependent variable that may contributed to the value of other factor [9]. An ANOVA two-way was performed in Table 5 using MINITAB 17. In testing ANOVA the following hypotheses were made:

- H0 : The factor does not have a significant effect  
H1 : The factor has a significant effect  
Critical Region : H0 is rejected if P-Value  $\leq \alpha$ , where  $\alpha$  is 0.05

**Table 5.** ANOVA result of the factors

<b>Factors</b>	<b>DF</b>	<b>F-Value</b>	<b>P-Value</b>
Core Inner Radius	3	113.16	0
Upper Flange Thickness	3	8.02	0.016
Coefficient of Thermal Expansion	3	0.26	0.851

From Table 5, the core inner radius and upper flange thickness had a significant influence on the thermal stress of the assembly upon reflow soldering. This finding provides guidelines for the ferrite core designer in designing the drum core of a sleeveless power inductor. To minimize the effect of thermal stress of reflow soldering, it is recommended to select a larger inner radius of the drum core and increasing the thickness of upper flange. The P-Value inercation between each factor is nearly perfect, MINITAB shows a message that the P-Value can not be estimated [10]. It shows, the relationship between each factor and the dependent variable may depend on the value of the other factor.

## Conclusions

Enhancing thermal-stress reliability of a sleeveless power inductor has been investigated. The finding as below:

1. The optimum combination of factor and level factor for enhancing the thermal-stress reliability of a power inductor assembly were at 0.5 mm inner radius of drum core, 0.3 mm upper flange thickness and 2.8 ppm/K coefficient of thermal expansion.
2. The core inner radius and upper flange thickness are the most influencing factor on thermal-stress reliability of a sleeveless power inductor.

## References

- [1] S. Stoyanov, C. Bailey, and M. Desmulliez: *Solder. Surf. Mt. Technol* Vol. 21 (2009), pp. 11–24
- [2] M. Cai, D. Yang, Y. Tao, C. Su, B. Wu, and Z. Cui: *Proc. - Int. Symp. Adv. Packag. Mater* (2011), pp. 262–266
- [3] H. S. Choi, K. D. Kim, and J. S. Jang: *Electron. Mater. Lett* Vol. 7 (2011), pp. 63–70
- [4] E. H. et al Amalu: *Finite Elem. Anal. Des* Vol. 107 (2011), pp. 13–27
- [5] I. W. Yudhatama, M. I. P. Hidayat, and W. Jatimurti: *Vol.7* (2018), p.2
- [6] C. S. Lau, M. Z. Abdullah, and F. Che Ani: *Microelectron. Reliab* Vol. 52 (2012), pp. 1143–1152
- [7] Information on <https://www.makeitfrom.com>
- [8] K. Krishmaiah and P. Shahabudeen: *Applied Design of Experiments and Taguchi Methods* (PHI Learning Private Limited Publications, New Delhi. 2012).
- [9] A. Field: *Discovering Statistics Using SPSS*, (SAGE Publications Ltd, London 2009).
- [10] Information on <https://support.minitab.com>