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Goulven Janod, Lucas Chachay, Jonathan Schoenleber, Yvan Avenas, Didier Bouvard, et al.. Evaluation of Thermocompressed Nanoporous Copper Deposit to Replace Soldering for Power Electronic Metal Foam Heat Sinks. *IEEE Transactions on Components, Packaging and Manufacturing Technology*, 2024, 14 (8), pp.1359-1366. 10.1109/TCPMT.2024.3418673 . hal-04785342

**HAL Id: hal-04785342**

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Submitted on 25 Nov 2024

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# Evaluation of Thermocompressed Nanoporous Copper Deposit to Replace Soldering for Power Electronic Metal Foam Heat Sinks

Goulven Janod, Lucas Chachay<sup>1</sup>, Jonathan Schoenleber, Yvan Avenas<sup>2</sup>, Didier Bouvard, Rémi Daudin, Jean-Michel Missiaen<sup>3</sup>, Marie-Pierre Gigandet, Jean-Yves Hihn<sup>4</sup>, and Rabih Khazaka<sup>5</sup>

**Abstract**—Metal foams appear as innovative solutions for cooling high-density power electronic systems. In these assemblies, the foam is currently soldered on a copper substrate. However, the temperature of solders is limited and their aging under high thermomechanical constraints is a clear weakness of this solution. A novel way to attach metal foams to copper substrates is presented in this article, the thermocompression of a nanoporous copper deposit. The obtained attachments show good densification of the deposit, and the conducted shear tests show an increase in the contact mechanical strength with increasing thermocompression time. In addition, using a dynamic methodology, the thermal contact resistance of such joints is evaluated which shows results similar to those obtained on soldered joints.

**Index Terms**—Copper foam, power electronics, thermal management, thermocompression.

## I. INTRODUCTION

DIFFERENT solutions are currently used to dissipate the heat generated by power components, from liquid cold plates [1] to jet impingement technologies [2], [3], [4]. Another promising solution involves using liquid-cooled metal foams [5], [6], [7], [8]. Indeed, metal foams present a large specific surface area, a high convective heat transfer coefficient, and good thermal conductivity. All these attributes participate in reducing the thermal resistance between the components and the cooling fluid. However, the foam must be attached to either a baseplate or a substrate in a power assembly, and due to the porosity of the foam, a significant thermal

contact resistance is created at the interface [9], [10], [11]. Usually, the attachment is made by soldering, but this method has several drawbacks. Notably, the displacement of the solder into the foam by capillarity after melting can affect the foam's properties and lead to a lack of solder at the interface. This can make the soldering technique unsuitable for attaching certain types of foams. The low thermal conductivity of the solder joints (around 50 W/m.K), compared to the other materials of a power assembly (usually higher than 100 W/m.K), is also a drawback. In addition, after the soldering process and during temperature aging, brittle intermetallics are formed between copper (widely used in power assembly) and solder material [12] which cause reliability issues. Finally, the temperature of the soldering process is relatively close to the operating temperature of power electronics systems, which is also a cause of early aging or failure.

This article presents a new technique to attach metal foams to copper substrates, which involves the thermocompression of a nanoporous copper deposit [13]. With this method, several issues of solders are avoided:

- 1) No melting during the process and thus no capillary problems;
- 2) No intermetallics; and
- 3) Melting temperature of the thermocompressed copper (1085 °C) much higher than the operating temperature.

Other very important properties of the joint may also be affected by solders including the following:

- 1) The thermal conductivity of the created interface, and therefore, the thermal contact resistance between the foam and the substrate;
- 2) The mechanical strength; and
- 3) The thermomechanical behavior during thermal cycling.

Mechanical tests and thermal measurements will thus be presented in this article. However, as this article presents a preliminary evaluation of this novel attachment technique, thermal aging tests have not yet been conducted to further study the reliability of this technique. More precisely, the obtained joints are observed by optical microscopy and scanning electron microscopy (SEM), characterized mechanically by shear tests,

Manuscript received 30 March 2024; revised 2 June 2024; accepted 18 June 2024. Date of publication 24 June 2024; date of current version 11 September 2024. This work is supported by the ANR Agency under project CopperPack (ANR-19-CE05-0011). Recommended for publication by Associate Editor C. S. Tan upon evaluation of reviewers' comments. (*Corresponding author: Yvan Avenas.*)

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Digital Object Identifier 10.1109/TCPMT.2024.3418673

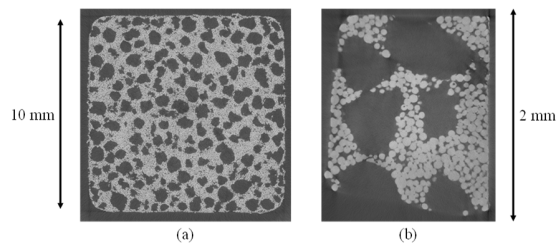


Fig. 1. Versarien foam images obtained by micro-tomography. (a) Large scale. (b) Smaller scale. The copper part appears in light, whereas the porosity is darker.

and the thermal contact resistance (TCR) between foam and bulk copper is evaluated using a dynamic method. Mechanical and thermal characterizations are also conducted on soldered joints in order to compare results and to evaluate the feasibility of replacing those.

The first part of the article presents the studied foam and its properties, the nanoporous copper deposit, and the thermocompression process. After this, the characterization methods along with the corresponding sample preparation are described. Then, the results are presented and discussed. The conclusion highlights the perspectives of this work.

## II. STUDIED FOAM AND ATTACHMENT METHOD

### A. Copper Foam

The copper foam studied in this article has been provided by Versarien<sup>1</sup> plc. It has been realized by sintering a 50  $\mu\text{m}$  diameter copper powder with a pore former compound ( $\text{K}_2\text{CO}_3$  in this case). Fig. 1 shows a 2-D view of this copper foam. Although most metal foam liquid cooling systems use high porosity metal foams (>80% porosity) [7], [8], [14], [15], [16], here, a relatively low porosity metal foam (60%) has been chosen because it has shown interesting results [17], [18]. Indeed, Glass et al. [17] carried out an optimization process of a metal foam heat sink considering both thermal behavior (thermal resistance) and pressure drops. It was shown that a porosity close to 60% was a good compromise: with lower porosity, pressure losses are very high, and with higher porosity, the decrease of the effective thermal conductivity of the foam induces a high thermal resistance increase. Also, the low porosity allows successful mechanical contact with bulk copper using the thermocompressed method presented hereafter. In fact, compared to high porosity foams, the area of the thermocompressed joint is larger, and the higher mechanical strength of the foam allows applying higher pressure during thermocompression.

The equivalent thermal conductivity of the foam has been evaluated by analyzing 3-D images, obtained by micro-tomography, with a Geodict software. For different foam samples, the average value was 92 W/m/K, with a 5% relative error between samples. This disparity is discussed later in the article. The average size of the larger pores, which have been created by the pore former, was measured at 450  $\mu\text{m}$ .

<sup>1</sup>Trademarked.

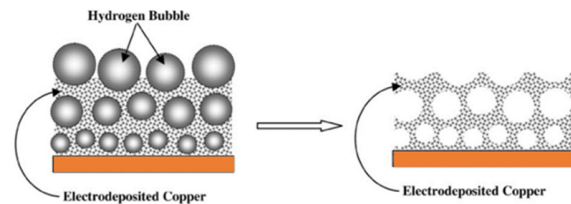


Fig. 2. DHBT deposit principle [19].



Fig. 3. Sideview of the obtained DHBT deposit.

### B. Copper Deposit

The nanoporous copper deposit is fabricated directly on a bulk copper surface that will later be in contact with the copper foam by an electrochemical method called “dynamic hydrogen bubble template” (DHBT), presented in Fig. 2. Copper ions in an aqueous solution react at the contact of the substrate (used as a negative electrode) to form solid copper. At the same time,  $\text{H}^+$  ions also react at the same place to form gaseous  $\text{H}_2$  bubbles, which move away from the substrate. The growth of the copper deposit is then channeled by the bubbles.

The thickness and the morphology (pore density and size, ligament size) of the deposit can be controlled by the current density passing through the electrode, current modulation strategies, additives in the electrolytic bath, and the time during which the current passes [13]. For all tests, we selected a deposit time of 20 s and a current density of 300 A/dm<sup>2</sup>. The obtained deposit is shown in Fig. 3.

A major issue with the obtained deposits is that they are oxidized. As copper oxide has poor thermal properties, it is of great importance to reduce the oxides of the deposits. For this purpose, they are placed into an oven under a reducing atmosphere ( $\text{He-H}_2$ ). Then, the oven is heated up to 500  $^\circ\text{C}$  for 1 h. Then an optical inspection is carried out to verify that the oxides are eliminated before starting the thermocompression process. Later in the article, a comparison between untreated (oxidized) and reduced samples is presented to show the importance of this reduction process. Note that the deoxidation step could also be done by a chemical treatment.

### C. Thermocompression Process

The principle of thermocompression is to apply pressure onto the assembly (bulk copper with deposit + copper foam) at high temperatures. The temperature and the pressure allow for both densification of the copper deposit and bonding of the two surfaces in contact. The thermocompression method is explained in Fig. 4. As it is a complex manipulation, particular attention was paid to the following points:

- 1) Air atmosphere at a high temperature (300  $^\circ\text{C}$ ) can oxidize the deposit. To avoid that, the whole process is carried out in a dynamic vacuum below  $10^{-1}$  mbar.

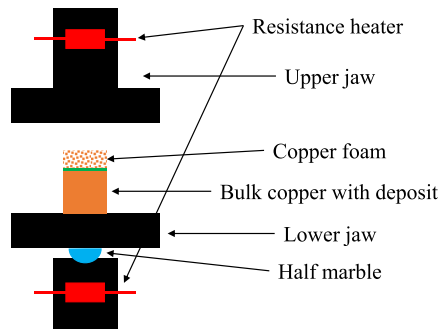


Fig. 4. Schematic presentation of the thermocompression setup.

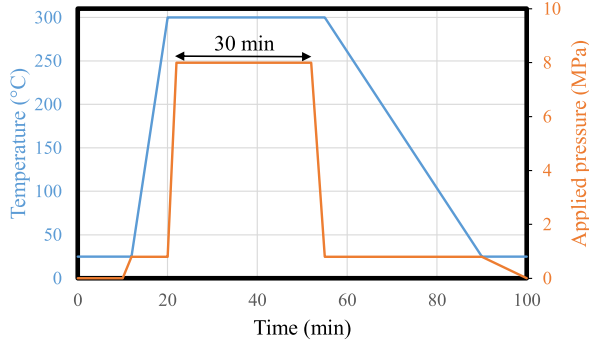


Fig. 5. Evolution of the temperature and the applied pressure for a 30 min thermocompression process.

- 2) An 8 MPa pressure is applied. It has been found to be the highest pressure that does not plastically deform the foam, which would significantly change its thermal-hydraulic properties. Indeed, different pressures were tested and, for 8 MPa, the deformation of the foam was lower than 2%, which was considered negligible for this application.
- 3) In order for the pressure to be homogeneously applied on the whole surface of the deposit, the lower jaw is equipped with a half marble that corrects all thickness inequalities.

In addition, a particular pattern is precisely followed for each thermocompression experiment, so that it can be as repeatable as possible. This pattern is depicted as follows and presented in Fig. 5:

- 1) The upper jaw comes in contact with the copper foam and applies a small pressure of 0.8 MPa.
- 2) The resistance heaters start to heat up the sample up to 300 °C.
- 3) Once the temperature is stabilized, the complete pressure of 8 MPa is applied, for the desired time.
- 4) At the end of that time, the pressure goes back to 0.8 MPa.
- 5) The heaters are stopped and the temperature decreases back to ambient in approximately half an hour.
- 6) The upper jaw goes up to free the sample.

There are three important parameters during the thermocompression process: the applied pressure, the temperature, and the duration of the process. The value of the pressure as already been discussed is set at 8 MPa. It was decided to study a fixed temperature of 300 °C, as it is the maximum temperature that

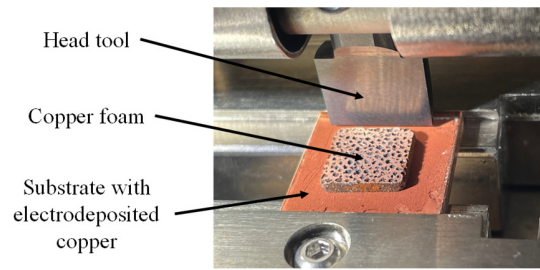


Fig. 6. Photography of the sample used for shear tests.

electronic dies can withstand during attachment without being damaged. The last parameter is the process duration. Three values have been compared: 10, 30, and 60 min.

### III. CHARACTERIZATION METHODS AND SAMPLES

#### A. Optical Characterization

To get a closer look at the contacts obtained after thermocompression of the deposits, an Olympus DSX500 optical microscope is used. Three samples, polished down to a 1  $\mu\text{m}$  diamond solution, are looked at for each thermocompression time. For each sample, ten measures of the deposit thickness are taken at different locations of the contact, which gives 30 measurements for each thermocompression time to limit experimental bias.

#### B. Shear Tests Characterization and SEM

To conduct the shear tests, the two objects in contact should have different surface areas. Nanoporous copper deposits for these tests have thus been made on a  $2 \times 2 \times 0.2 \text{ cm}^3$  copper substrate so that a  $1 \times 1 \times 0.18 \text{ cm}^3$  copper foam could be thermocompressed on it, while not recovering the entire surface of the substrate. Shear testing was carried out using a Royce 600-series bond test equipment with a head tool larger than the foam length, as shown in Fig. 6. The head tool was positioned 20  $\mu\text{m}$  above the substrate surface and the displacement rate was fixed at 1 mm/min. Three samples have been tested for each thermocompression time.

After every shear test, the remaining interfaces have been observed by SEM with a JEOL 5600LV apparatus. This observation will help us to better understand what part of the interface is the weakest. In addition, the optical microscope presented before was used to measure the profile of the copper substrates after shearing.

#### C. Dynamic Thermal Characterization

1) *Sample Preparation:* In order to compare the TCR of soldered and thermocompressed contacts using a dynamic method, more precisely described in [20], the different samples are designed as presented in Fig. 7.

The samples are divided into five main parts as follows:

- 1) A MOSFET in a TO247 package that generates a heat flux using the body diode of the MOSFET. The source to drain voltage  $V_{SD}$  of the body diode is also used as a thermosensitive electrical parameter to estimate the junction temperature of the device. The TO247 package is soldered onto a copper cube presented hereafter.

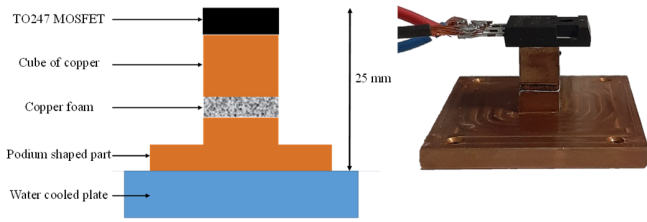


Fig. 7. Schematic and photographic view of the samples designed for thermal measurement.

- 2) A  $1 \times 1 \times 1 \text{ cm}^3$  cube of copper that aims at spreading the heat flux so that it can be considered homogeneous at the cube/foam interface.
- 3) A  $1 \times 1 \times 0.18 \text{ cm}^3$  copper foam sample. The contact between the foam and the upper cube of copper is the one that is studied in this article; it is either soldered or thermocompressed. The lower contact, with the podium-shaped part, is always soldered.
- 4) A podium-shaped copper part that aims at spreading the heat flux to reduce the total thermal resistance of the sample. In this way, the studied TCR influence is larger, thus allowing for more precise results.
- 5) A water-cooled plate that is used to evacuate the heat flux.
- 6) As previously written, the other contacts—TO247/cube of copper and lower contact of the foam—are soldered using a CHIPQUICK TS391AX10 paste. Because the total assembly has a high thermal capacitance, the soldering thermal cycle has been optimized to get the lowest TCR value for those contacts.

The complete sample is placed on the water-cooled plate and maintained on it with four screws at each corner of the podium-shaped copper part. A thin sheet of soft-PGS graphite is placed between the sample and the water-cooled plate to ensure good thermal contact. To avoid losses with ambient air, the sample is covered with a 1.5 cm thick Armaflex insulating foam ( $k = 0.04 \text{ W/m/K}$ ).

Despite all those precautions, there still can be an experimental bias, particularly on the thermal properties of the foam and on the lower foam TCR. To minimize that issue, three samples are realized for each condition: 10, 30, and 60 min thermocompression and three completely soldered samples used for comparison.

2) *Measurement Method:* An Analysis tech. phase 12B thermal analyzer is used to calculate a structure function [21] for each sample. As written in the previous section, the  $V_{SD}$  voltage of the body diode allows evaluation of the junction temperature of the MOSFET. In order to estimate the junction temperature  $T_j$ , the voltage drop  $V_{SD}$  of the body diode of the MOSFET for a current of 10 mA is used as an electrical thermosensitive parameter. For the calibration of  $V_{SD}(T_j)$ , devices are heated in an oven up to 130 °C. As the temperature slowly falls, a sense-current of 10 mA is applied every 5 °C and the resulting  $V_{SD}$  is measured and recorded. The calibration curve of  $V_{SD} = f(T_j)$  shows a linear dependence and the slope of this curve is 2.26 mV/°C.

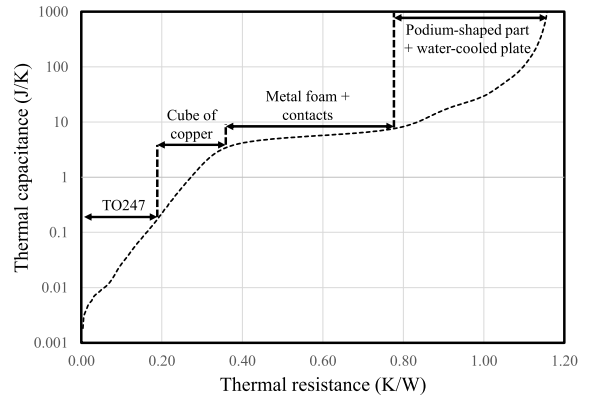


Fig. 8. Example of a structure function that depicts the thermal environment of the MOSFET.

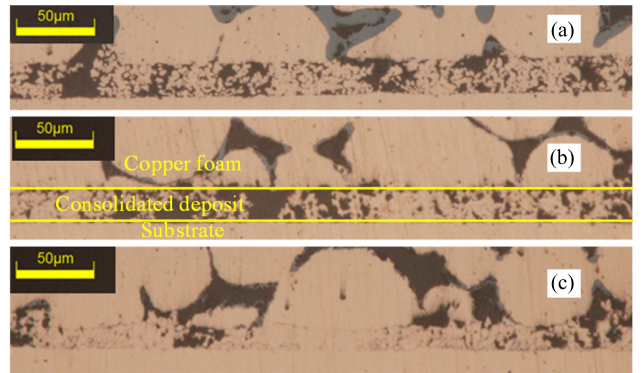


Fig. 9. Microstructure of the contacts after different thermocompression times. (a) 10 min. (b) 30 min. (c) 60 min.

The samples are heated up until they reach a steady state, with a precisely measured junction reach temperature of around 85 °C. Then, the analyzer stops the power and measures the junction temperature evolution (thermal impedance) until it reaches the water temperature (25 °C). Using a Cauer mathematical model [21], the analyzer calculates a structure function for each sample. This function provides information about the thermal environment of the MOSFET as presented in Fig. 8.

The flatter zone in the plot represents the influence of the copper foam and its contacts. Indeed, compared to the rest of the curve, it has a lower thermal capacitance and a higher thermal resistance, which is in accordance with the sample design. Therefore, comparing the length of this plateau for each sample gives information on the quality of the contacts. However, this implies two important assumptions as follows:

- 1) All the foam samples have the same thermal properties. The choice of placing a thin copper foam (1.8 mm) limits the influence of thermal properties disparities on the plateau length.
- 2) All the lower-soldered contacts have the same TCR. This assumption is discussed in Section III-C1.

## IV. RESULTS AND DISCUSSION

### A. Optical Microscopy of the Contacts

Images obtained from optical microscopy are depicted in Fig. 9, along with measurements of the deposit thickness

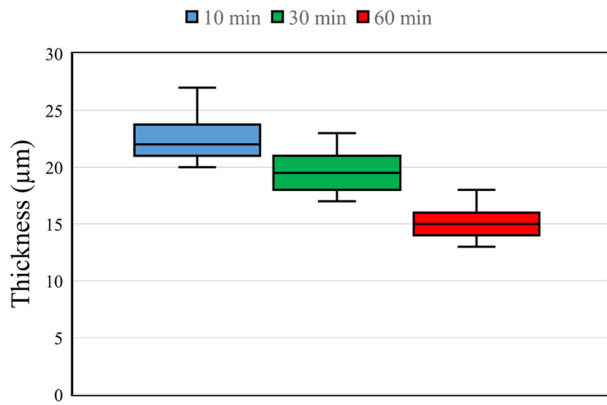


Fig. 10. Evolution of the thermocompressed deposit thickness as a function of the thermocompression time.

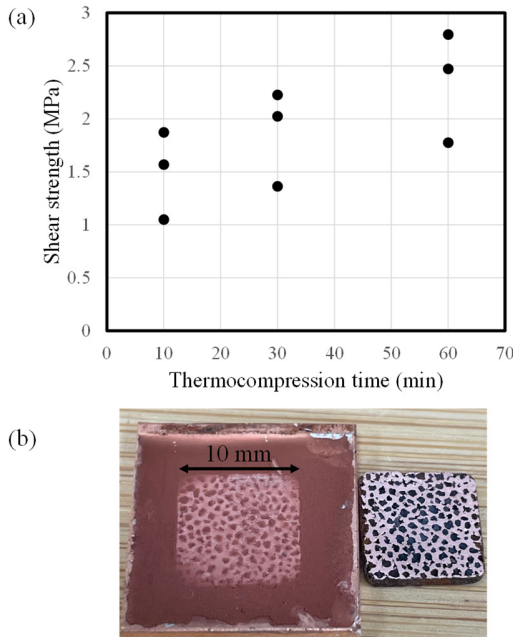


Fig. 11. (a) Shear test results. (b) Pictures of the contact after the test.

after thermocompression in Fig. 10. In the images, a densification of the deposit seems to appear with the process duration. It is confirmed by the measurements where a decrease of several  $\mu\text{m}$  of the deposit thickness with increasing time can be observed. For instance, the mean value shows a 35% decrease, going from 23  $\mu\text{m}$  for 10 min to 15  $\mu\text{m}$  for 60 min thermocompression time. This could signify that the contact is strengthening with thermocompression time.

### B. Shear Tests Results

To confirm the strengthening of the joint, shear tests results are presented in Fig. 11. Even though large disparities can be observed in the results, overall, they show an increase in the shear strength value with increasing thermocompression time. Therefore, it is confirmed that a mechanical improvement comes with a longer thermocompression time.

Another interesting result of shear tests is the shear strength values. They are ranging between 1 and 3 MPa. In comparison, soldered copper foams were also shear tested and held

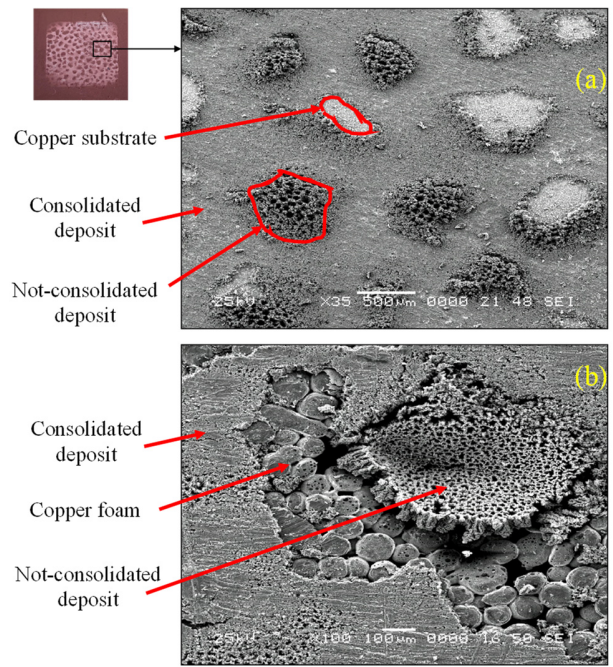


Fig. 12. SEM images. (a) Substrate side after a shear test, most usual case (8 out 9 samples). (b) Foam side after shear test, less usual case. The thermocompression time is 30 min.

up to 6 MPa. At this value, the foams started to plastically deform themselves, therefore, it was not relevant to go further in the tests, but the contacts still held. This indicates that thermocompressed samples are not as strong mechanically as soldered ones.

Yu et al. [22] have reported shear strength between 10 and 15 MPa on electronic dies for the thermocompression of copper nanowires. Considering that they used a higher applied pressure (15 MPa at least) and that they attached massive materials, the shear values found here with a 60% porosity material seem acceptable.

A SEM image of a substrate after the shear test is presented in Fig. 12(a). Three different zones can be observed as follows:

- 1) The lighter and the darker parts [circled in red in Fig. 12(a)] indicate zones of the assembly where the deposit was not consolidated during thermocompression because there was a foam pore just above it. During shearing, these fragments of the deposit either remained on the substrate [“not-consolidated deposit” (CD) in Fig. 12(a)] or were torn off by the foam [Fig. 12(b)], making the “copper substrate” appear.
- 2) The greyer part, labeled “CD” indicates a spot where the deposit bonded to either the substrate or the foam during thermocompression and then still held on it after shearing.

In order to better understand where the contact breaks during the shear tests—in the deposit, at the substrate/deposit interface, or at the copper foam/deposit interface—the copper foams were also observed by SEM, after shearing. It was found that the CD was either located on the substrate side [Fig. 12(a)] or on the foam side [Fig. 12(b)], but never split on both sides. This indicates that the core of the deposit is stronger than the

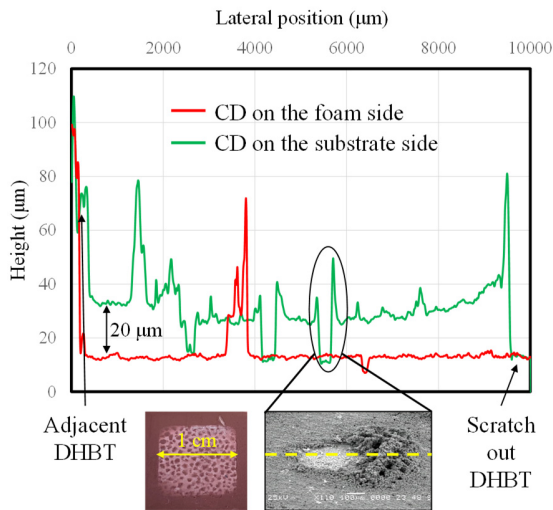


Fig. 13. Typical measurements on copper substrates after shearing with a thermocompression time of 30 min.

two interfaces. Looking more closely at the images, for 8 out of 9 samples, a large majority of the CD was still on the substrate side, as can be seen in Fig. 12(a). This indicates that the contacts mainly broke at the copper foam/deposit interface, which is thus the weakest part of the contact, among the three possibilities mentioned above. This result is understandable as it demonstrates that the interface created by thermocompression between two porous materials (foam and deposit) is weaker than the one made by electrodeposition.

To confirm the conclusion above, Fig. 13 presents the profile of the surface of the substrate after shearing for two samples with a thermocompression time of 30 min. The results were very close with the other samples.

The measurement is made over a length a bit larger than the foam width, as shown by the yellow line in the insert at the bottom left. On the left part of the graph (0–200  $\mu\text{m}$ ), the not-CD adjacent to the foam can be spotted. Conversely, on the right part, the deposit has been scratched out, so that the measured height corresponds to the upper surface of the substrate. In green, a typical measurement for a sample where the major part of the deposit remained on the substrate side shows the three different zones identified earlier in Fig. 12(a). It confirms the assumption that the contact broke at the foam/joint interface (around 20  $\mu\text{m}$  above the substrate, as already measured in Fig. 10). The SEM image insert at the bottom right of Fig. 13 matches a fraction of the profile with a zone where the “not-CD” has been partially scratched out during shearing. In red, a measurement made on the sample where most of the deposit was located on the foam side also confirms the nearly complete absence of deposit on the substrate.

### C. Thermal Results

1) *Variability of the Results for Completely Soldered Samples:* Before analyzing the thermal results obtained with the thermocompressed sample, it seems important to show that the dynamic method is reliable for soldered samples that are easier to control. To that end, Fig. 14 shows the structure

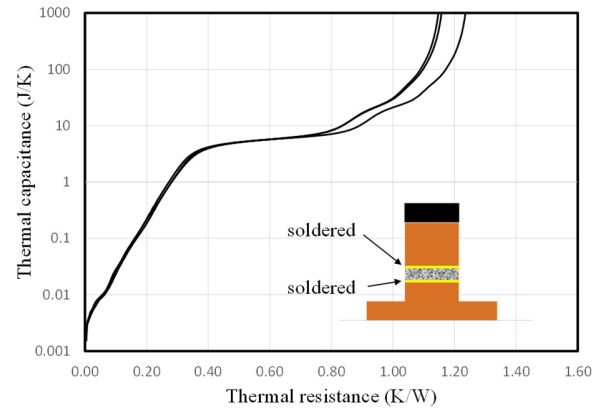


Fig. 14. Variability of the results for the structure functions obtained for three soldered samples.

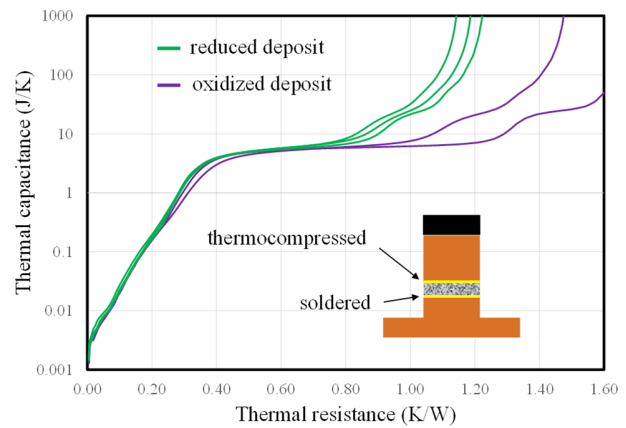


Fig. 15. Structure functions with an oxidized deposit for 30 min thermocompression time.

functions obtained for three soldered samples manufactured in the same conditions. It can be seen that there is a small difference between the three structure functions. This disparity can be explained by the fact that the two assumptions made earlier are not entirely true: there is a disparity in thermal properties between the different foam samples and in the TCR of soldered contacts. Now, as the idea of this article is to give a first comparison of the two attaching techniques, this disparity is acceptable.

2) *Influence of the Deposit Reduction:* As previously mentioned, the quality of the deposit is of great importance for the thermocompression process. Fig. 15 shows structure functions obtained for a 30 min thermocompression time for two types of deposit: previously reduced and oxidized (untreated). As can be seen, untreated samples not only present a significantly longer plateau, i.e., a higher TCR value, but also a larger disparity of the results, compared to the reduced samples. This means that the reduction process of the deposits has indeed several benefits: it shows better TCR values and harmonizes the quality of the deposit.

Additionally, it can be noted that many more untreated deposit samples have been thermocompressed, but most of them did not hold together mechanically, making them untestable for thermal characterization. This emphasizes the large disparity of the results from untreated deposit samples.

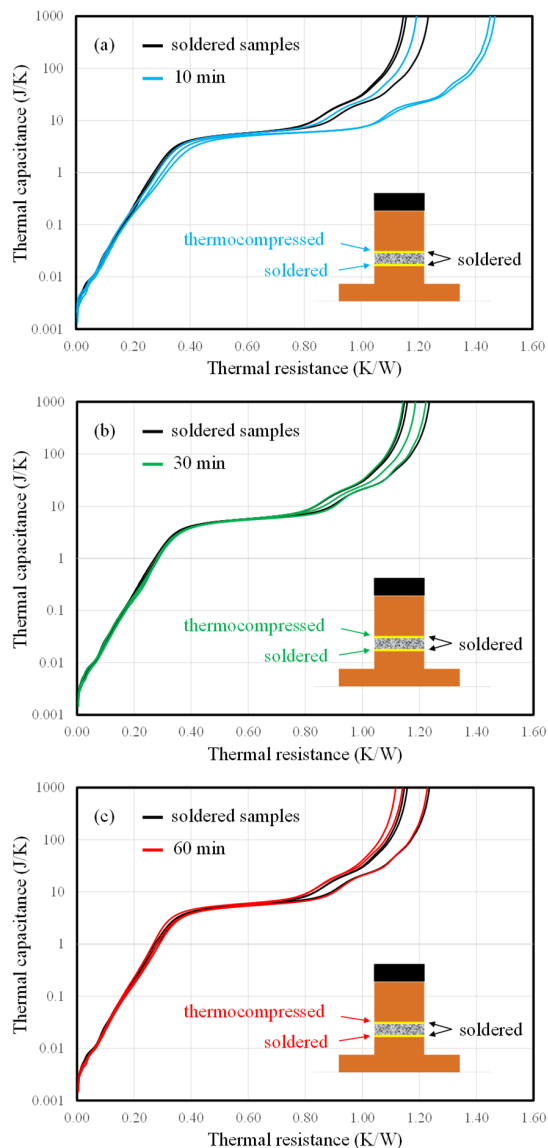


Fig. 16. Comparison between soldered and thermocompressed samples, with different thermocompression times of (a) 10 min, (b) 30 min, and (c) 60 min.

3) *Influence of the Thermocompression Time/Comparison With Completely Soldered Samples:* In Fig. 16, the structure functions obtained for thermocompressed samples are compared to the abovementioned soldered ones, for different thermocompression times. Overall, it can be noted that most of the thermocompressed samples show a plateau length close to the ones of soldered samples. It means that the TCR values also are close too.

Looking more in detail at the results, it appears that for two out of three of the 10 min samples, the plateau length is much longer than the one of completely soldered samples, suggesting that the TCR values are higher. The third sample shows better results, it can also be a sign that after 10 min, the thermocompression process is not completely reliable, contrary to 30 and 60 min samples, for which the three structure functions are much closer to one another.

For 30 and 60 min samples [Fig. 16(b) and (c)], the plateau length is very similar to soldered samples, and no significant improvement can be noted between those two times. On the

one hand, it seems contradictory with the results provided by shear tests where the contact keeps on strengthening after 30 min. On the other hand, this test only characterizes the thermal quality of the contact, which can be different from its mechanical strength. It could suggest that the contact cannot be thermally improved anymore after 30 min.

## V. CONCLUSION AND PERSPECTIVES

In this article, a new attachment method for metal foam heat sinks was studied. Designed to replace usual soldering, this attachment was proposed to be carried out by thermocompression of a porous copper deposit to avoid issues due to capillarity at the interface. Thermocompressed contacts as thermally good as soldered ones can be obtained but they are not as strong mechanically. It has been shown that the contacts can be improved using a longer thermocompression time, but there is still the need for improvement, particularly regarding its mechanical behavior. Thus, the studied attachment process is not yet comparable with soldered joints, but it has shown promising results.

Also, the cost of this solution (time, energy...) remains largely higher than soldering. Even if this method has several advantages, it is mandatory to look for solutions to decrease its cost. For instance, the electrodeposition could be optimized: the copper deposit features can be tailored using different process parameters such as pulsed current and chemical additives. Changing its features could have a high influence on a thermocompression process by modifying the size of the copper ligaments, allowing for changes in the ductility of the deposit and promoting greater atomic diffusion. To reduce the cost, it could be also interesting to assemble different elements of the system at the same time. For instance, it could be possible to assemble power semiconductor dies with the same method.

Concerning the improvement of the shear strength, the influence of other thermocompression parameters could also be studied, particularly the process temperature. Here, it was fixed at 300 °C considering that it is the highest temperature that electronic components can withstand during attachment. However, in the case where the copper foam is attached to a ceramic substrate/baseplate before the components, the process temperature could then be higher, probably allowing for better contact. Also, with a view to using this technique to replace solder interfaces in power modules, additional tests such as thermal aging or thermal cycling should be run to ensure that it is more reliable than soldering over time. A major issue that should be studied in the future is the oxidation of the copper, which could have an impact on the shear strength of the joint between the foam and the bulk copper.

Here, the contact studied is the one between a substrate and a heat sink but the DHBT deposit technique can also be used to replace any interface in a power module. For instance, the thermocompression of components onto substrates is currently under study.

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