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Micro Heat Pipe Design and Fabrication on LTCC

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Abstract—This paper presents work on micro heat pipe (MHP) fabrication in Low Temperature Cofired Ceramics (LTCC) modules for cooling purpose. The MHPs are fabricated in a 10 layer structure using ESL41020 tape. Different fabrication settings have been tested to minimize swelling and groove deformation. The best result is obtained by using fugitive tape, extended firing profile, and hot lamination at 50°C for 5 minutes with 70 bar pressure.

Keywords—Micro Heat Pipe (MHP), Low temperature Co-fired Ceramics (LTCC), Sacrificial volume material (SVM), thermal management

I. INTRODUCTION

For heat dissipating electronic modules a thermal management solution, such as integrated heat pipes, is required to guarantee performance and longevity. Often it is vital that the cooling solution is small in size and, if possible, incorporated within the package. This can be done by the use of micro heat pipes (MHP), which is an all passive solution providing a more than competitive thermal conductivity based on heat transfer from a hot source to a cold source [1] where the heat outflow is enhanced by the phase change of the coolant circulating in the device.

Recently, MHPs in copper have successfully been integrated with PCB based electronics [2]. For Low Temperature Co-fired Ceramics (LTCC) modules, such heat pipes are challenging to integrate due to the large Coefficient of Thermal Expansion (CTE) mismatch between the copper heat pipe and the ceramic material. MHPs realized in LTCC, as was done by [3] and [4], solve this mismatch problem while, simultaneously, the LTCC can be used a regular chip package containing chips, electrical interconnections, DC feed network, in out connectors, etc. These proposed MHPs are fabricated in DuPont 951 having dimensions of 108 mm × 26.5 mm × 4 mm [3] and in Ferro-A6-M with the dimensions 10 mm × 3 mm × 1.2 mm [4], the latter with a heat transfer capacity of 1.504 W.

Working on a future D-band (110-170 GHz) front end LTCC module, using ESL41020 tape [5] from Electro Science Labs, the MHP seems to be a good candidate to evacuate the power dissipated from a medium power amplifier. While no MHPs have been reported in literature for the ESL41020 tape,

all production steps and parameters for MHP production need to be investigated. The dimensional constraints of the front end module is a maximum of 12 mm × 12 mm in the lateral directions including three MMIC chips (multiplier, mixer and amplifier), DC feed network, LO, IF and RF in/output interconnections and a thermal management solution.

II. MHP STRUCTURE

Our proposed MHP test structure consists of ten 90 μm thick LTCC layers. Layers 1 to 3 are full layers, 4 and 7 contain grooves to form the wick structure, 5 to 6 form the vapor space cavity, whereas top layers 8 to 10 include “chimneys” to evacuate the sacrificial volume material (SVM) during sintering. The grooves have a width of 100 μm and the vapor space cavity length is 9.6 mm (limited by the module size).

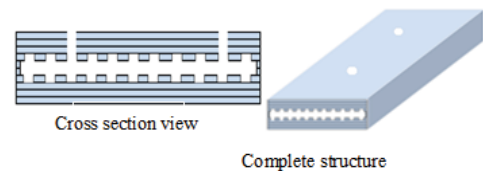


Fig. 1. MHP structure

III. FABRICATION OF MHP

The MHP, Fig. 1, is formed using standard LTCC fabrication steps: laser cut out of the cavities and grooves, stacking, under vacuum setting for 10 minutes, lamination (220 bar at 68°C for 10 minutes) and firing. The cavities on layers 5 and 6 are filled with a fugitive tape (FT), the ESL49000 [6] that acts as an SVM to protect them from deforming during the lamination step. The grooves are left unfilled due to the difficulty to process such small FT ribbons (100 μm × 9.6 mm). Fig. 2 shows the sintered result for the first prototype with evidence of swelling and groove deformation.



Fig. 2. Cross section view of realized MHP

IV. IMPROVED MHPs

The swelling occurs when CO_2 , formed by the oxidation of the FT during firing, remains captured in the vapor space cavity due to the LTCC densification [8] and the deformation of the grooves stems from the lamination step. The improvement work is done in two steps, first we work on the swelling and once that problem is solved we will work on the grooves' deformation problem.

A. First improvement

To address the swelling issue, a change of SVM from FT to PMMA [6], as proposed in [9], might work since the PMMA produces no gas in the firing stage. Another possibility could be to introduce a firing profile plateau at 720°C for at least 1 hour, letting the CO_2 out before reaching the densification temperature, as proposed in [8]. To prepare the work on the groove deformation problem, we have also included a lamination parameter test during this prototype run. To evaluate these approaches we use a three-factor and two-level full factorial experience plan, 2^3 . Eight prototypes with different settings are prepared varying the lamination (hot/cold), SVM (FT/PMMA) and firing profile (standard/extended with a plateau of 720°C for 2 hours). The hot lamination settings are 220 bar, 68°C for 10 minutes, while the cold lamination is done at 10 bar, 25°C during 1 minute using honey as adhesive between each layer. The dimensions of the MHP, designed to dissipate 1.2 W of power, are presented in TABLE I. while Fig. 3 gives an overview of the different dimensions and Fig. 4 shows the cross section of the eight fabricated prototypes after sintering.

TABLE I. HEAT PIPE DIMENSIONS

W_v	4 mm
t_v	0.15 mm
tg_1 and tg_2	0.075 mm
L_1 and L_2	0.3 mm
α_1 and α_2	90°
N: Number of grooves	20

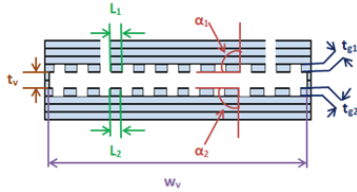


Fig. 3. Design dimensions of the MHP structure

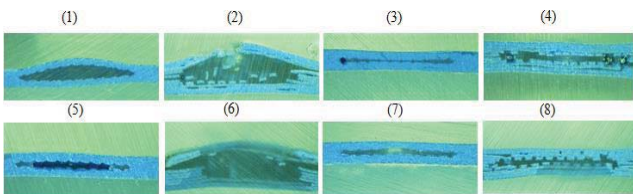


Fig. 4. Cross sectional view of the prototypes: (1) FT, hot lamination and standard profile, (2) FT, cold lamination and standard profile, (3) PMMA, hot lamination and standard profile, (4) PMMA, cold lamination and standard profile, (5) FT, hot lamination and extended profile, (6) FT, cold lamination and extended profile, (7) PMMA, hot lamination and extended profile, (8) PMMA, cold lamination and extended profile

The response value is the vapor space thickness, t_v , given that it is directly proportional to the heat transfer capacity. This is taken as the highest measure over the cross section of the MHP structure.

1) Analysis:

Looking at the cross sections in Fig. 4 it is evident that the prototypes number 3, 5 and 7 have the best appearance since number 1 is swollen and the prototypes number 2, 4, 6, and 8 show severe delamination between layers. Delamination takes place in all cases for the prototypes where cold lamination is used. Thus, the cold lamination as performed here is an erroneous track and therefore these prototypes are omitted from further investigation. The performed analysis is presented in Fig. 5 and Fig. 6.

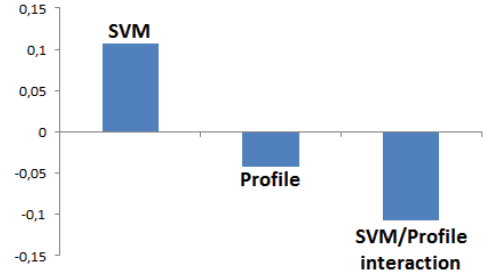


Fig. 5. Main effects and interaction plot for the vapor space thickness, t_v .

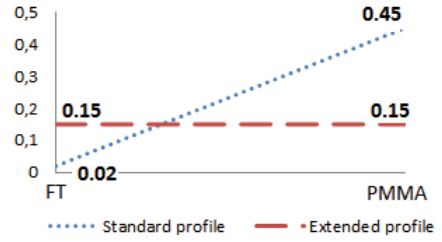


Fig. 6. Interaction plot between the SVM and the profile parameter.

From Fig. 5, it is observed that largest effect is the interaction between SVM and firing profile. Fig. 6 shows that this interaction is indeed real. However, it also shows that the required value of t_v is obtained when the extended firing profile is used. In this case, the SVM choice has no influence on the result value of t_v . The prototypes number 5 and 7 depicts this case. Comparing the complete set of dimensions of the analyzed prototypes in Fig. 4 with the designed values, the prototype number 5 is closest to the designed dimensions. The settings for this prototype were FT, hot lamination and extended firing profile. The remaining problem is the groove angles which are found to be 140° and 160° on this prototype instead of the intended 90° . To improve the shape of the wick grooves (reduce the angles), another test is performed as explained in the next section.

B. Second improvement

The grooves' angles α_1 and α_2 are important to the wick structure's capacity to transport the condensed liquid from the condenser part back to the heaters position. The deformation of

the grooves primary stems from the lamination procedure (pressure, temperature and time) which is what we now need to address. Based on the rather correct results of previous prototype number 5 we will use FT and extended firing profile as fixed values. Also, from the previous prototype run we have seen that a 68°C lamination temperature seems to be too high, while 20° doesn't work at all, even though using honey as adhesive. Regarding pressure and time, the 220 bar pressure and 10 minutes of pressure time used in the prototypes 1, 3, 5 and 7 is too tough on the grooves. Thus, after some initial testing we have chosen 50°C as a fixed temperature while the pressure is varied in three levels (70, 90 and 150 bars) and the time in two levels (2 and 5 minutes). The cross-sections of the resulting prototypes are presented in Fig. 7.

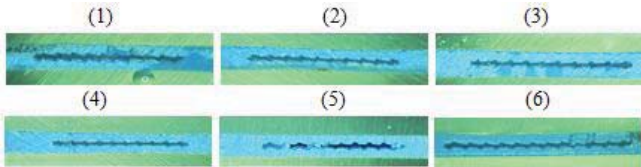


Fig. 7. Prototypes: (1) 70 bar, 2 min, (2) 70 bar, 5 min, (3) 90 bar, 2 min, (4) 90 bar, 5 min, (5) 150 bar, 2 min, (6) 150 bar, 5 min

1) Analyze:

From the main effects and interactions, as presented in Fig. 8, it is observed that the pressure has the most influence on the angles α_1 and α_2 . The interaction between time and pressure is very limited. From Fig. 4, where the resulting values for the 2 and 5 minute prototypes is presented as a function of pressure, α_1 and α_2 are closest to 90° when the applied pressure is 70 bar. The best result is achieved with 5 minutes.

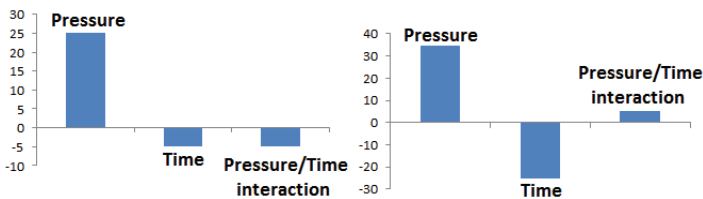


Fig. 8. Main effects and interactions (α_1 :left and α_2 :right)

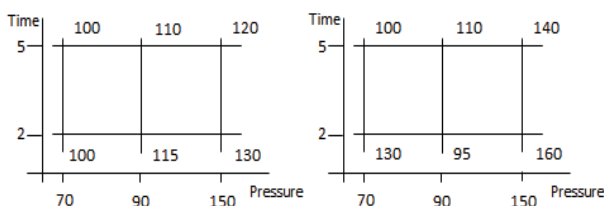


Fig. 9. Obtained values (α_1 :left and α_2 :right)

Thus, the best settings found are: FT as SVM, 70 bar for 5 minutes at 50°C as lamination parameters and an extended firing profile as is the case for prototype number 2 in 0.

V. CONCLUSION

MHP structures design and fabrication in the ESL41020 tape is presented. Initial problems as swelling, and grooves deformation have been solved. By the use of an extended firing profile including a plateau at 720°C during 2 hours the CO₂ gas, formed by the oxidation of the FT during firing, is readily evacuated. Furthermore, by lowering the lamination parameters to 70 bar, 5 minutes and 50°C the best shape of the wick grooves is obtained while no delamination is seen between the tape layers. Cold lamination with honey as interlayer adhesive resulted in delamination between layers and cannot recommended for this type of structure.

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