The Effect of EMC Material Properties on Large Area Silver Sintering Process in Power Module

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***Abstract*—With the development of transfer-molded power module devices in electric vehicle field, a large area silver sintering process has become one of the feasible solutions for connecting substrate to heat sink, due to the high thermal conductivity and reliability it can offer. However, silver sintering needs to be carried out under specific temperature and pressure conditions. During the sintering process, thermal stress can occur inside the power module due to the thermal mismatch between the epoxy molding compound (EMC) and the Si3N4 ceramic substrate, resulting in module warpage with a crying or smiling face. Severe warpage often leads to a high failure rate in large-area silver sintering. However, this problem can be mitigated by selecting an appropriate EMC material. Additionally, the mechanical behavior of EMC materials is closely related to temperature, which can also affect the failure rate of the silver sintering process. Although the effect of EMC material on the silver sintering process is very significant, there are few relevant studies on it. In this paper, the failure mechanism of the module in the sintering process is analyzed by the finite element simulation method (FEM). At the same time, simulation model is used to explore the effects of EMC's material parameters such as thermal expansion coefficient (CTE), glass transition temperature (Tg), and modulus on power module warpage and ceramic substrate stress. The simulation results offer crucial guidance for the selection of EMC and the setting of process parameters in silver sintering.**

Keywords*—*Power module, silver sintering, EMC, substrate failure, simulation.

I. INTRODUCTION

With the continuous development of silicon carbide devices, transfer-molded power module has become more and more widely used in electric vehicles due to its advantages such as high operating junction temperature and high power [1][2][3]. Generally, to improve thermal conductivity, the module is typically connected to a heat sink. Reflow soldering is often used to bond the module and heat sink in potting gel modules [4]. However, the use of reflow soldering in transfer-molded modules often results in difficulties with the process, poor reliability and low thermal conductivity. The silver sintering process has become an emerging solution for large-area bonding [5][6][7], due to its advantages such as high thermal conductivity and high reliability. Some companies have already implemented this technology in mass-produced vehicles, such as Tesla's use of silver sintering in their inverter [8].

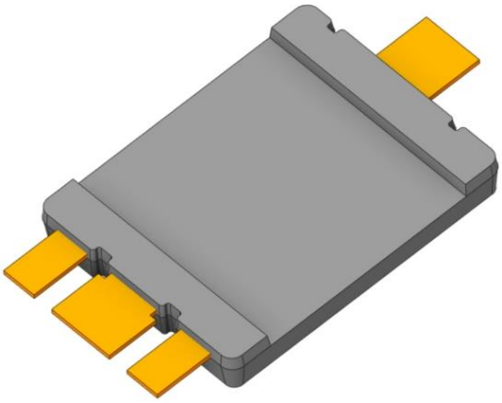


Fig. 1. Transfer-molded power module

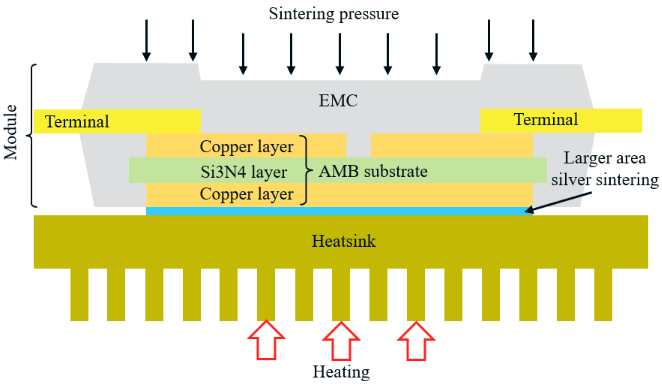


Fig. 2. Schematic diagram of large area silver sintering process

As shown in Fig. 2, the large-area silver sintering process requires relatively high temperature and high sintering pressure to form a good silver joint, which may damage the internal structure of the module (shown in Fig. 3). It's worth noting that the EMC material used in the module can have significant effects on the failure rate of silver sintering. This is likely due to the thermal mismatch between the EMC and substrate, which can cause thermal stress inside the module and result in module warpage [1][2]. If the module warpage is too severe, it can lead to failure during the sintering process. Furthermore, the mechanical behavior of various types of EMC materials can differ greatly, which may also affect the failure rate of the silver sintering process.

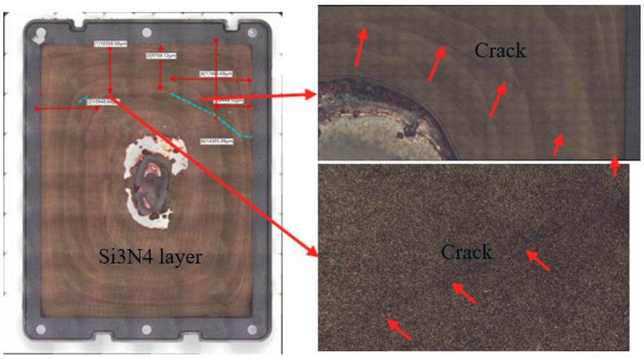


Fig. 3. Cracks appeared in ceramic substrate after silver sintering process

Despite the significant effect of EMC material on the silver sintering process, there have been few relevant references on the topic. This paper aims to analyze the failure mechanism of the module in the sintering process using the FEM. At the same time, simulation model is used to explore the effects of EMC's material parameters such as thermal expansion coefficient (CTE), glass transition temperature (Tg) and modulus on module warpage and ceramic substrate stress. The simulation results offer crucial guidance for the selection of EMC and the setting of process parameters in silver sintering.

II. METHOD AND SIMULATION MODEL

A. Process Analysis

The silver sintering process involves applying nano-silver paste between the module and the heat sink, followed by placing the module in sintering equipment at low temperature. Next, the sintering equipment presses the module and heat sink together using sintering tooling. Later, the module is heated to high temperature, allowing the silver paste to solidify. If only the stress in silver sintering is considered, the process can be simplified into two steps. 1) Flattening the module with warpage at low temperature using sintering tooling; 2) Flattening the module with warpage at high temperature using sintering tooling.

The stress in the silver sintering process is a result of the combined action of thermal stress and mechanical stress. FEM is commonly used to study packaging stress issues. Thus, we will utilize FEM to analyze the effect of EMC on the sintering process. Additionally, to simplify the simulation method and reduce the calculation amount, we will decouple the thermal stress and mechanical stress during the sintering process. The following will include the simulations for module warpage and sintering respectively.

B. Simulation Model

Warpage simulation is utilized to simulate module warpage caused by internal thermal stress in the module at different temperatures. The module structure includes EMC, terminals, and substrate, and the material properties of the module are shown in TABLE I. The mesh is built in HyperMesh and imports into Abaqus for boundary condition loading, simulation calculation, and post-processing. In this paper, the transfer molding temperature is set to 175°C, and the module warpage is found to be very small at this temperature during measurement. Therefore, we consider 175°C as the stress-free temperature for the warpage simulation. The module exhibits different warpage at room temperature and high temperature (above 175°C). Therefore, separate simulations are built for low-temperature warpage during the process from 175°C to room temperature and high-temperature warpage during the sintering process from 175°C to high temperature (above 175°C).

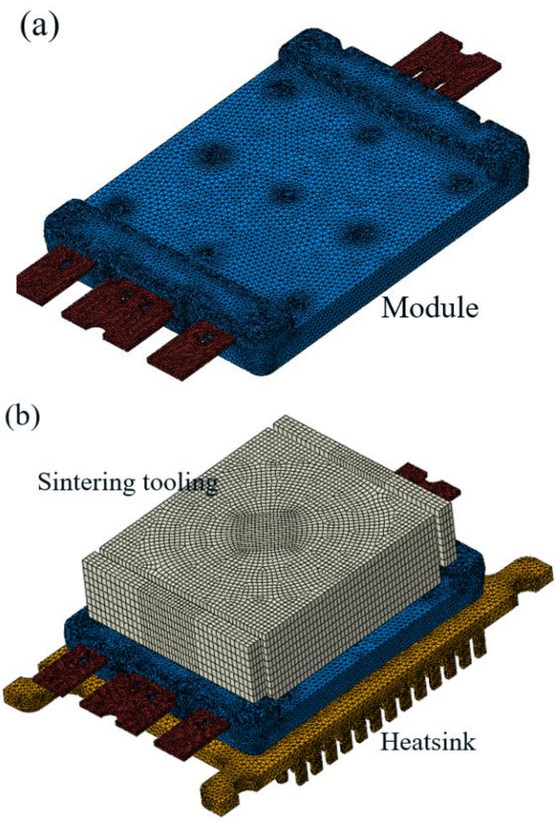


Fig .4. (a) The warpage simulation model of the module; (b) the sintering simulation model of the module

TABLE I. MATERIAL PARAMETERS

Material	**Modulus (MPa)**	**Poisson's ratio**	**Yield (MPa)**	**CTE (ppm/°C)**
Lead frame	117000	0.32	207 - 303	17.6
Lead frame Attach	20000	0.4	40	27
AMB copper	110000	0.32	69	18
AMB Si3N4	310000	0.26	-	3.2
Substrate attach	10000	0.37	43	19
	40000	0.35	50	24
Heat sink	110000	0.32	138	17.6
EMC	TABLE II			

TABLE II. MATERIAL PARAMETERS OF EMC

Parameter		**Unit**	**EMC A**	**EMC B**
CTE	CTE 1	ppm/°C	13	10
	CTE 2	ppm/°C	45	38
Tg		°C	175	195
Modulus	25 °C	MPa	20000~25000	20000~25000
	250°C	MPa	1000~3000	1000~3000

Sintering simulation is used to simulate the module being flattened by the sintering tooling during the sintering process at different temperature. The method of building a simulation model is similar to the above and will not be described in detail here. Corresponding to the sintering process, the module being flattened by the sintering tooling at low temperature is equivalent to low-temperature sintering simulation, and the module being flattened by the sintering tooling at high temperature is equivalent to high-temperature sintering simulation. Furthermore, we import the simulation results of module warpage into the sintering simulation to enhance the accuracy of the sintering simulation.

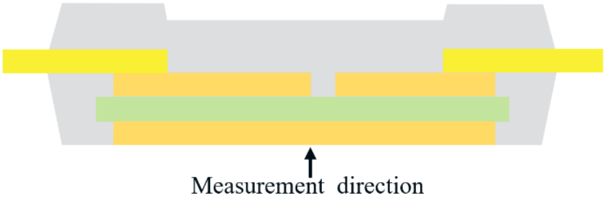


Fig .5. Schematic diagram of warpage measurement

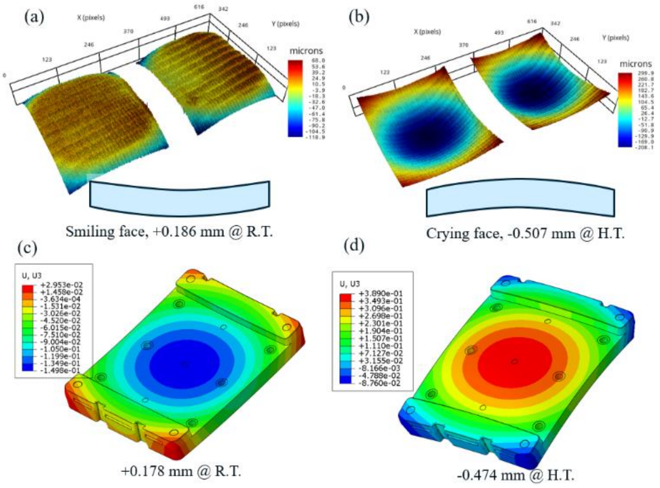


Fig. 6. (a) Warpage test results at room temperature; (b) warpage test results at high temperature; (c) warpage simulation results at room temperature; (d) warpage simulation results at high temperature

III. RESULTS AND DISCUSSIONS

A. Comparison between module warpage measurement and module warpage simulation

Before building the simulation, we utilize Shadow Moiré to measure the module warpage at different temperatures (with EMC A). Fig. 5 depicts the schematic diagram of measuring module warpage. The warpage of the module is measured from the back of the module. Hence, the warpage results should be observed in reverse (shown in Fig. 6a and Fig. 6b). We specify that when the module is placed in the forward direction, the warpage shape in which the four corners of the module are higher than the middle is defined as a smiling face, and the symbol is marked as "+", as shown in Fig. 6a. The warpage shape in the middle of the module that is higher than the four corners is defined as a crying face, and the symbol is marked as "-", as shown in Fig. 6b. The warpage of the module is +0.186 mm at low temperature and -0.507 mm at high temperature. Moreover, the module warpage simulation results are consistent with the measurement results, and the warpage values are also close.

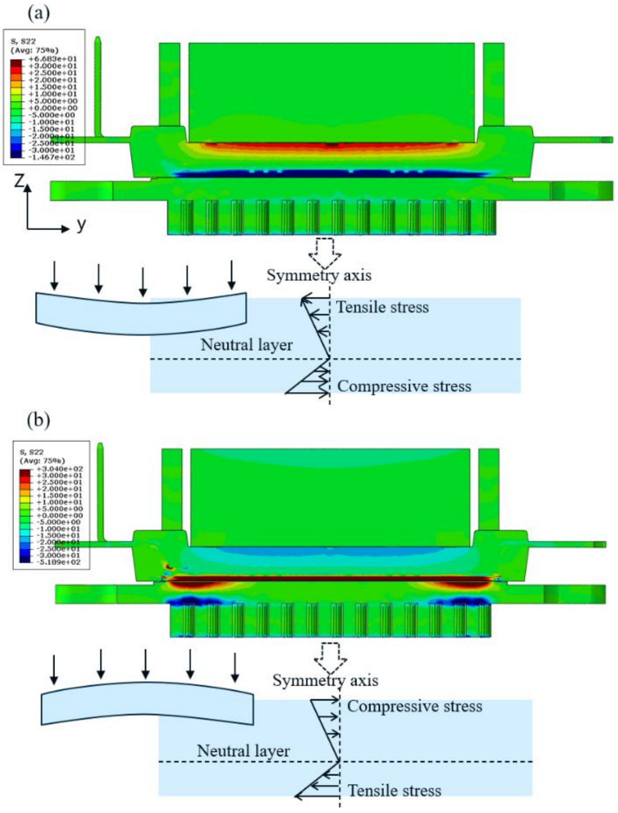


Fig. 7. (a) the stress distribution of the module along the Y direction in low-temperature sintering simulation; (b) the stress distribution of the module along the Y direction in high-temperature sintering simulation

Moreover, the measurement results indicate that the high-temperature warpage of the module is significantly higher than the low-temperature warpage. This is primarily due to the fact that the CTE2 of EMC A is much larger than the CTE1 of EMC A. A larger CTE implies that the thermal mismatch within the module is more severe, leading to a higher warpage of the module at high temperatures.

B. Effect of module warpage shape on sintering simulation

The warpage shape of the module (crying face or smiling face) during the sintering process has a significant impact on the stress state of the material inside the module. Fig. 7 illustrates the stress contour of the module along the y direction in the sintering simulation. A positive stress indicates tensile stress of the material, while a negative stress indicates compressive stress of the material. In Fig. 7a, for low-temperature sintering simulation, the EMC stress contour is red (indicating positive stress), indicating that the EMC is under tensile stress, while the ceramic substrate stress contour is blue (indicating negative stress), indicating that the ceramic substrate is under compressive stress. Contrary to the above, the results of high-temperature sintering simulation are the opposite, as shown in Fig. 7(b).

We can equate the stress contour of low-temperature sintering simulation to the schematic diagram in Fig. 7(a). In low-temperature sintering simulation, EMC is mainly above the neutral layer. When the module is flattened by pressure, the upper EMC is mainly subjected to tensile stress. The ceramic substrate is mainly under the neutral layer. When the module is flattened by pressure, the ceramic substrate is mainly subjected to compressive stress. Similarly, in high-temperature sintering simulation, the upper EMC is mainly subjected to compressive stress, while the ceramic substrate is mainly subjected to tensile stress. Ceramic substrates are brittle materials that easily break when subjected to tension but are not easily damaged when subjected to compression [9]. Thus, compared to smiling face warpage, modules with crying face warpage have a higher risk of ceramic substrate failure during the sintering process.

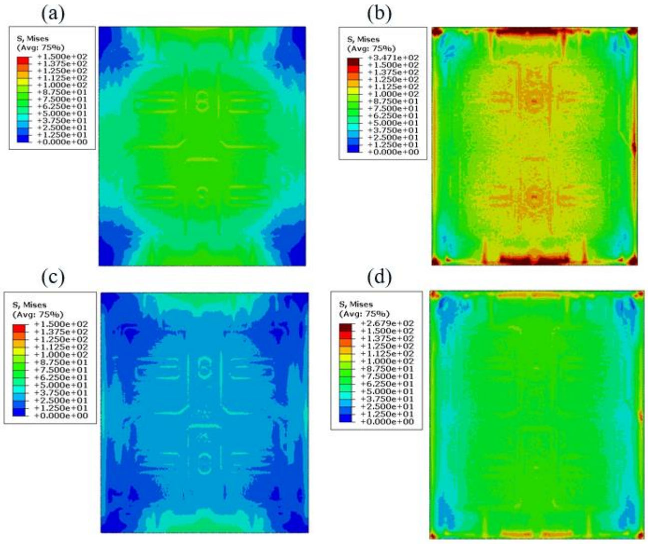


Fig. 8. (a) The Mises stress of ceramic substrate in low-temperature sintering simulation (with EMC A); (b) the Mises stress of ceramic substrate in high-temperature sintering simulation (with EMC A); (c) the Mises stress of ceramic substrate in low-temperature sintering simulation (with EMC B); (d) the Mises stress of ceramic substrate in high-temperature sintering simulation (with EMC B)

Furthermore, the Mises stress of the ceramic substrate during high-temperature sintering simulation is higher than that of the low-temperature sintering simulation (shown in Fig. 8a and Fig. 8b). This indicates a higher risk of the ceramic substrate cracking during high-temperature sintering. In addition, the actual location of the ceramic substrate cracking (shown in Fig. 3) is in close proximity to the high-stress risk area of the ceramic substrate during high-temperature sintering simulation (shown in Fig. 8a). The edge area of the ceramic substrate experiences some stress concentration during high-temperature sintering simulation, which may be due to the simulation model and is not discussed here. In short, the high-temperature sintering simulation exposes the ceramic substrate to a tensile stress state with a larger value of Mises stress compared to the low-temperature sintering simulation, making the ceramic substrate more susceptible to failure.

C. *Effect of EMC's CTE and Tg on sintering simulation*

Modules that are encapsulated with EMC A have a high failure rate during the sintering process. However, after replacing EMC A with EMC B, the failure rate of the module during the sintering process has significantly decreased. This improvement is mainly attributed to the difference in Tg and CTE between the two EMC materials. To investigate the effect of these factors, four groups of warpage simulations are conducted, as presented in Table III. By comparing Group 1 and Group 2, it can be observed that increasing the EMC's Tg can significantly reduce high-temperature warpage. Comparing Group 2 and Group 3, it can be seen that decreasing EMC's CTE1 can significantly reduce low-temperature warpage, but has less of an impact on high-temperature warpage. Similarly, comparing Group 3 and Group 4, it can be observed that reducing EMC's CTE2 can significantly reduce high-temperature warpage but has less of an effect on low-temperature warpage. Therefore, compared to EMC A, EMC B has a higher Tg and lower CTE1/CTE2, resulting in reduced warpage of the module at both low and high temperatures, with a significant reduction in warpage at high temperatures.

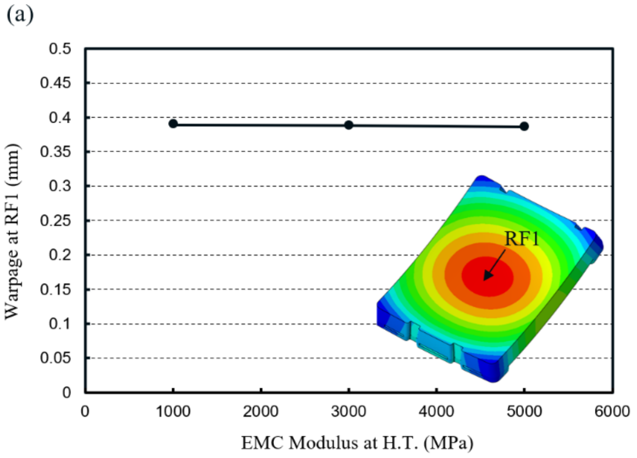
TABLE III. SIMULATION RESULTS OF MODULE WARPAGE UNDER DIFFERENT EMC MATERIALS

Group	**Parameter**	**Warpage at R.T.**	**Warpage at H.T.**
1 (EMC A)	CTE1：13 ppm/℃ CTE2：45 ppm/℃ Tg：175 ℃	+0.178 mm	-0.474 mm
2	CTE1：13 ppm/℃ CTE2：45 ppm/℃ Tg：195℃	+0.178 mm	-0.345 mm
3	CTE1：10 ppm/℃ CTE2：45 ppm/℃ Tg：195 ℃	+0.12 mm	-0.333 mm
4 (EMC B)	CTE1：10 ppm/℃ CTE2：38 ppm/℃ Tg：195 ℃	+0.12 mm	-0.270 mm

Lower module warpage in sintering simulations also indicates lower ceramic substrate stress, as shown in Fig. 8. Therefore, when EMC B is used, the module warpage is significantly reduced, resulting in a considerable reduction in the failure rate of the sintering process. Therefore, to minimize the failure rate during sintering, it is recommended to choose an EMC material with a higher Tg and smaller CTE.

D. *Effect of EMC's modulus on sintering simulation*

The mechanical properties of EMC material will change with temperature due to its characteristics as a polymer material. Therefore, the high-temperature modulus of different EMC materials may vary significantly. However, in high-temperature warpage simulation, it is found that even when the modulus of the EMC material varies within a wide range, the high-temperature warpage of the module remains relatively stable, as shown in Fig. 9a. It is important to note that in high-temperature sintering simulation, decreasing the modulus of the EMC material resulted in a significant reduction in the stress on the ceramic substrate, as shown in Fig. 9b. This can be attributed to the fact that the lower modulus of the EMC material can absorb more mechanical stress and thus alleviate the stress on the ceramic substrate during the sintering process.



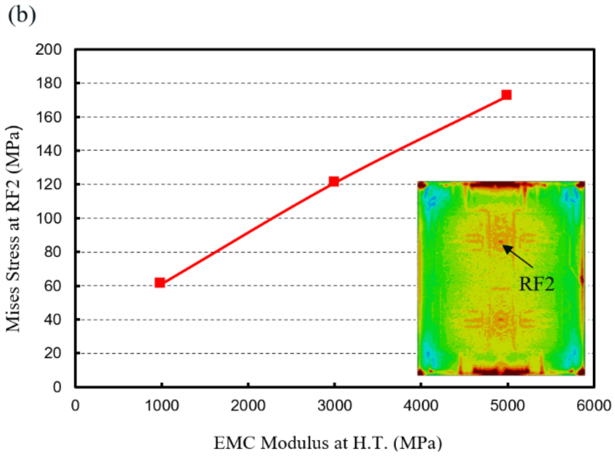


Fig. 9. (a) The relationship curve between module warpage and EMC modulus in high-temperature warpage simulation; (b) the relationship curve between ceramic substrate stress and EMC modulus in high-temperature sintering simulation.

IV. CONCLUSION

This paper presents a simulation analysis of the failure of ceramic substrates during the large-area silver sintering process of transfer-molded power modules. The main conclusions are as follows. 1) Ceramic substrate failure is likely to occur during the high-temperature sintering process due to the greater module warpage with crying face. 2) The risk of ceramic substrate failure increases with greater module warpage during sintering. However, using EMC with higher Tg and smaller CTE can significantly reduce module warpage and mitigate the risk of ceramic substrate failure. 3) The modulus of EMC has minimal impact on module warpage; however, lower modulus EMC can partially alleviate stress on the ceramic substrate during the high-temperature sintering process. These conclusions can be used to analyze the root causes of failures during the silver sintering process and serve as a reference for selecting appropriate EMC materials and process parameters in silver sintering.

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