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EVALUATING JOULE HEATING EFFECTS AND ELECTRICAL CURRENT FLOW THROUGH COPPER LAYERS INSIDE PCB USING FINITE ELEMENT ANALYSIS

BY

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Abstract. The increasing complexity of electronics, particularly in the automotive industry, demands effective thermal management for multilayer Printed Circuit Boards (PCBs). Traditional analysis methods often involve simplifications. This study utilizes Finite Element Analysis (FEA) with Siemens Simcenter FLOEFD to simulate current distribution, the Joule heating effect, and thermal behavior in a simplified 4-layer PCB CAD model subjected to a 7A DC current. A mesh independence study confirmed the reliability of the results. The initial simulation revealed non-uniform current density, highlighting underutilized copper areas in trace corners and vias. Based on these findings, the CAD model was optimized by strategically removing these low-current-density regions, achieving a total copper volume reduction of approximately 13% (35%

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for vias). Re-simulation of the optimized model showed an increase in maximum temperature by about 8°C (a ~10% relative increase) and a ~6% rise in total dissipated power, attributed to higher current density in the remaining paths. FEA is demonstrated as an effective tool for identifying PCB design optimization opportunities and quantifying the trade-off between material cost reduction and thermal performance.

Keywords: FEA, PCB, thermal, simulation, FLOEFD.

1. Introduction

The number of electronic components and PCB is higher than ever, at least in the automotive industry, where the electrification of the cars contributes significantly. Also, the computations power needed is higher, the demand for higher performance and the dissipated power inside the electronic components increased (Mei *et al*., 2018). Over the entire lifetime of a product, multiple rises in temperature may affect the structural integrity of the assembly (Lee *et al*., 2024).

A printed circuit board is usually made of a dielectric material and copper areas that serve as a conduction path for the electric current and heat. In the current market, the focus is sometimes on the current conduction and the thermal design is not always a priority (Zhang and Bagnoli, 2014). Modern PCBs contain multiple copper layers, each one of them with multiple trace segments. The layers are connected to each other using vias (Shankaran *et al*., 2010).

Thermal conduction in Printed Circuit Boards (PCB) and their thermal behavior was and is a common research area. Thermal evaluation of a PCB can help the developers or designers to identify potential thermal problems, as overheat risks or cooling issues, from the early staged of a product development. Using thermal simulation, the development team can also optimize the PCB layout and cooling solutions (Zhang and Chen, 2024).

Multiple analyzing methods, analytical or numerical solutions were used to predict or evaluate the thermal conductivity inside the layers or copper vias of a PCB. Some methods are used to find the orthotropic thermal conductivity in some areas of the PCB based on the copper volume, but this is an approximate method and is not offering accurate results. Other methods are evaluating the thermal behavior of PCBs based on the copper layers, without considering the copper density in all the areas or the connection between layers (Bagnoli and Zhang, 2010).

One of the main problems when evaluating the thermal behavior of a PCB is the non-uniform structure inside it, the number of layers, number and position of copper vias, insulating layers and any approximation increases the results accuracy. However, the ability of copper to conduct and spread the heat

is much higher than the dielectric materials, so the copper geometry should not be neglected or modified.

Over time, research papers authors evaluated the thermal behavior of PCBs using different calculation models, but reducing the calculation complexity to 2D models (Zhang *et al*., 2012). One of the issues for this kind of approach is that the conduction between the copper layers is not considered and the PCB can not be seen as a whole.

When evaluating the thermal behavior of a conductor is important to understand the factors that will cause a heat dissipation inside the conductor and the negative effect that the increase in temperature may have on the conductor and surrounding areas. Finite element simulations can evaluate the Joule heating effect when a current is passing a conductor and also gives us the value of the power dissipated inside the conductor (Yao *et al*., 2024). Non-homogeneous PCBs are hard to be evaluated, therefore finite element simulations are a better option when a PCB is design and thermally evaluated (Adam, 2004; Shankaran *et al*., 2010).

2. CAD model and simulation setup

To evaluate the software capability to simulate copper layers, as well as the current distribution and Joule heating effect in the copper conductors, a simplified CAD model was built. A printed circuit board (PCB) with 4 layers was made, but only the copper used to transfer the DC Current was kept, all other copper areas were neglected. The rest of the material, around the copper is dielectric FR4. The PCB is fixed on an aluminum base plate using stainless steel screws. Since the screws do not have a role in current conduction, they were simplified, but the exterior dimensions are from M2 screws.

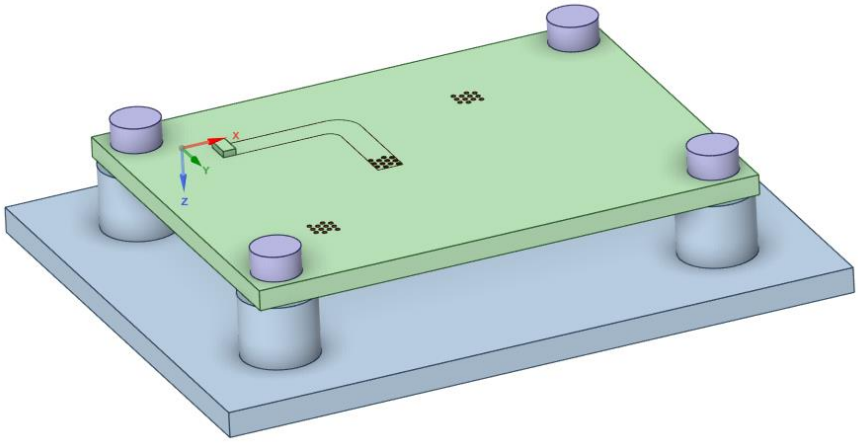
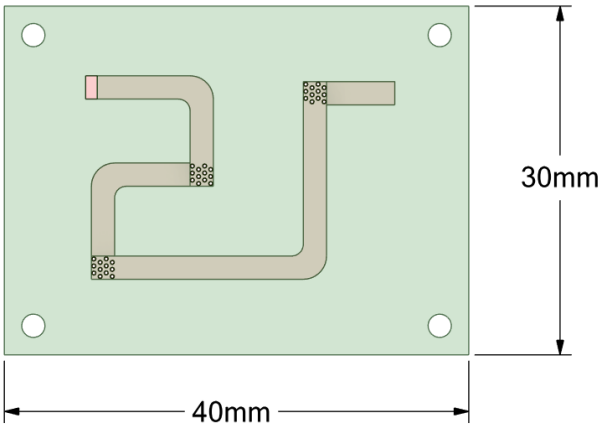
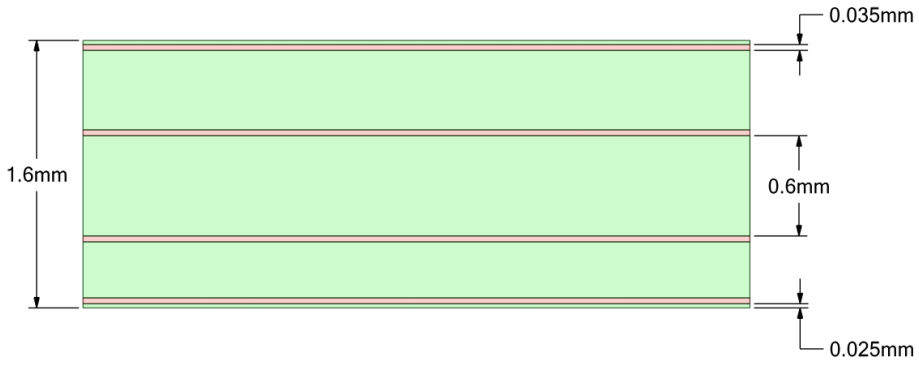


Fig. 1 – Assembly overview.

The size of the PCB is 40 mm by 30 mm and 1.6 mm thickness. The thickness of the PCB is the one usually used in low voltage applications. The thickness of the copper layers is also one value found in most PCBs, 1 oz or 0.035 mm (Adam J., 2004). The dielectric thickness is different, depending on the layer. In Fig. 2 the position of the copper layers can be seen inside the FR4 material.



(a)



(b)

Fig. 2 – (a) PCB dimensions; (b) PCB section view.

To apply the DC current on the copper layers, 2 parts were made and were used as an input and output areas. Since the copper layers are covered by the dielectric material on other areas, except the contact with the inlet and outlet surfaces. The dimensions of the parts are 1 mm by 2 mm. as it can be seen in Fig. 3.

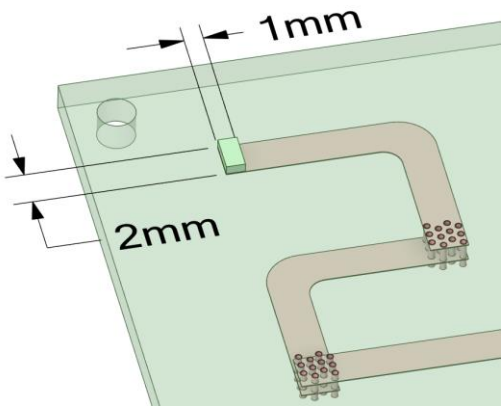
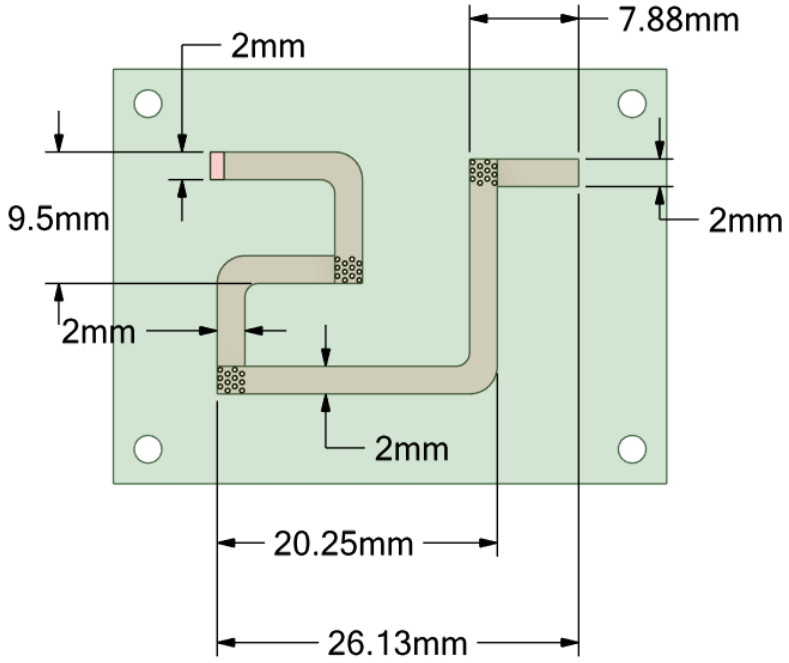
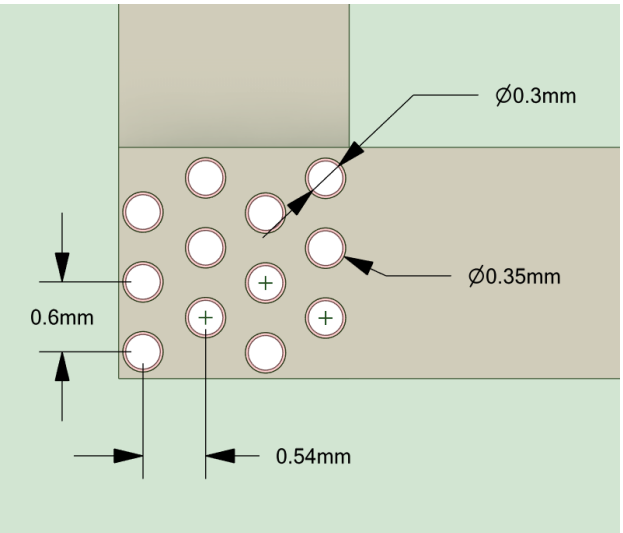


Fig. 3 – Current inlet area.

All the copper layers found in the PCB were made with random dimensions, except the thickness and width of the copper conductor. All the copper conductors have the same 0.035 mm thickness and 2 mm width.



(a)



(b)

Fig. 4 – (a) Copper layers dimensions; (b) Copper vias dimensions.

The connection between the layers were made using vias. The dimensions of the vias are the used usually found in the electronic components, with the exterior diameter of 0.35 mm and the inner diameter of 0.3 mm. Therefore, the copper cylinder has a plating of 0.025 mm. A number of 12 vias were used to connect the layers and the same pattern and dimensions were used for all the copper conductors.

The vias are not filled with dielectric material, so air can pass through, improving the cooling through convection or radiation.

To evaluate the thermal behavior of the PCB due to Joule heating effect, a DC current is passing through the copper conductor. The value of the DC current is set at 7 A. On the current outlet area, a voltage of 1 V is set.

3. Mesh independent results

To reduce the negative effect of the mesh density on the simulation results, a mesh independent results investigation was performed. Therefore, the number of mesh elements were increased until the maximum temperature for each copper layer and the dielectric element is not significantly changed.

This method ensures that the error given by the mesh is reduced as much as possible, trying to eliminate one error source that may appear when finite element method is used to analyze an assembly.

The simulation software used for the electrical and thermal simulation is Siemens Simcenter FLOEFD 2412. Since software as FLOEFD and Flotherm

XT offer mesh independent results, this study is a confirmation that, for this geometry as well, the mesh has no significant impact on the results.

In order to evaluate the mesh influence, an electrical and thermal simulation was performed, increasing the number of mesh elements step by step and comparing the maximum temperature found on the busbars, thermal vias, the dielectric material from the PCB (FR4) and the aluminum housing that keeps the PCB fixed. Therefore, 4 different values were compared to the ones obtained in the other simulations.

Six different simulations were solved, the only difference between them is the number of elements. Since the simulations are CFD simulations, where the fluid movement is taken into consideration, the number of fluid cells is also important. Since it's a passive cooled assembly, radiation and conduction play a significant role in the heat dissipation process, so the fluid cells contacting solids is also important, because they represent the boundary layer where the heat dissipation happens.

In Table 1 the values for the maximum temperature can be seen. The conclusion is that the number of elements is not significantly influencing the temperature results, since the difference between the maximum and minimum temperature found on each part is less than 1°C.

Table 1

Mesh independent results

	Mesh number				Maximum temperature			
Sim No.	Total cells	Fluid cells	Solid cells	Fluid cells contacting solids	Busbars [°C]	Vias [°C]	FR4 [°C]	Housing [°C]
1	134901	55875	79026	18513	94.74	93.8	60.76	31.77
2	191593	77205	114388	21849	95.04	93.89	61.11	31.53
3	300561	130112	170449	31609	95.44	94.42	61.41	31.72
4	493867	251134	242733	48039	95.08	94.02	61.08	31.83
5	684011	270546	413465	58599	95.15	94.39	61.1	31.88
6	769095	298205	470890	74892	95.17	94.39	61.12	31.87

4. Simulation results

After the simulation with 7 A DC current input is solved, the simulation software can plot the current density on the assembly. Our goal is to evaluate the current density is the copper conductor and copper vias.

In Fig. 5 the DC current density can be seen in all the copper components.

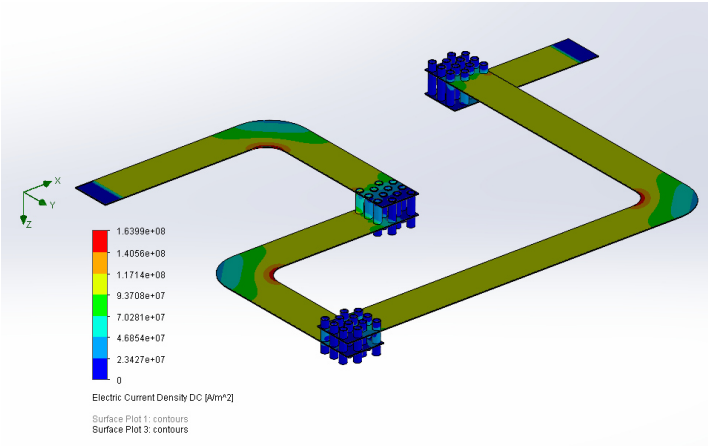


Fig. 5 – Electric current density plot.

In Fig 6 details of the copper areas can be found. In the copper layers, where the conductor is turning at a 90° angle, the DC current density increases on the inner side of the conductor. On the outer side of the conductor, the DC current density decreases towards 0. This behavior shows us that, if the copper layer needs to bend or make a turn, that area can be optimized to reduce the quantity of copper used inside the PCB.

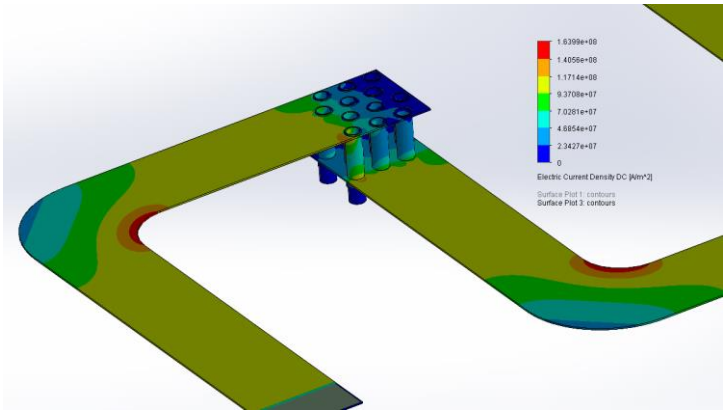


Fig. 6 – Electric current density – close up.

In Fig. 7 a detailed of the copper vias can be observed. Based on the current density distribution, we can see that the current density is different on

each via conductor. This is because the current is passing through the areas with the smallest resistance or the shortest length. Therefore, the vias placed in the corner of the copper layers, are not fully used to transfer the current. In this kind of scenario, the number of vias can be optimized and of course, reduced, in order to reduce the quantity of copper used inside the PCB.

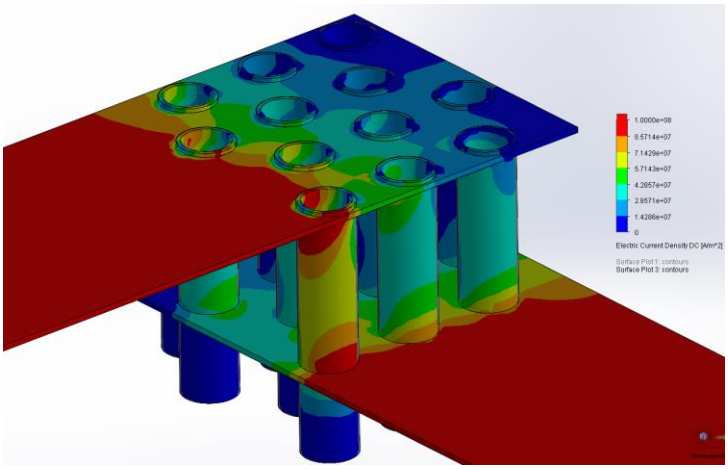


Fig. 7 – Electric current density on vias.

Another simulation result evaluated is the Joule effect in the copper areas and it can be observed in Fig. 8. With small exceptions, it has an uniform distribution around the copper layers.

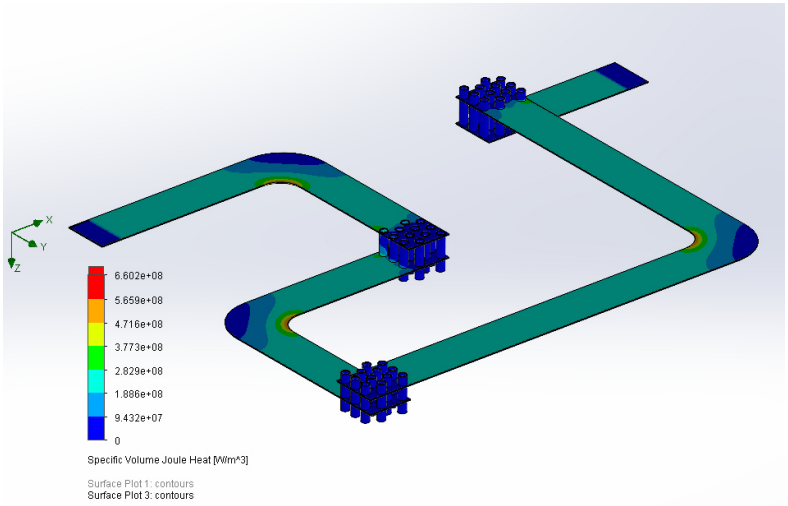


Fig. 8 – Specific volume Joule heat.

In Fig. 9, a closer detailed of the Joule effect can be seen, with a different temperature plot, to highlight the affected areas better. The areas where the current density is higher have also the highest Joule heating effect. This is as expected, since the results are related to each other.

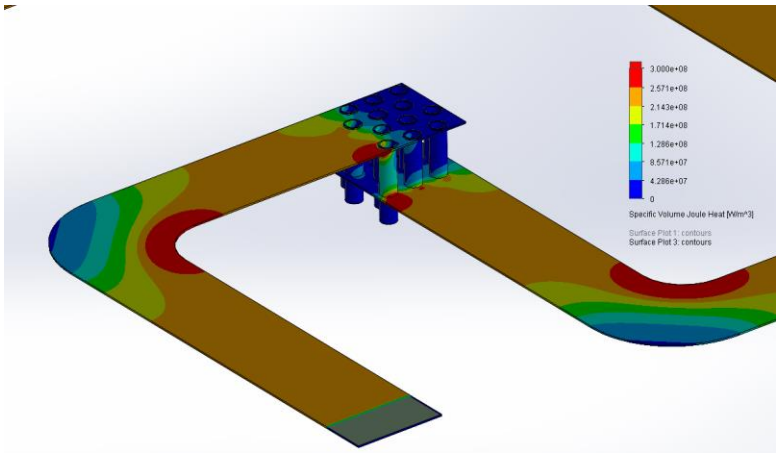
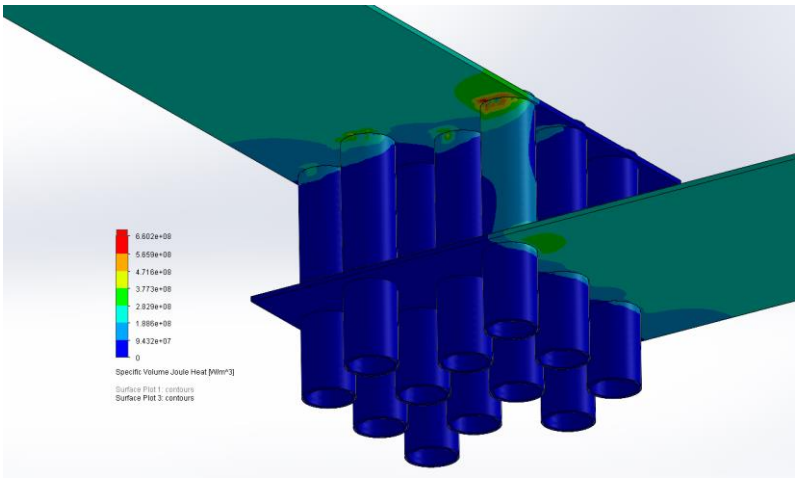


Fig. 9 – Specific volume Joule heat – close up.

Since the current density is higher on some copper vias, the joule heating effect is also higher in the same areas. The areas on the via components with higher Joule heating effect can be observed in Fig. 10. Since the temperature of the copper conductors rise due to Joule heating effect, the temperature of the copper vias has to be evaluated, to prevent potential damage that may appear due to the temperature increase.



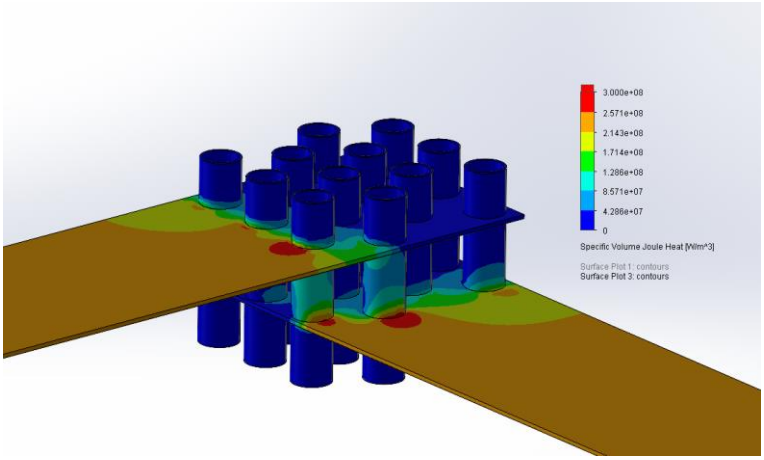


Fig. 10 – Specific volume Joule heat on vias.

The temperature plot of the copper components can be seen in Fig. 11. The ambient temperature, therefore, the starting temperature of all the components is 20°C. The copper components have at the end of the simulation, a temperature between 82.6°C and 101.2°C, so a increase in temperature between 62.6°C and 81.2°C.

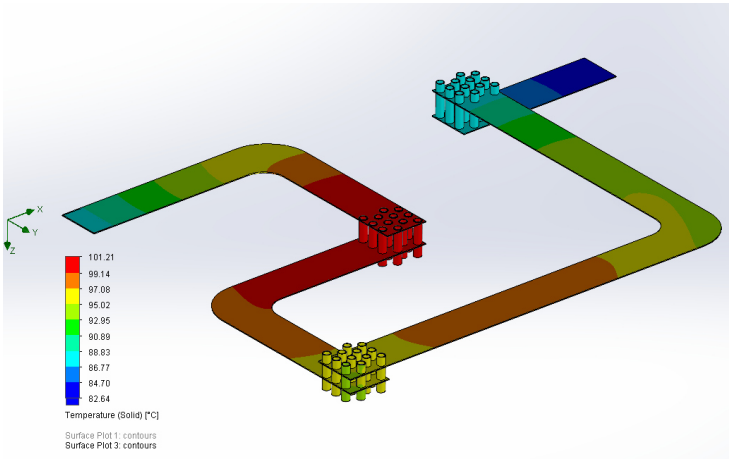


Fig. 11 – Temperature plot.

The maximum temperature is reached om the inner layers. The copper layers that are in contact with the inlet and outlet parts are cooled better, due to convection and radiation into the ambient air. The copper vias are also cooled, since they are not filled, but due to the very small diameter, the quantity of air moving through them and transferring the heat is reduced.

5. CAD optimization

Since cost is a very important factor when it comes to designing and producing new products, one of the goals of this investigation is to modify the copper geometry in order to reduce the volume and to evaluate the change in temperature caused by it.

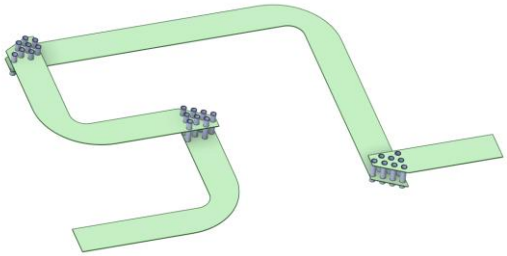


Fig. 12 – Optimized copper layers.

Since the DC current follows the path with the least electrical resistance or shortest path, we saw in the first simulation results that some of the vias are not used a lot, as well as some copper layer corners. Therefore, the copper with smallest current density was removed. In the new CAD model, only 10 copper vias were used each time the current is moving from one copper layer to another.

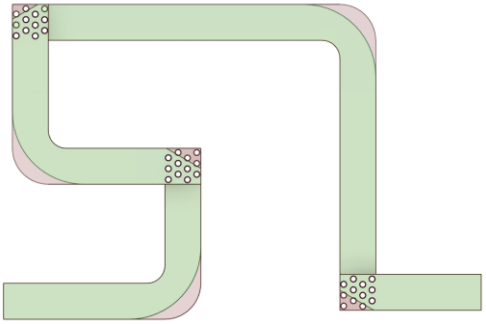


Fig. 13 – Copper layers comparison.

In Table 2 the copper volume for the busbars and vias can be seen, as well as the copper volume reduction is percentage. There is a significant decrease in volume for the vias, of almost 35%. The total volume of copper is reduced with approximately 13% from the previous CAD model. The areas of copper removed are filled with FR4. As in the previous CAD model, the copper is in contact with the FR4, except the interior faces of the copper vias.

Table 2
Copper volume comparison

		Busbars	Vias	Total
Volume [mm^3]	Initial CAD	5.302758	1.436674	6.739432
	Optimized CAD	4.921925	0.938185	5.86011
Volume reduction [%]		7.181791	34.69745	13.04742

For the second simulation, all the boundary conditions were kept the same. Only the CAD model was updated to the new version.

In Table 3 the temperature values and volume dissipated power by Joule heating can be seen for both the old and new CAD model. The average and maximum temperature values are expressed for busbars and vias in 2 separate columns. The total dissipated power by Joule heating in the system was also calculated.

Table 3
Temperature values and dissipated power

		Busbars	Vias	Total
Average temperature [°C]	Initial CAD	95.17	94.39	
	Optimized CAD	101.18	100.75	
Maximum temperature [°C]	Initial CAD	101.21	100.73	
	Optimized CAD	109.06	108.57	
Dissipated power [W]	Initial CAD	0.99957	0.025098	1.024668
	Optimized CAD	1.059198	0.027752	1.08695

In Table 4 the differences between the old and new CAD model can be seen. The delta T value for average temperature, maximum temperature and dissipated power can be seen, as well as the increase expressed in percentage. The increase in temperature expressed in percentage is calculated using only the heat-up, so after the ambient temperature is subtracted, using the following equation:

Increase in temperature [%] = temperature difference / (Temperature of initial CAD – Ambient temperature) * 100

It can be observed that the increase in maximum temperature is almost 8°C for both copper layers and vias. This is approximately 10% for both component types.

Table 4
Increase in temperature

		Busbars	Vias	Total
Average temp	delta T	6.01	6.36	
	%	7.995211	8.549536	
Max temp	delta T	7.85	7.84	
	%	9.666297	9.711384	
Dissipated power [W]	delta T	0.059628	0.002654	0.062282
	%	5.965365	10.57455	6.078261447

Even if the increase of the dissipated power expressed in W has a small value, actually the increase in dissipated power expressed in percentage is up to 10% for the copper vias. This leads to a increase in dissipated power of approximately 6% for the entire system.

6. Conclusions

Finite element analysis using the CAD model is a good method to simulate and predict the current flow through conductors, the dissipated power generated by the Joule heating effect and the current density. Based on these results, the geometry can be changed and optimized to improve the cost or performance of the product.

Reducing the quantity or volume of copper by removing the areas with a low current density will generate an increase in temperature due to an increase in Joule heating effect. This happens because the current density in the remaining copper conductor is higher.

Reducing the volume of copper with approximately 13% caused an increase in total dissipated power by approximately 6%. If the total heat up is not a concern, the FEA simulation has an important role in predicting which areas can be removed from the copper conductor in order to optimize the CAD model.

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EVALUAREA EFECTELOR ÎNCĂLZIRII JOULE ŞI A CONDUCŢIEI CURENTULUI ELECTRIC ÎN STRATURILE DE CUPRU ALE PCB-ULUI PRIN ANALIZĂ CU ELEMENT FINIT

(Rezumat)

Complexitatea tot mai mare a electronicelor, în special în industria auto, necesită un management termic eficient pentru plăcile cu circuite imprimate multistrat (PCB-uri). Metodele tradiționale de analiză implică adesea simplificări. Acest studiu utilizează Analiza cu Elemente Finite (FEA) cu Siemens Simcenter FLOEFD pentru a simula distribuția curentului, efectul de încălzire Joule și comportamentul termic într-un model CAD simplificat de PCB cu 4 straturi, supus unui curent continuu de 7A. Un studiu de independență a rețelei a confirmat fiabilitatea rezultatelor. Simulare inițială a relevat o distribuție neuniformă a densității de curent, evidențiind zonele de cupru subutilizate în colțurile traseelor și în via-uri. Pe baza acestor constatări, modelul CAD a fost optimizat prin îndepărtarea strategică a acestor regiuni cu densitate mică de curent, obținând o reducere totală a volumului de cupru de aproximativ 13% (35% pentru via-uri). Re-simularea modelului optimizat a arătat o creștere a temperaturii maxime cu aproximativ 8°C (o creștere relativă de ~10%) și o creștere cu ~6% a puterii totale disipate, atribuită densității mai mari de curent în traseele rămase. FEA este demonstrată ca un instrument eficient pentru identificarea oportunităților de optimizare a designului PCB și cuantificarea compromisului dintre reducerea costului materialelor și performanța termică.