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Research paper

TRIZ Trends of Engineering System Evolution of Silver Sintering Tools Used to Produce Power Module in Hybrids and Electric Vehicles

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Abstract

Silver sintering is used for bonding of semiconductor dies to the substrate as part of a power module/device packaging. Power-module consisting inverters and converters are used to manage the electric drive systems in the hybrids and electric vehicles (HEVs). Many pressure-sintering tools and processes have been patented to produce reliable sintered silver joints for these power applications, and those invented by Siemens, Infineon Technologies, Danfoss, and Valtion (VTT) are analyzed based on the Theory of Inventive Problem Solving (TRIZ) framework. The level of inventiveness for each patent is evaluated, and respective function analysis is conducted to understand the interactions of the components in each sintering tool. This paper is expected to be useful to engineers who are interested in understanding the evolutionary patterns of a technical system especially silver sintering tools

Keywords: *hybrid electric vehicles, power module, Pressure sintering, sintered silver, TRIZ.*

1. Introduction

The market for hybrids and electric vehicles (HEV) is ever increasing with growing demand to meet the global CO2 emission regulations worldwide by 2020. For example, Europe set the most stringent requirement to be 95 g of CO2 /km, followed by Japan (105 g/km) and China (117 g/km) [1]. This demand fuels the research to produce high-performance inverter and converter packaged in the power module to manage the electrical drive systems in the hybrids and electric vehicles (HEV). The advent of wide-band gap semiconductors, such as silicon carbide and gallium nitride fulfils this higher performance but necessitates the use of die-bonding with higher thermal conductivity than the conventional solder joint. At the same time, this conventional solder joint also faced the additional pressure of being phased out due to its environmental and health issue, as mandated by the European Union Restriction of Hazardous Substance by 2021 [2].

Sintered silver (Ag) joint emerges as one of the four possible bonding techniques to bond this inverter/ converter to the power module substrate because of its almost pure, albeit porous Ag joint to achieve melting temperature above 900oC, superior thermal-electrical conductivities and good mechanical properties [3-5]. The sintered Ag joints are produced from Ag pastes consisting of silver fillers, capping agents, binders and solvents. While the dimension of silver fillers can be nano-sized, micron-sized or mixed, the binders and solvents are varied and mixed to ease their applications in printing, dispensing or laminating on the substrates or wafer for subsequent bonding step. The different formulation of Ag pastes and application approaches have been documented elsewhere, and a summary of the main process step is shown in Figure 1 [3,6].

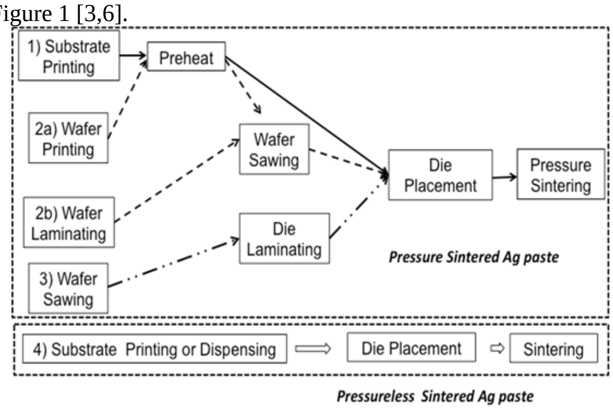

Fig. 1: Main processing steps for four different approaches to forming pressure assisted and pressureless sintered Ag joints [3].

Preheating step removes the solvents from the Ag paste before die placement, while binders and capping agents are typically removed during the sintering step to form the final porous Ag joints [7]. Figure 1 (2b and 3) also shows that the sintered Ag joints are also formed from Ag laminates or films, and this approach does not go through the pre-heating stage to remove the solvent, but instead goes through similar sintering step to remove the binders and capping agents.

On the other hand, the pressureless sintered Ag joints are formed and sintered in a reflow profile similar to epoxy die-attach, albeit of the higher temperature range and longer duration. Due to this similarity, pressureless sintered Ag paste is the preferred approach by industry, but its reliability is less convincing because of its unstable microstructure and high porosity in the sintered Ag joints [2,8]. Hence, pressure assisted sintering is still needed in the formation of reliable sintered Ag joints especially for large die sizes (circa > 100 mm2) typically used in the power module industry. In addition, others explored the use of electrical current sintering to initiate this bonding step [9]. Key patents in pressure sintering and electrical sintering, which are analyzed based on TRIZ framework, will be discussed in the next section. Patent is a rich source of information on innovation and evolution of technology because only 20% of the information in the patent can be found elsewhere [10]. Elsewhere, the TRIZ-based approach has also been used to solve milling and turning problems [11,12].

2. Methodology

In this paper, we reviewed and analyzed three pressure assisted sintering tools based on the disclosure filed by Siemens [13], Infineon Technologies [14], Danfoss [15], and an electric current assisted sintering from Valtion [9] based on function analysis to describe the relationship between the different components in the sintering system. Common words, instead of scientific terms, are used to state this relationship between different components, and those used here are listed in Table 1.

Table 1: Terms and descriptions used in function analysis

No	Terms	Description of Terms
1	Conduct	Transmit (electric or heat)
2	Control	Set a direction/ limit
3	Hold	Connect with / support
4	Move	Make something translate to another position
5	Press	Exert pressure into an immobile object

In addition, TRIZ methodology broadly classifies inventions into five levels of inventiveness with descriptions and examples shown in Table 2 [16-18]. The purpose of this classification is to evaluate the current state and the designs of the patents so that the researchers can further develop the product.

Besides this classification of inventiveness, TRIZ also provides an overall framework entitled "Trends of Engineering System Evolution" to predict the evolution of technological progress for any class of technology (Figure 2) [19]. This evolution follows a system of increasing value to culminate in the Trend of S-Curve Evolution. Here, value refers to main parameter value (MPV), which often characterizes the y-axis of the S-curve Evolution; MPV is defined as total functions/total costs.

Due to lack of a suitable MPV (i.e. cost is not available), this study abandons the S-Curve Evolution, but instead, includes the "trend of increasing degree of trimming" to complement the analysis of inventiveness level in Table 2. Trimming is a method of removing the components from an engineering system to eliminate disadvantages of that trimmed components; the useful function associated with that element will be distributed to another operation. The trimming operations are carried out in the following order; corrective (trimmed first), providing and productive (trimmed last) functions [19]. A corrective operation will be trimmed if the defect does not influence the subsequent operation. Providing operations can be trimmed if the transported/target objects or supported operations are non-existence. A productive operation can be trimmed if it is no longer necessary to perform the function, or the function is taken over by other operation.

Table 2: Different level of inventiveness according to TRIZ

Level of Solutions	Descriptions	Example
Level 1	Modification of parameters without any novelty or addition.	A thicker insulation to decrease heat loss.
Level 2	A qualitative improvement of components in a system or simply merger of several existing technical systems	Fire extinguisher added to a welding device
Level 3	Application of known functions and combination of principles from other industries to a new application area or to provide a new purpose to this combination	"See through" function of medical x-ray emission applied to the airport security systems.
Level 4	Creation of new technical systems based on the discovered scientific principles	Semiconductor transistor utilizing the effect of the semiconductivity to amplify the electronic signal
Level 5	Scientific discovery that expands the borders of science and forms the basis for technological advancement.	Photo-voltaic effect, Hall effect,

Quantitatively, this trimming classification consists of many steps and parameters, and the final trimming value is illustrated in one example for a static chair in Table 3. The trimming value is calculated using the formulae 1 to 4. Table 3 suggests the screws can be trimmed with minimum impact to the function of a chair, and such designs are likely to be seen in the technological evolution of a chair.

$$function = \frac{10\ (\text{total number of components}+1+\left(\frac{\#\text{useful function}}{2}\right)-n)}{\text{total number of components}+1} \quad (1)$$

$$problem = \frac{\#\text{function x rating}}{2} \quad (2)$$

$$cost = \frac{\#\text{Cost}}{\text{total number of components}} \quad (3)$$

$$Trim\ Value = \frac{(\text{function})^2}{\text{problem}+\text{cost}} \quad (4)$$

3. Results and Discussion

3.1. Function analysis of key patents/patents applications in sintering tools

3.1.1. Siemens (US4810672)

Siemens (US4810672) patent is one of the earliest patents describing the die-attaching or bonding for large-area thyristor with a pressure sintering step [13]. It introduced a preheating stage to eliminate the channelling voids associated with the die-attach of large dies before pressure sintering. This preheating stage also solved the engineering contradiction associated with it; if pressure is increased during sintering, the bonding is more stable with fewer voids, but the suitable die sizes will be small, and as-printed Ag pastes will be displaced from the die backside. The TRIZ inventive principle used to solve this contradiction is “preliminary anti-action/ prior counter-action” which is a preheating stage that dried the Ag paste, rendering them suitable for pressure sintering and the die sizes to be inconsequential during this bonding process.

Table 3: Trimming process / step for a static chair [19]

n	Component	#Cost (%)	#Useful Function	Insufficient / Excessive		Calculation			Trim Value
				#function	rating	function	problem	cost	
1	seat	30	1	1	5.0	10.0	2.5	7.5	10.0
2	back rest	20	1	1	5.0	7.0	2.5	5.0	6.5
3	frame	40	2	0	0	6.0	0	10.0	3.6
4	screws	10	3	3	6.7	5.0	10.0	2.5	2.0

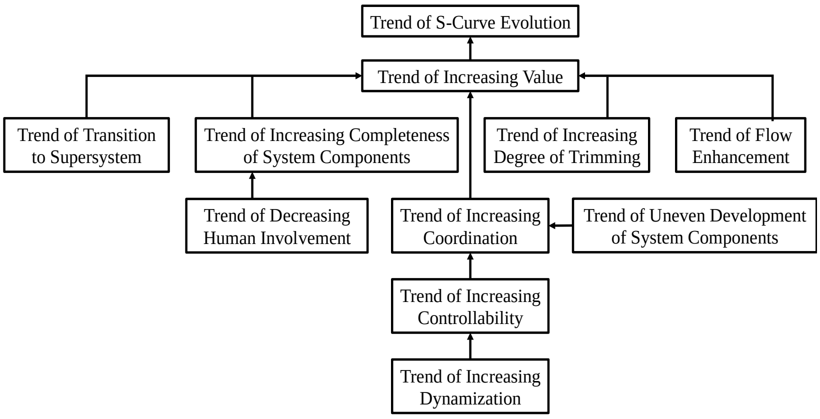

Fig. 2: Various trends classified in the TRIZ Trends of Engineering System Evaluation [18].

Table 4: Rating of insufficient or excessive function

Severity	Rating	Description
slight effect	5	Slight effect on system or output performance
significant effect	10	Significant effect on system or output performance. Subsequent processes will probably be impacted
major effect	15	Overall performance measurably degraded but operable. Action plan and repair required.
hazardous effect	20	System inoperable. System down.

Based on Figure 3, the preheated Ag paste is pressure-sintered to hold contact surface on the substrate to the thyristor under the pressure of 9 MPa, and temperature between 180 oC and 250 oC. In Figure 3, the bolded lines indicate the excessive movement of the rams and the excessive pressure on the thyristor as well as the substrate. These components might need to be "trimmed" or improved to ensure that the pressure sintering process did not damage the thyristor or substrate.
Since an earlier patent (German OS3414065) described a similar process of pressure-sintering, albeit, at less than 1 MPa, this Siemens patent was classified as level 2 for the degree of inventiveness because the introduction of preheating before the pressure-sintering stage was just a qualitative improvement to an established process.

3.1.2. Infineon Technologies (US7851334B2)

Infineon Technologies (US7851334B2) patent is a TRIZ level 2 solution to address the positioning accuracy of the semiconductor dies on the substrate by merging the assembly process and the sintering process of semiconductor modules and holding the semiconductor chips on the desired positions during the assembly process [14]. The introduction of an adhesive layer on support film-strip is based on the TRIZ inventive principle of "preliminary action" to solve the engineering contradiction associated with this patent; if the sintering process is separated from the assembly process, then the output of the sintering process will increase, but the position accuracy will be compromised.

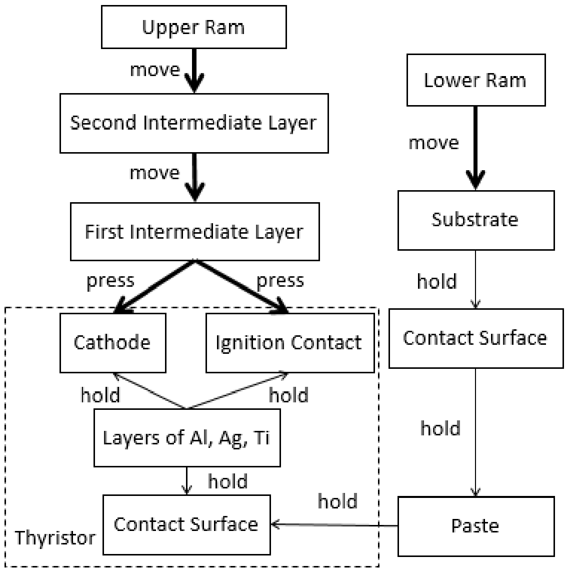

Fig. 3: Function analysis of pressure sintering process and components by Siemens with components of thyristor being bracketed [10].

Figure 4 shows the function analysis of the assembly and sintering steps of this patent. The assembly arrangement attached the semiconductor dies to the support film-strip - a conveyor belt with an adhesive layer on the surface - in a predetermined layout arrangement The semiconductor dies were then transferred to the second arrangement for the sintering process with the substrates. During the sintering process, the upper and the lower part of the sintering tool moved towards each other vertically to generate a pressure of at least 30 MPa on the semiconductor module. A heat source was placed near the sintering tool to elevate the temperature to at least 220oC to initiate the sintering of the Ag paste. At the same time, the heat and the pressure weakened the adhesion of the adhesive layer to detach the semiconductor dies from the support film-strip. However, the absence of pressure-monitoring sensor at the upper and lower parts of the sintering tool might exert excessive forces to release the semiconductor dies adhered and the substrate, resulting in cracks on the dies.

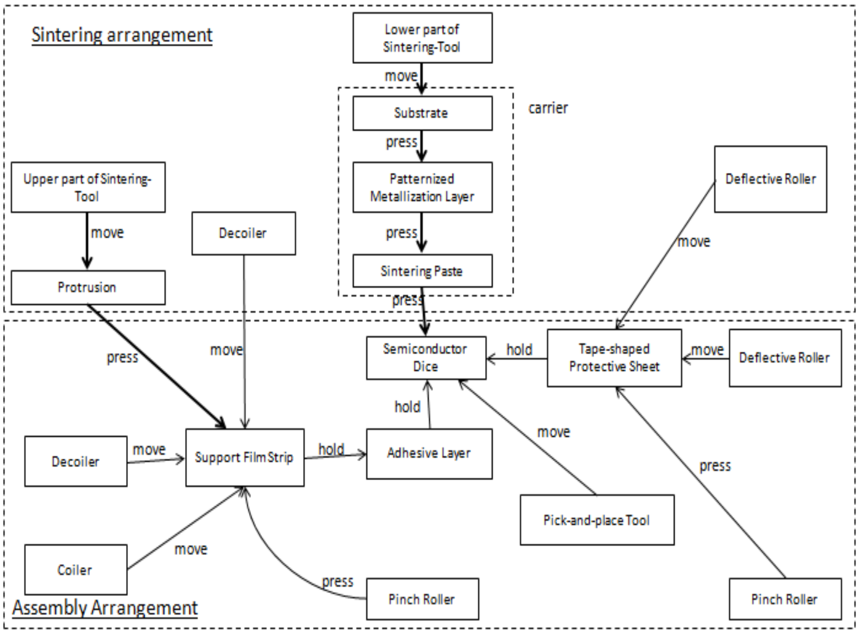

Fig. 4: Function analysis of Infineon patent, which includes the assembly and sintering arrangement. The substrate, paste and patternized metallization layer were bracketed as the carrier for the semiconductor module [14].

3.1.3. Danfoss (WO2016050548A1)

Danfoss (WO2016050548A1) patent application is also a TRIZ level 2 in terms of degree of inventiveness to address the issue of oxidation of substrate during sintering by using four sintering chambers to produce the electronic subassembly [15]. The functions of the four chambers are:

1. First chamber: Preheat the substrate in an oxygen-free manner up to 100oC.
2. Second chamber: Perform the low-temperature pressure-sintering.
3. Third chamber: Reduce the residual oxides on the electronic subassembly with forming a gas or vaporous formic acid components.
4. Fourth chamber: Ensure an oxygen-free cooling down of the electronic subassembly to room temperature.

The introduction of these four chambers also solved the engineering contradiction associated with this patent based on the TRIZ inventive principle of "preliminary action"; if the pressure sintering is carried out at ambient temperature, then the output will be high, but oxidation of substrate will pose a reliability issue to the electronic assembly. Hence, the oxygen was purged out from the first chamber while the residual oxygen diffused from the separating film in the second chamber was sufficient to form the sintered Ag joints. The third chamber acted as an additional step to ensure the complete removal of any residual oxides formed.
Figure 5 shows the function analysis of the second chamber used in pressure sintering of the electronic subassembly. Bold lines indicate the excessive movement of the lower die (of the press) due to the excessive pressure from the electrohydraulic drive on the fluid. The dotted line indicates the insufficient control of the setting device on the orientation of the lower die. As the semiconductor carrier-die on the lower die (of the press) was pressed against the separating film on the pressure pad, there was a possibility of excessive pressure exerted on the semiconductor carrier-die. The pressure sintering process had a maximum temperature of 300oC and pressure of 30 MPa.

3.1.4. Trends of increasing degree of trimming for the pressure sinter equipment: Siemens, Infineon Technologies & Danfoss [13-15]

Table 5, 6 and 7 show the trimming value for different components in these patents. Since our analysis was not able to provide relative cost of the components used in the patents, we divided the cost of 100% by the total number of components in that invention. Our analysis showed that Siemens and Infineon patents have the lowest trimming values for the components of "upper and lower ram/sintering tool" which are similar to the component of "electrohydraulic drive" from the Danfoss patent.
In spite of their productive and providing functions, these three components should be trimmed because of their lowest trimming value. Coincidentally, these components also avoided the excess pressure applied to the bonding materials during sintering. This result is somewhat surprising yet prescient because of our assumption in dividing the cost equally amongst the components in the machine. This excessive pressure issue was addressed by Valtion patent which used the electric current sintering as the "productive operation" to replace the mechanism of mechanical pressure sintering steps, used in the earlier patents by Siemens, Infineon Technologies and Danfoss.

3.1.5. Valtion (US9011762B2)

Valtion (US9011762B2) patent has a TRIZ level 4 degree of inventiveness because of the use of an electric field to create tunnelling current to sinter the Ag fillers at room temperature, instead of the relatively high pressure and temperature used in the pressure sintering mentioned earlier [9]. This application is based on the TRIZ inventive principle of "mechanics substitution" to solve the engineering contradiction encountered in the traditional pressure sintering: if pressure sintering uses external heating, then sintering temperature can be lowered to avoid oxidation and increase output, but the choice of substrate will be limited.
Figure 6 shows the function analysis of Valtion setup in carrying out the electrical sintering. Two conductors were arranged on top of a substrate before the Ag ink/ paste was dispensed. The semiconductor die was placed on top of this ink to ensure their terminal areas were aligned with the conductors. Voltages between 5V and

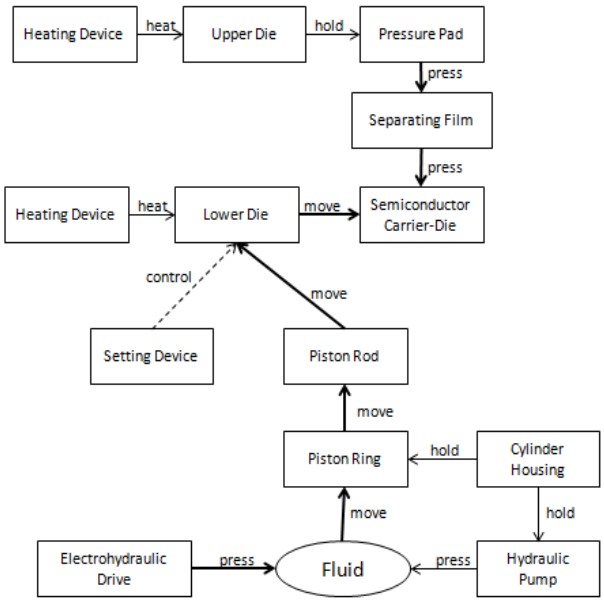

Fig. 5: Function analysis of the components in the sintering chamber of Danfoss' patent [15].

Table 5: Trimming analysis for Siemens Patent (US4810672)

n	Component	#Cost (%)	#Useful Function	Insufficient / Excessive		Calculation			Trim Value
				#function	severity	function	problem	cost	
1	paste	14.3	1	0	0	10.0	0	2.0	49.0
2	contact surface	14.3	1	0	0	8.1	0	2.0	32.3
3	first intermediate	14.3	2	2	10	7.5	10.0	2.0	4.7
4	second intermediate	14.3	1	1	10	5.6	5.0	2.0	4.5
5	substrate	14.3	1	0	0	4.4	0	2.0	9.4
6	upper ram	14.3	1	1	5	3.1	2.5	2.0	2.2
7	lower ram	14.3	1	1	5	1.9	2.5	2.0	0.8

Table 6: Trimming analysis for Infineon Technologies Patent (US7851334B2)

n	Component	#Cost (%)	#Useful Function	Insufficient / Excessive		Calculation			Trim Value
				#function	severity	function	problem	cost	
1	sintering paste	7.7	1	1	5	10.0	2.5	0.6	32.3
2	adhesive layer	7.7	1	0	0	8.9	0	0.6	134.7
3	tape-shape protective sheet	7.7	1	0	0	8.2	0	0.6	114.0
4	pick & place tool	7.7	1	0	0	7.5	0	0.6	95.1
5	patternized metallization layer	7.7	1	1	5	6.8	2.5	0.6	14.9
6	deflective & pinch roller	7.7	1	0	0	6.1	0	0.6	62.3
7	support film strip	7.7	1	0	0	5.4	0	0.6	48.5
8	substrate	7.7	1	1	5	4.6	2.5	0.6	7.0
9	decoiler & coiler	7.7	1	0	0	3.9	0	0.6	26.1
10	pinch roller	7.7	1	0	0	3.2	0	0.6	17.5
11	protrusion	7.7	1	1	5	2.5	2.5	0.6	2.0
12	lower part of sintering tool	7.7	1	1	10	1.8	5.0	0.6	0.6
13	upper part of sintering tool	7.7	1	1	10	1.1	5.0	0.6	0.2

Table 7: Trimming analysis for Danfoss Patent (WO2016050548A1)

n	Component	#Cost (%)	#Useful Function	Insufficient / Excessive		Calculation			Trim Value
				#function	severity	function	problem	cost	
1	lower die	7.7	1	1	5	10.0	2.5	0.6	32.3
2	separating film	7.7	1	1	5	8.9	2.5	0.6	25.8
3	presssure pad	7.7	1	1	10	8.2	5.0	0.6	12.1
4	heating device (upper)	7.7	1	0	0	7.5	0	0.6	95.1
5	piston rod	7.7	1	1	5	6.8	2.5	0.6	14.9
6	setting device	7.7	1	0	0	6.1	0	0.6	62.3
7	upper die	7.7	1	0	0	5.4	0	0.6	48.5
8	piston ring	7.7	1	1	5	4.6	2.5	0.6	7.0
9	heating device (lower)	7.7	1	0	0	3.9	0	0.6	26.1
10	cylinder house	7.7	2	0	0	3.6	0	0.6	21.6
11	fluid	7.7	1	1	5	2.5	2.5	0.6	2.0
12	hydraulic pump	7.7	1	0	0	1.8	0	0.6	5.4
13	electrohydraulic drive	7.7	1	1	10	1.1	5.0	0.6	0.2

8V were then applied between the contact terminals of the semiconductor die and the conductors to sinter this intermediate area of dried Ag ink/paste. The dotted lines indicate the insufficient strength of the nano-ink in bonding the die and the substrate.

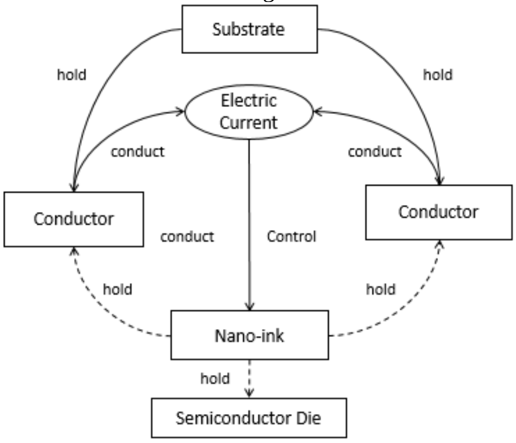

Fig. 6: Function analysis of Valtion patent [9].

4. Conclusion

In conclusion, we postulated the level of inventiveness within four Ag sintering related patents (applications), analysed their associated engineering contradictions as per TRIZ and used function analysis to show the interactions between the components in these inventions. This function analysis showed that these four patents (applications) also move towards ideality to maximize their functions and minimize their disadvantages in terms of harmfulness (broken dies or low bonding strength), which is illustrated in Figure 6. The improvement in this sintering technology will lead to higher performance power module used in HEVs.

The complementary analysis with the trend of increasing degree of trimming showed that the sintering tools from Siemens and Infineon Technologies should be trimmed or improved to achieve the optimum assembly control since their functions were low and high harm, as demonstrated in Figure 7. Future research will look into this trimming trend again with more accurate cost structure than the current average cost amongst all components.

High Functions	*Valtion*	
Low Functions	*Danfoss*	*Siemens Infineon Technologies*
	Low "Harm"	*High "Harm"*

Fig. 7: Classification of four patents (applications) related to sintering tools based on a matrix of functions versus harm.

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