Liquid Metal Jetting for High-Performance Computing Applications

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Abstract
Gallium-based liquid metals (LMs) are materials that possess some unique properties. Just like any other metals, they have high thermal conductivity and low interfacial resistance, but they are in a liquid phase at room temperature. In contrast to mercury alloys, gallium alloys are non-toxic. They don't evaporate, and they can't be inhaled. The viscosity of those alloys is very similar to water, but they are six times as dense as water. All those properties make gallium-based liquid metals very good candidates for thermal interface material (TIM) in electronics applications. On the other hand, the reaction and incompatibility of those alloys with some metals is one of the challenges for this type of TIM. The other challenge is that those materials are not just thermally, but also electrically conductive, and that is not a desirable property for TIM. A suitable barrier that will prevent any leakage of LMs and the best way to apply the appropriate volume of LM in high-volume production (HVP) would be one of the most important things for any application.

A key challenge is applying the liquid metal consistently through a traditional dispensing method due to its property and behavior which involves high surface tension. Through advanced dispensing techniques like jetting technology, liquid metal can be applied reliably on a flat, uneven surface or in arrays of minuscule confined spaces or cavities. This paper highlights the dispense quality, weight repeatability from one substrate to another, and valve hardware stability. This paper also addresses the challenges faced during dispensing of liquid metal in high volume manufacturing, and how to achieve desired bondline thickness with jet dispensing for higher throughput and process reliability.

Key words
Bondline Thickness (BLT), Dispensing, Jetting, Liquid Metal (LM), Thermal Interface Material (TIM)

I. Introduction

Liquid metals are low-melting point alloys that are liquid at room temperature. This paper will discuss gallium-based liquid metals, the mechanical properties of those alloys, and their usage as a thermal interface material (TIM) in semiconductor applications. When alloyed with tin and/or indium, gallium creates low-toxic alloys that are liquid at room temperature. These alloys have a water-like viscosity but are six-times denser than water (Fig. 1). Gallium-based alloys also have low-vapor pressure, don't evaporate, and cannot be inhaled. Similar to other metals and alloys, gallium-based alloys will have high thermal conductivity, which is a highly desirable property for any TIM.

Fig. 1. Gallium-based liquid metal [1]

Interfacial resistance and thickness also play an important role in the TIM's overall performance. Metals tend to have high-bulk thermal conductivity. They also have very good heat-spreading as well as through conduction. Due to their composition, metals will not dry out over time or degrade in their performance due to temperature changes; however, most metal TIMs are very stiff. This makes it difficult for metal TIMs to make a close connection between the heat source and the heat sink or heat spreader. Overcoming interfacial resistance is the biggest challenge for any metal TIM (Fig. 2).

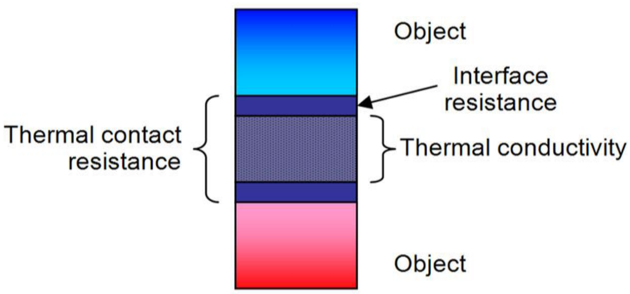

Fig. 2. Illustration showing areas of interfacial resistance [2]

Since gallium-based liquid metals are liquid at room temperature, they can make a close connection between the surfaces they are connecting. The thermal resistance of any TIM will be defined as:

$$TI_T = BLT/K + R_C$$

Where:
TI_T – Total thermal impedance
BLT – Bondline thickness of the TIM
K – Bulk thermal conductivity of the TIM
R_C – Thermal contact resistance at the interface (Fig. 3)

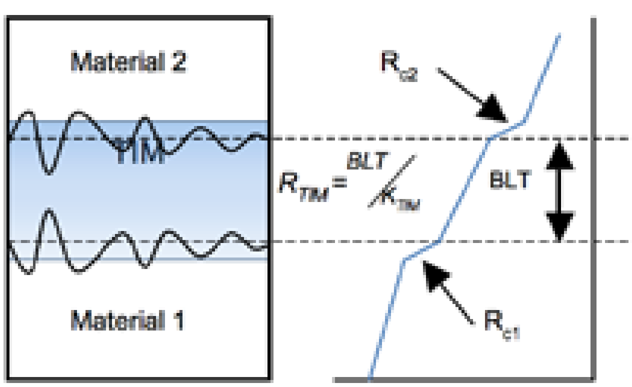

Fig. 3. Total thermal impedance [3]

With reasonably high thermal resistance and very low interfacial resistance, bondline thickness does not play a big role in liquid metal. Even when they are applied in a thicker layer, they can achieve very low thermal resistance (Fig. 4).

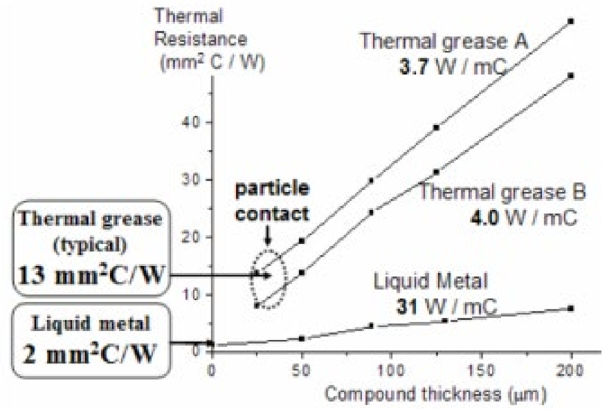

Fig. 4. How thermal resistance will change with compound thickness [4]

Liquid metals are not only thermally conductive, but also electrically conductive; leaking liquid metals can cause an electrical shortage of electric devices. All liquid metal alloys contain gallium, which can damage some metals, especially aluminum. Another challenge for using these materials is oxidation, as seen in Fig. 5. Passivating oxide layers in liquid alloys causes constant disruption, allowing oxidation of the newly exposed surfaces. Oxidation can degrade thermal contact and reduce the lifespan of the TIM. In order to use liquid metal as a TIM, the liquid metal should be contained to prevent any potential leaking and nearby components should be insulated. Fig. 6 illustrates one of the solutions for using a liquid metal TIM.

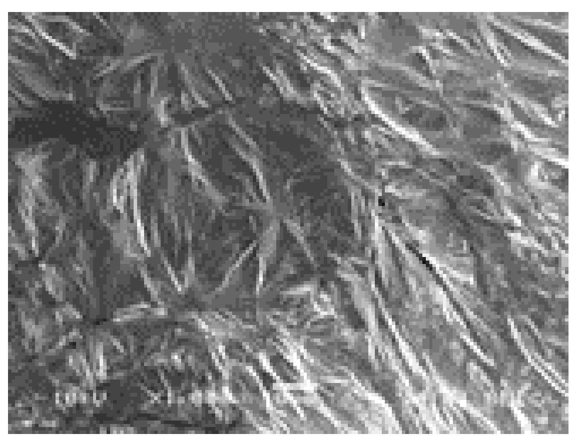

Fig. 5. SEM imaging of the oxide skin material formed readily by eutectic gallium indium in the presence of oxygen; the oxide skin was drawn off the surface of the liquid metal body before imaging [1]

Materials used for barriers should be electrically non-conductive. Different types of adhesives and polymers are often used for those barriers. In this case, one UV-cured polymer was used.

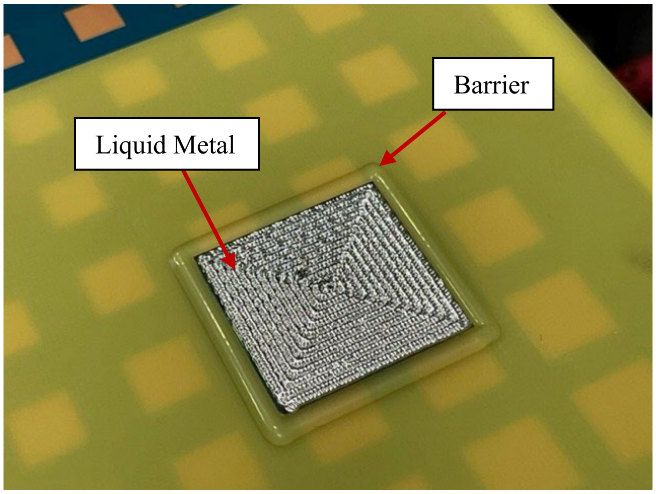

Fig. 6. The barrier for liquid metals

Another interesting property of gallium-based liquid metals is that their thermal conductivity increases with an increase of temperature, meaning that the thermal performance of liquid metal TIMs will improve with increasing temperature (Fig. 7) [5].

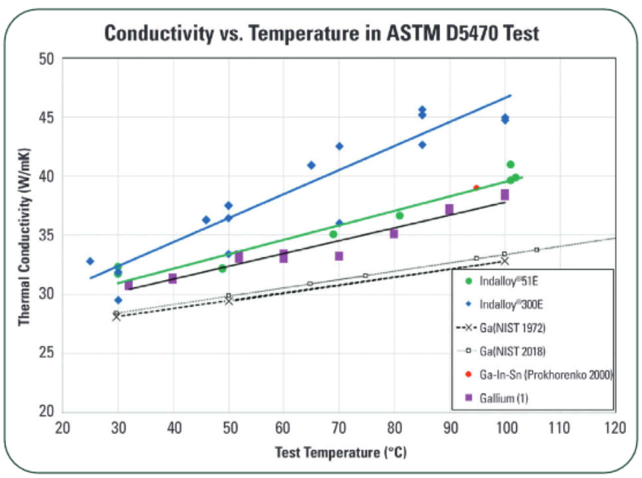

Fig. 7. Thermal conductivity vs. temperature for gallium-based liquid metals

There are several liquid metal alloys that are available on the market now. Table I shows the current most popular liquid metal alloys.

As shown in Table I, Indalloy®300E, eutectic alloy of gallium and indium, has the highest thermal conductivity. On the other hand, Indalloy®306 is very often used in gaming consoles and gaming laptops. This paper will discuss how Indalloy®306 can be applied in high-volume production.

Table I. The current three most popular liquid metal alloys

Indalloy® Number	51E	300E	306 (AKA)
Composition	66.5Ga 20.5In 13Sn	78.6Ga 21.4In	68.5Ga 21.5In 10Sn
When to Choose	Lower melting point eutectic alloy best used in dispensing and printing applications	Highest thermal conductivity and best for jetting applications	Widely used in high-end gaming platforms
Liquidus (°C)	11	15.7	19
Solidus (°C)	11	15.7	10
Thermal Conductivity (@ 85°C W/mK)	37	44	35
Electrical Resistivity	28.9	27	29
Density (g/cc)	6.32	6.16	6.44
RoHS Compliant	Yes	Yes	Yes

II. Dispensing

Dispensing techniques have evolved from needle contact dispensing methods to non-contact (jetting) dispensing technology. Early dispensing approaches were used for rework applications on components with deficient fills of adhesives onto the substrates or die surfaces. More recently, researchers have proposed the use of dispensing for independent operation of fluids application, such as epoxies, onto the PCB for securing components. Needle contact applications like time-pressure, and rotary auger screw dispensing fall under the same application to dispense the fluid through the needle contact to the printed circuit board.

Jetting, as shown in Figure 8, is termed as a technology where material is dispensed as individual droplets onto the PCB through a jet dispenser without any needle contact with the PCB. Jetting technology uses the "ball and seat" mechanism to supply the fluid to the ball seat area with the application of pressure. For this method, as the ball moves in the downward direction to strike the seat, it dispenses the fluid in the form of a droplet onto the substrate [6].

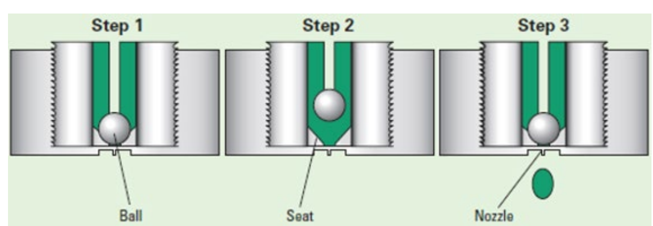

Fig. 8. Jetting technology [11]

The time-pressure dispensing mechanism as shown in Figure 9 (a) drives the fluid out of the needle through application of pressure onto the syringe. The fluid will stop dispensing from the needle as the applied pressure is switched off from the actuator. In rotary auger-screw dispensing, shown in Figure 9 (b), the fluid is moved along the cartridge by the rotary motion of the helical auger screw controlled by the driven motor through application of pressure onto the syringe and finally driving it out of the needle. It is generally used for high viscosity applications due to steady movement of the fluid through the cartridge and developed high pressure at the bottom of the cartridge due to a shearing force from the rotary motion of the auger. Jetting works mostly on the principle of positive-piston displacement fluid dispensing (Figure 9 (c)) which involves a mechanism of pushing the fluid along the cylinder chamber through the reciprocating motion of the piston which forces the material out of the needle. Herein, the piston and cylinder are the two essential components in this driving mechanism.

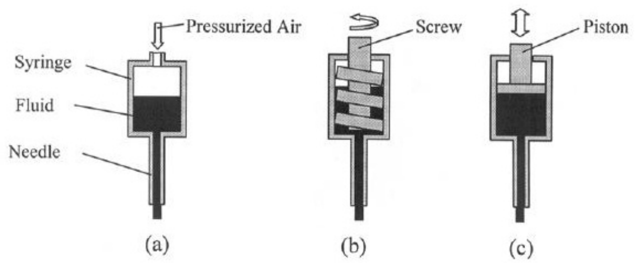

Fig. 9. Schematic Diagrams of the Fluid Dispensing Systems: (a) time-pressure, (b) rotary auger-screw, (c) positive-displacement [9].

Although all three of them dispense fluids, each uses a slightly different approach and so is better suited for some applications than others. The time-pressure mechanism is used for a higher variety of situations due to its low maintenance, cost, and ease of operation. However, it is difficult to control due to the amount of pressure variability in the syringe, which can affect the dispensing quality and consistency. Also, the fluid looks to drool from the needle tip due to build up residual back pressure from the fluid. Both time pressure and rotary auger-screw have no inbuilt mechanism to seal the fluid chamber at the needle end in comparison to jetting where ball sits onto the seat to seal the fluid chamber.

The dispensing of fluid volumes in short bursts of applied syringe pressure makes the application process unpredictable as the flow rate of the fluid is time dependent with time - pressure. Rotary auger-screw tends to agitate some of the materials inside the helical groove which leads to clogging issues. Time-pressure dispensing has been the main area of attraction for the past twenty years, but to mitigate the drawbacks has to evolve from needle contact dispensing to jetting technology. Jetting involves tapping of the piston with a ball end onto the conical seat opening to eject a droplet at a constant volume in a more repeatable and precise manner resulting in good dot quality at a particular syringe pressure. Liquid metal has been feasible in mainstream applications nowadays which involves graphics processing units (GPU), central processing units (CPU) either on laptops or gaming consoles. A more thermally efficient TIM which is called liquid metal conducts the heat out of the processor to the heatsink on a level of 17 times faster than the traditional thermal interface materials [12]. Liquid metal is applied manually with minimal level of automation these days to maintain the required bondline thickness with challenges. Bondline thickness plays a very crucial factor in having the components packed tight enough, so the final product could be as thin and light as possible. A tiny non-conductive barrier is required to contain the electrically conductive liquid metal to avoid any short circuits.

III. Experimental Methodology and Analysis

A. Objective

The main objective of this research is to conduct a detailed study to repeatedly dispense a liquid metal to understand the dispense characteristics like weight repeatability and dispense performance. The study involves the use of a high-speed dispensing system with a piezoelectric jetting pump installed which can dispense material in a repeatable manner without affecting the dot quality. Indy alloy number 306 packed in cartridge sizes of 10cc was used for this study.

B. Experimental Set up

The sample fire-resistant (FR4) green substrate as shown in Figure 10 was used to simulate a 20 x 20 millimeters rectangular pattern very similar to the one used in high speed computing applications involving GPUs and CPUs. A weigh measuring cup placed onto the high precision weight measuring scale was used for pre-weighing the sample to ensure dispensing volume is tightly controlled before dispensing the rectangular pattern onto the FR4 substrate.

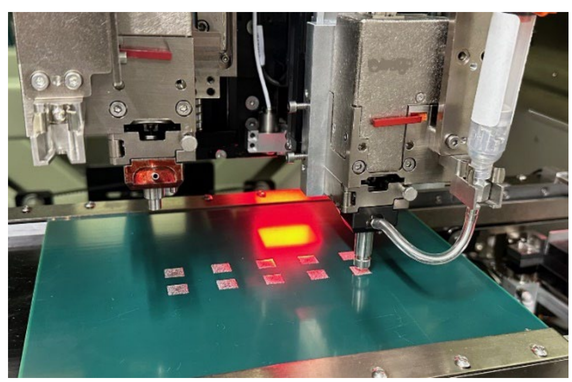

Fig. 10. Experimental set up with piezoelectric jetting pump dispensing liquid metal onto the FR4 substrate.

The jetting pump is set up by dispensing a 20x20 millimeters rectangular pattern with a 100 micron precision needle tip. The pump makes an adjustment based on the target total weight with defined process tolerance of ±5 percent to adjust the number of extruded dots to dispense the correct amount of material into the weight-measuring cup followed by deposition onto the FR4 substrate. The standard process program involves dispensing target total weight of 100 milligrams into the weight measuring cup, cleaning the needle, sensing the height of the substrate, and then dispensing the rectangular pattern onto the FR4 substrate. Target total weight for liquid metal (LM) weigh repeatability on the weight precision scale on the machine was defined as 100 milligrams with process tolerance of ±5 percent while the pattern weight on FR4 substrate was targeted to 200 milligrams total weight.

C. Weight Repeatability Analysis

Control charts are used to determine the variation in the process for analysis purposes. Figure 11 shows Individual and Moving Range control chart created on Minitab statistical software for liquid metal weight repeatability into the weight scale cup. Sample size was chosen to be 50 for this study. Centerline on the I chart is the average of individual weight samples collected. Lower and Upper Control limits are defined as 3 standard deviations on either side of the centerline. Individual chart for liquid metal weight repeatability shows no points fall beyond the 3 standard deviation control limit which reveals a stable process [11]. Two test points fall outside the control limits on the moving range (MR) chart. This indicates special cause variation which may be due to the compressible nature of the material which leads to slightly big deviation from one sample to the other.

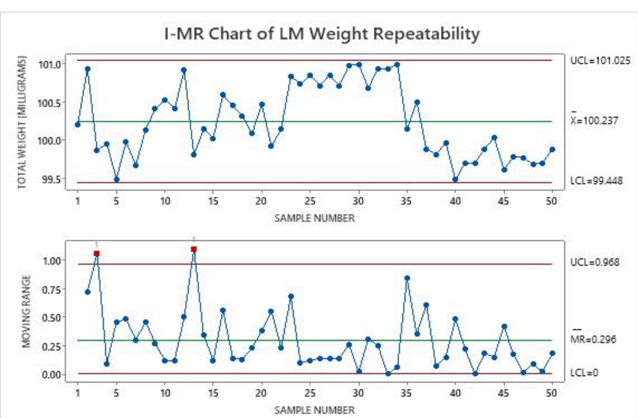

Fig. 11. I-MR Chart of Liquid Metal (LM) weight repeatability with a piezoelectric jetting pump.

Test Results for MR Chart of LM Weight Repeatability
TEST 1. One point more than 3.00 standard deviations from center line.
Test Failed at points: 3, 13

D. Process Capability Analysis

For the interpretation of process capability statistics, the data should approximately follow a normal distribution. *Cp* indices recognize the fact that the samples represent rational subgroups, which indicate how the process would perform if the shift and drift between subgroups could be eliminated. Therefore, it calculates process spread using within-subgroup variation. Process capability index *Cpk* measures how close the process is to the target and how consistent the process is around its average performance. An operator may be performing with minimum variation, but he/she can be away from his/her target towards one of the specification limits, which indicates lower *Cpk*, whereas *Cp* will be high. For both the shifts, high value of *Cp* and low value of *Cpk* indicate that the process has a centering problem [8, 10]. A generally accepted minimum value for the indices is 1.33 according to industry guidelines to determine whether the process is capable [7]. Figure 12 shows that both tails for target total weight of 100 milligrams fall inside the specification limits for tolerance level of ±5 percent at ±6 sigma capability.

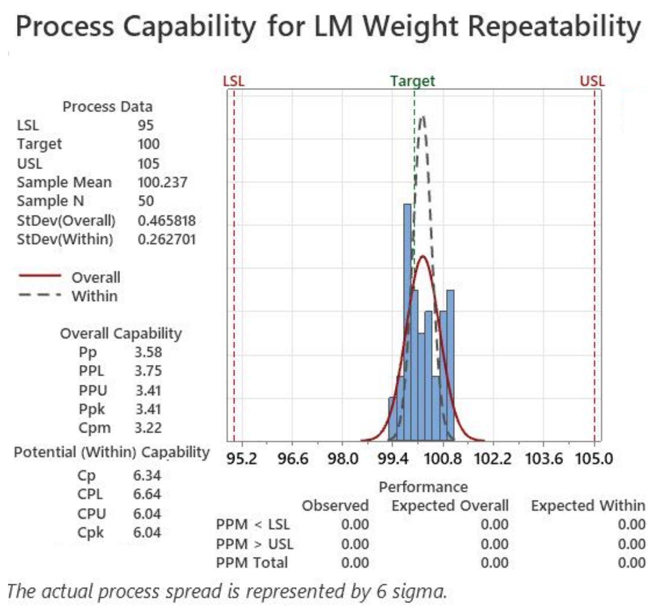

Fig. 12. Process Capability Study of Liquid metal weight repeatability

E. Bondline Thickness Analysis (BLT)

The thickness of a bond line is crucial, especially for liquid-dispensed materials, as it varies based on the stand-off in each application. While minimum bond line thickness is emphasized in part specifications, it is frequently neglected and not properly managed during the process and manufacturing engineering stages. Inadequate bond line thickness poses risks such as low strength, subpar electrical properties, and increased thermal resistance. Bondline thickness of 225 ± 25 micron was required for a gaming consumer application to maintain a dispense weight of 200 milligrams across the 20x20 millimeters rectangular chip. A solder paste inspection (SPI) system is used to measure the bondline thickness across a sample size of 50.

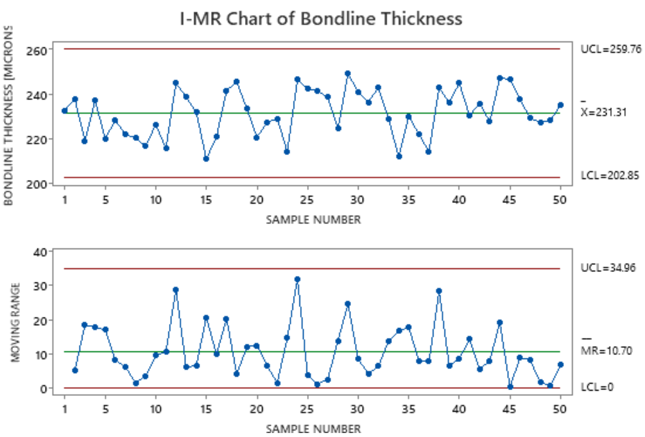

Fig. 13. I-MR Chart of Bondline thickness for Liquid metal

Figure 13 shows both individual and moving range charts for bondline thickness; no points fall beyond the 3 standard deviation control limit which reveals a stable process. Figure 14 shows the profile measurements of bondline thickness across 2 pads placed next to each other. Average bondline thickness across those pads was around 230 microns which is very close to the desired target of 225 microns.

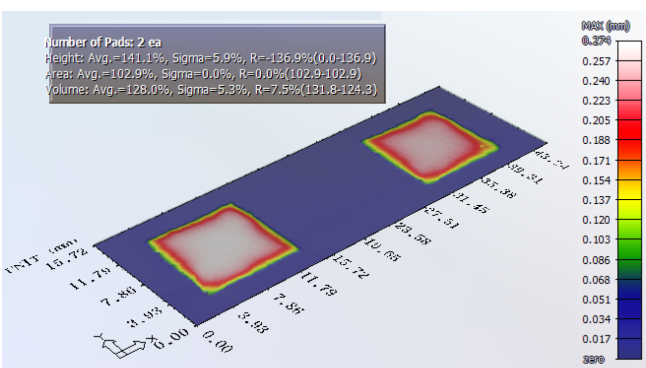

Fig. 14. Liquid metal bondline thickness

IV. Conclusion

With their unique properties, liquid metals are one of the best options for TIMs. Just like any other metal, they have high thermal conductivity, but since they are liquid at room temperature, they can adopt any imperfections of the surfaces they are connecting, and they don't need to be compressed with high pressure to achieve very low thermal resistance. Even though the BLT of LM will not affect the overall thermal performance of LM thermal interface material, it's very important to keep volumes within certain ranges, and that is why having a uniform BLT is crucial. With this study liquid metals have also been proven to have achieved desired bondline thickness with good control on dispense volume for high volume assembly production.

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