Metal Microchannel Lamination Using Surface Mount Adhesives for Low-Temperature Heat Exchangers

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Abstract

This paper reports the feasibility of using surface mount adhesives to produce low temperature microchannel arrays in a wide variety of metals. Sheet metal embossing and chemical etching processes have been used to produce sealing bosses that eliminate channel laminae, resulting in approximately 50% material savings over traditional methods. An assembly process using adhesive dispense and cure is outlined to produce leak-free devices. Optimal fill ratios were determined to be between 1.1 and 1.25. Bond strength investigation reveals robustness to surface conditions and a bond strength of 5.5-8.5 MPa using a 3X safety factor. Dimensional characterization reveals a two sigma (95%) post-bonded channel height tolerance under 10% after bonding. Patterning tolerance and surface roughness of the laminae faying surfaces were found to have a significant influence on the final post-bonded channel height. Leakage and burst pressure testing on several samples has established confidence that adhesive bonding can produce leak-free joints. Operating pressures up to 413 kPa have been satisfied equating to tensile pressure on bond joints of 1.9 MPa. Higher operating pressures can be accommodated by increasing the bond area of devices.

Keywords: Adhesive bonding, microchannel array, microlamination, low temperature heat exchanger.

1. Introduction

Microchannel process technology (MPT) is the use of microchannel arrays for the bulk processing of mass and energy. Although MPT devices can be on the order of meters in dimension, MPT devices include critical microchannel dimensions ranging from 100 μm to several mm [1]. One of the major advantages of MPT is the high surface area to volume ratios compared to conventional fluidic technology. These ratios allow accelerated rates of heat and mass transfer within microchannels due to shorter diffusional distances. Consequently, microchannels provide the ability to reduce the size and weight of energy and chemical systems [2]. Applications of MPT include portable heat exchange, distributed climate control, solvent separation, fuel processing, and at-home hemodialysis among others [1]; [3].

One growing area for MPT application is low-temperature thermal management, such as the cooling of consumer electronics. The improved performance and shrinking dimensions of integrated circuits have resulted in the need to dissipate ever-increasing amounts of power. Today, microprocessors require heat dissipation of 50-75W for standard applications, and well in excess of 100W for enthusiast and gamer applications. While the thermal dissipation requirements of microprocessors have steadily increased, the maximum allowable temperature of these devices has remained relatively steady around 65-85°C, limited by many factors including ergonomics and safety. Due to these limits, several researchers have shown that the theoretical maximum for air cooling of electronic components is in the range of 100 -130 W [4]; [5].

Traditional strategies for increasing heat dissipation have centered on reducing the thermal resistance of the heat sink assembly by increasing the convective surface area through finned surfaces and the use of fans to increase the convective heat transfer coefficient. However, increases in surface area are usually accompanied by increases in mass and cost. Alternatively, microchannel arrays provide a means of increasing surface area per unit mass, while increasing convective heat transfer coefficients [6].

To further reduce thermal resistance, the ideal microchannel heat sink would be made of a high thermal conductivity material. Copper has the highest thermal conductivity among engineering materials, and has been extensively used for both passive and active heat sinks including microchannel heat exchangers for the cooling of laser diode arrays [7]; [8]. Aluminum alloys offer several advantages over copper alloys as

a heat exchanger material. While the thermal conductivity of aluminum is not as good as copper (though comparable), aluminum alloys are light-weight (almost 3x lighter than copper) and are lower in material cost. Aluminum also forms a very stable and tenacious oxide that is resistant to surface corrosion. For these reasons, 300X series aluminum alloys are widely used in the traditional heat exchanger industry. Aluminum microchannel heat exchangers have not been reported for application in the electronics industry. This is largely due to challenges associated with bonding of aluminum microchannel arrays.

Beyond the electronics industry, other low temperature heat exchanger applications require low thermal conductivity materials such as stainless steel. In some heat exchanger applications, such as regenerators within heat engines, low thermal conductivity metals such as stainless steel are actually desirable [9]. For a given microchannel heat exchanger, it has been shown that an optimal thermal conductivity exists that minimizes axial conductive transfer down microchannel fins without significantly penalizing conductive heat transfer across the fin in the thickness direction [10]. Maranzana et al. [10] also showed that in low-temperature (below 100°C) countercurrent microchannel heat exchanger applications, a stainless steel heat exchanger can be as much as 20% more efficient than a copper one.

In the context of low temperature heat exchange, it is desirable to find fabrication methods that can be applied to many materials. Fabrication methods used for microchannel arrays are based on microchannel lamination [1], or microlamination architectures involving the patterning, registration and bonding of thin foils of metal called laminae. Lamina patterning generally includes either surface machining, through cutting or forming processes. Once patterned, the laminae are registered relative to each other and bonded together in a stack to make a monolithic device. Typical patterning and bonding steps for microlaminated components are chemical etching and diffusion bonding. The objective of this paper is to introduce a microlamination architecture capable of meeting the requirements for low temperature heat exchanger applications across a wide variety of materials.

1.1. Current Fabrication Techniques

Patterning processes used for microchannel laminae include laser cutting, chemical etching, machining or other processes to produce the desired features. Laser cutting is a through-cutting process, while chemical etching is capable of both through-cutting and blind-cutting. Through-cutting processes are only capable of producing through-cut slots and holes. In order to form a channel using a through-cut process, three laminae are needed; one fin lamina each on top and bottom and one in the middle called a spacer lamina. Figure 1 shows a schematic of a microchannel cross-section formed by soldering through-cut Cu laminae with a Sn-Pb solder as proposed by Sharma et al. [3]. In this architecture, the spacer lamina establishes the height of the microchannels (the critical feature). Blind-cutting processes such as chemical etching are capable of eliminating spacer laminae by etching the pattern directly into the adjacent fin lamina. The elimination of spacer laminae results in approximately 50% fewer laminae, which can significantly improve economics.

A variety of bonding approaches have been used to fabricate MPT devices including diffusion bonding [11]; [12], ultrasonic welding [12] and diffusion brazing [13]. Diffusion bonding and diffusion brazing are energy-intensive processes with long cycle times. Further, both processes require expensive capital equipment for providing an inert atmosphere or vacuum to avoid oxidation during bonding. Although ultrasonic welding has been used to join stainless steel laminae, multi-layer aluminum microchannel arrays have not been reported using this method. Ultrasonic techniques can be difficult to adapt to alternative material sets.

In transient liquid-phase diffusion brazing, a thin layer of filler material, called an interlayer, is applied to the faying surfaces and a transient liquid phase is produced at the bonding temperature. The liquid phase accelerates transport into the material enabling lower pressures, temperatures and times compared with diffusion bonding. Diffusion brazing has been reported to be effective in overcoming the bonding of materials with stable oxide layer such as aluminum alloys. At bonding temperature, the liquid phase permeates the native oxide resulting in deeper diffusion within the parent aluminum [14]. This is typically achieved with alloying which complicates the bond metallurgy leading to reliability concerns. Additional heat treatment can be needed to drive-in filler metals leading to even longer cycle times. Further, each brazing interlayer is highly unique to the parent microstructure. Interlayer materials can be applied as pastes or foils. For the production of microchannel arrays, foils must be patterned and have

finite thicknesses which do not permit full drive-in of brazing materials. Due to these complexities, fluxless methods are considered expensive and not yet suited to MPT production.

As mentioned above, the use of Sn-Pb solders to produce copper microchannel arrays has been demonstrated by Sharma et al. [3]. In addition to the fact that Sn-Pb creeps at room temperature, this process necessitates a fluxing operation prior to reflow. Thick, native aluminum oxide films make soldering or brazing of aluminum difficult [15]. The use of aggressive fluxes can lead to reliability concerns requiring the removal of flux residues after soldering which can be difficult in microchannel geometries.

1.2. Surface Mount Adhesives

Past efforts to employ adhesives for microchannel lamination have relied upon the patterning and registering of adhesive films prior to thermal curing [16]. In contrast, viscous surface mount adhesives have not been applied to microlamination architectures but have been successfully used in electronics assembly for many years. Surface mount adhesives are used to bond a wide variety of materials such as epoxy FR-4, plastic bodies of components, metal leads, etc. These adhesives have some very desirable features such as very low volatile-organic-compounds (VOC's) resulting in low shrinkage. Another critical property is the slump resistance of these materials, ensuring that the adhesive does not sag or run during cure. The curing process is also greatly simplified as it does not require high temperatures or pressures compared to diffusion bonding. After bonding, most of these adhesives are limited to operating temperatures below 150°C. Such a method could be ideally suited to low-temperature thermal management applications such as electronics cooling.

The use of adhesive bonding eliminates some of the drawbacks of using solder. No surface preparation or pre-fluxing operations are required with adhesive bonding. The adhesive process eliminates the need for cleaning the device post-assembly to remove flux residues. Lastly, adhesives are readily adaptable to a wide variety of materials such as aluminum, copper, titanium, stainless steel and Ni superalloys. In this paper, we introduce a novel microlamination architecture for using surface mount adhesives to produce low-temperature microchannel arrays capable of being applied across a wide variety of materials.

2. Experimental Approach

The experimental objective in this paper is to demonstrate a microlamination protocol utilizing surface mount adhesives to make microchannel arrays. Specifically, the process was designed to meet the requirements for low temperature microchannel heat exchangers including the ability to bond to different heat exchanger materials with adequate bond strength, dimensional tolerance, and hermeticity. The method provides a wider material selection being compatible with many different materials. Aluminum 3003, a common heat exchanger material, and SS 316L were chosen for this study due to their good formability, low material cost and good corrosion resistance.

2.1. Fabrication Protocol

Lamina patterning methods investigated in this paper include both sheet metal embossing and photochemical machining. In early test articles, height control features (Figure 2 - circled in yellow) were embossed into fin laminae thereby eliminating the need for spacer laminae. In later test articles, these height control features became sealing bosses used to constrain the adhesive to desired locations for bonding, establish the height of microchannels during bonding and provide a protective shroud for the adhesive during flow operation. These types of embossed features provide an added degree of freedom over etched features by allowing for multiple step heights within a single lamina. This is a significant advantage over typical blind etching approaches which are constrained to etching roughly one-half the lamina thickness assuming the need to produce through-holes in the same foil.

The assembly sequence used in this study involved adhesive dispense onto the patterned laminae followed by manual stacking and adhesive curing to form the final monolithic test article. Adhesive dispense was performed on each lamina both manually and in a controlled fashion using an automated adhesive dispenser.

The dispensing process was designed to produce an adhesive bead just higher than the lamina height control features allowing for the adjacent lamina to make consistent contact with the adhesive during the stacking operation. In later test articles, in order to keep the adhesive from seeping outside of the sealing

boss into adjacent channels, the total volume of adhesive could not exceed the space adjacent to bosses available to receive the adhesive. One potential advantage of using these types of adhesive dispense techniques is the ability to scale deposition using screen printing processes as is done in electronics assembly.

In some test articles, features such as chamfers were used to align the lamina to ensure proper orientation. Fixtures were used to provide repeatability in the alignment process. Bonding was accomplished by thermally curing the adhesive at a low temperature (e.g. 100 to 150°C) for one to four hours yielding a microchannel array.

2.2. Test Articles

Several test articles were fabricated to determine the suitability of various surface mount adhesives to produce microchannel arrays. Generation 1 (G1) test articles were used to determine the feasibility of using adhesives to produce aluminum microchannels. Aluminum 3003 laminae 50mm X 50mm X 500μm thick were used. Height control features were produced by embossing projections (200μm) in the laminae using a die. Each lamina also had a 6.25mm hole to establish a fluid connection for leak testing. A single channel device was formed by stacking the embossed lamina over a flat bottom plate. A one-part epoxy material (Loctite CNB 3509) was used as the bonding adhesive. The samples were cleaned with isopropyl alcohol and adhesive was dispensed on the periphery of embossed lamina using a manual pneumatic dispenser. After dispense, the flat bottom plate was picked up using vacuum tweezers and stacked on the lamina containing the adhesive. Coarse alignment was done using the edges of the laminae. The samples were then placed on a palette and cured through a reflow oven using a Sn-Pb profile. The reflow profile was a straight ramp from room temperature to 225°C, with a time above liquidus (183°C) of 60-90 seconds and a cycle time of ~6 minutes. A small weight (~150 g) was placed on the top plate to ensure contact between laminae. A cured G1 test article is shown in figure 3.

Generation 2 (G2) test articles were used to evaluate the use of height control features to constrain the adhesive and prevent it from leaking into the active area. An optimized bonding adhesive (Loctite 3615 [17]) with higher bond strength and a quicker cure was used. A continuous sealing boss (in the form of a groove) and a set of projections were used to control the channel height. The continuous boss was used to keep adhesive out of the channel. The embossed features were staggered from layer to layer to prevent nesting. The two lamina designs are shown in figure 4. Several 2-layer test articles were produced using the same approach described above. Figure 5 shows the cross-section of a 2-layer device.

Generation 3 (G3) devices were 122.4x145.9mm made from stainless steel and were etched using photochemical machining (PCM), since the cost of embossing dies were prohibitive. A higher temperature version of the G2 adhesive was used for these test articles (Loctite 3621). Double sealing bosses (figure 6) were introduced to further constrain the adhesive, along with an outer sealing boss for aesthetic purposes. Two lamina designs (lamina A-1016μm and lamina B-762μm thick) were used to demonstrate a two-fluid counterflow microchannel array with inlet/outlet ports for both fluids. Multi-layer (3, 5 and 7) test articles were assembled with fin aspect ratios from 12.5 to 100. These test articles were assembled in a similar fashion except through the use of an automated jet dispenser (Asymtek Spectrum S-820) and an alignment fixture for applying pressure during curing. The alignment fixture was designed to produce a pressure of approximately 276 kPa (40 psig) during thermal cure. Figure 7 shows the fixture used to align and compress the stack during adhesive cure.

2.3. Fill Ratio

The automated dispensing process was designed to produce an adhesive bead just higher than the sealing bosses to allow the adjacent lamina to make consistent contact with the adhesive during the stacking operation. In order to keep the adhesive from seeping outside of the sealing bosses into adjacent channels, the total volume of adhesive could not exceed the space between the sealing bosses available to receive the adhesive. Consequently, adhesive dispense rates ($\dot{v}$) and head travel rates (U_d) were related by the following equation:

$$U_d = \frac{\dot{v}}{A} \tag{1}$$

where *A* is the cross-sectional area of the space between the sealing bosses to be filled with adhesive. To help characterize adhesive dispensing, the fill ratio is defined as the volume of adhesive deposited to the theoretical volume between the sealing bosses. At a fill ratio of 1, the entire space (i.e. 100%) would be occupied by the deposited adhesive. At fill ratios greater than 1, the non-sag property of the adhesive is crucial for deposition of excess material without clogging the active channel areas. Figure 8 shows the concept with varying fill ratios.

3. Characterization and Analysis

3.1. Adhesive Characterization

The proposed approach uses the adhesive as a structural member, and requires a minimum bond strength to withstand operational pressures in the functional device. Data available from the vendor [17] indicates that the adhesive has a strength of at least 15MPa (2,175 psi), when bonded to grit blasted steel using ISO 4587 lap shear test. Surface treatment, roughness or conditioning was unknown. No information was available on bond strength for aluminum surfaces. In application, adhesive failure would likely be tension, shear or a combination of both. In comparing tension and shear tests, Godzimirski et al. [18] concludes that maximum normal stresses do not exceed adhesion strength values for lap samples without bending. Shear values are assumed to be equal to the tensile strength of the frontal adhesive layers. Chichili et al. [19] has also shown that shear tests successfully reflect trends due to tensile failure as well.

A lap shear test was constructed to determine the bond strength on Aluminum 3003. The samples were fabricated after ASTM D3163 test method. Each shear test specimen was constructed using two 12.5x50mm plates 0.5 mm thick. The adhesive wetting dimensions were 12.5x12.5mm resulting in a bond area of 156.25.mm^2 (0.25 in^2). Adhesive thickness was controlled using 3 layers of stacked Kapton tape (3M Corporation, 63.5µm thick), resulting in a bond line thickness of approximately 190µm. The Kapton tape also served to control the bonding area. A schematic of the test sample is shown in Figure 9.

In order to assess the sensitivity of the process to cleanliness, four uncleaned samples were processed as-procured. The samples were shear tested at a rate of 1.27mm/sec (0.050”/sec) in accordance with ASTM D3163 using an Instron 8874 tensile tester with a 8900N (2000lb) load cell. The test setup is shown in figure 10 (left). The shear test was abandoned after a few trials due to base metal fracture, instead of the adhesive bond. The as-procured samples, all fractured within the base metal at 1023 N (~230 lbs) (Figure 11). These tests suggest that with uncleaned samples, the adhesive has a minimum bond strength of at least 6.2 MPa (900 psi). These results suggest that the bonding process is very robust.

A second experiment was designed to determine the actual bond strength and variability for use in future designs. The lap shear test was repeated by increasing the thickness of shear test samples from the original 0.5mm to 6.25mm. The adhesive bond dimensions were increased to 15.9x12.5mm resulting in a total bond area of 198.75 mm^2 (0.325 in^2). The increased area was necessary to maintain uniform bond-line thickness during adhesive dispense and curing operations. As before, the adhesive bond-line thickness and bond area were controlled using three layers of stacked Kapton tape.

All samples were prepared by cleaning with an Aquaflux-Strip (Indusco) and water solution (25% concentration) in an ultrasonic bath. The samples were rinsed using deionized water and dried using shop air. The shear test was repeated using the same test procedure as before. The shear rate was increased to 2.54mm/sec (0.100”/sec), and 6 samples were tested to failure. The test setup is shown in Figure 10 (right) and test results are summarized in Table 1. All six samples were successfully tested and failed at the adhesive interface. Results show that the bond strength of the adhesive varies from 17-25 MPa (2400 to 3600 psi).

A failed sample is shown in figure 12. Investigation of the separated samples indicated that the dominant failure mechanism was adhesive separation from the metal surface. The analysis also indicated that the tape mechanism used to control the adhesive spread was not entirely successful and sometimes resulted in a larger bonding area than originally intended suggesting that the bond strength values in Table 1 are slightly inflated. Applying a 3x safety factor to the test results yields a bond strength of 5.5-8.5 MPa (~800-1200 psi) which is approximately 20% of the yield strength for common heat exchanger aluminum (Al3003).

3.2. Leak Testing and Failure Analysis

In the context of electronics cooling, Jang et al. [20] fabricated an aluminum microchannel heatsink using a micro-mechanical sawing process and tested at pressures of approximately 3.5 kPa (0.5 psig). Zhang et al. [6] used a micro-milled aluminum heatsink to cool ball grid array (BGA) components. Although absolute values of pressure are not stated, the system was limited to 100-280 kPa (15-40 psig) by compression springs in the setup. Recently, Ma et al. [21] demonstrated a piezoelectric micro-pump with a maximum pressure head of 9.8kPa (1.5psig) for cooling notebook computers. It should also be noted that most commercially available pumps for liquid cooling of computers (Koolance, Swiftech, etc) have maximum pressure heads ranging from 20-75kPa (3-11 psig).

Leak testing on G1 articles was performed by attaching 10mm diameter copper tubes to the microchannel. A blowtorch was initially used to attempt soldering using Sn3.5Ag solder preforms. The intense heat from the soldering destroyed several samples. Subsequent attachment was performed using quick set cement (JB Kwik). Plastic tubing was used to connect the devices to compressed shop air. The samples were immersed in a water bath and pressurized. The air pressure was adjusted in 35 kPa (~5 psig) increments and pressure to failure was noted. The test setup is shown in figure 13 and results are shown in table 2.

Most of the soldered samples had initial leaks, with one sample failing at 69 kPa (10 psig). The samples attached using quick set cement had no initial leaks and failed at 103 and 138 kPa (15 and 20 psig) respectively. Failure analysis of the soldered samples indicated that the adhesive had charred or delaminated due to the intense heat of the attach process.

Leakage testing of G2 test articles was performed as before by attaching 10mm diameter copper tubes to the microchannels using a 2-part quick set epoxy that hardens in 5 minutes (Dexter EPOXI-PATCH). Figure 14 shows the copper tube attach setup. Table 3 shows the results of the testing. For successful samples, the testing was stopped at a pressure of 276 kPa (40psig) for safety considerations. Figure 15 shows a failed sample. Analysis of the failed samples indicated that the load bearing adhesive area was not uniform. This is an artifact of the manual dispense process which did not produce a uniform adhesive bead. This suggested the need for an automated dispense process to reduce the variability of adhesive beads.

The geometry of the G3 devices was designed to hold a pressure of 413 kPa (60 psig). It should be noted that at 413 kPa, the pressure on the bond joints in tension is approximately 1.9MPa, compared to as-tested shear bond strength of 5.5-8.5 MPa. Leak test was done in a similar fashion as above. Multi-layer test articles were assembled with inlet/outlet manifolds (headers) for a single fluid. The inlet side was pressurized, while the outlet side was blocked (dead-ended). Pressure was maintained for a period of time under water to assess small leaks. Three revisions of the G3 device were pressure tested. The results of the pressure testing are summarized in table 4. Each device revision represented a modification of the adhesive dispense, and/or device assembly process.

Testing of initial G3 multi-layer (five or more) test articles resulted in catastrophic failures around 138 kPa (20 psig). A ruptured device is shown in figure 16. Failure analysis of the broken device revealed an insufficient amount of adhesive. As can be seen from the picture, the adjacent lamina shows white witness marks at areas of adhesive contact. A significant portion of the vertical and outer sealing bosses is shown to have insufficient adhesive which resulted in early failure. Fill ratios for this device were found to be 70 to 80%. Based on these results, the adhesive dispense program was modified to deposit 100% fill ratios.

A seven-layer device was built using the new adhesive dispensing parameters and shipped to colleagues for second party testing. The seven-layer device was found to have minor leaks from the start and failed catastrophically at 421 kPa (61 psig). Figure 17 shows the failed seven-layer device. Initial leaks were suspected to be caused by rough handling during shipping. The results indicate that the increase in adhesive and associated bonding area contributed to improved performance.

Based on these results, the adhesive dispense program was again modified to deposit more adhesive in the sealing bosses, resulting in fill ratios of 1.1 to 1.25. One-layer and three-layer devices were built using the additional adhesive. After assembly and leak testing, the devices were tested at 413 kPa (60 psig). The three-layer device was found to successfully hold 413 kPa pressure for several hours while the one-

layer device was found to develop pin hole leaks after several hours. Figure 18 shows the three-layer device under pressure. Destructive failure analysis was performed on the one-layer device to identify the source of the pin-hole leaks. Figure 19 shows the failure analysis of the 1-layer device. Careful analysis indicated the presence of grease residues inside the device. Grease had been administered on the fixture alignment pins prior to alignment and bonding to prevent adhesion of the device to the fixture. Apparently the grease diffused through the assembly at the curing temperature for the adhesive.

The assembly fixture was reworked to increase the clearance between the alignment pins and the lamina. Grease was eliminated and paper shims were used to prevent the device from sticking to the fixture. An additional four-layer device was produced which held pressure at 413 kPa without pin hole leaks. Thus leakage and pressure tests indicate that adhesive bonding can produce microchannel devices that are comparable or exceed results demonstrated using other manufacturing techniques. This illustrates that adhesive bonding process has significant potential for low temperature, low pressure applications such as electronics cooling.

Earlier investigations on bond strength revealed that the use of surface mount adhesive for bonding was fairly robust relative to surface cleanliness. However, it is apparent that grease and other types of residues interfere with forming hermetic bonds.

3.3. Dimensional Characterization

It is well known that the maldistribution of flow within microchannel devices is undesirable. Chowdhury and Sarangi [22] and Kitto and Robertson [23] both showed that passage-to-passage nonuniformity has a significant effect on the thermal performance of compact heat exchangers. Lalot et al. [24] demonstrated that at velocity ratios up to 15, flow maldistribution could lead to 7% loss of effectiveness in condensers and counterflow heat exchangers, and up to 25% for cross-flow heat exchangers. Wattanutchariya [25] showed for heat exchanger applications, channel deviations greater than 10% of the channel dimension had significant impact on effectiveness and channel deviations on the order of 20% require heat exchangers double in size [1].

The primary dimension in microchannel arrays is the channel height. Measurements were performed on incoming laminae (pre-bonding) and after assembly (post-bonding) to correlate channel height with control feature size and tolerance.

3.3.1. Lamina Analysis

Detailed dimensional characterization was performed on G3 laminae patterned by PCM. The two lamina designs in the G3 test article were 1016 μm and 762 μm thick, with stated feature heights of 508 μm and 254 μm respectively. The height of the control features (i.e. bosses) was characterized by selecting a random lamina from each of the two lamina designs and measuring numerous points on each plate. A vertical displacement microscope (Titan ZDM-1) with 100x magnification was used for the measurement. The height of the feature was measured by manually focusing the microscope on the artifact of interest. The accuracy of the depth gage was verified by calibration to be 2μm. The measurement setup is shown in figure 20. Table 5 shows the summary of measurements for pre-bonding lamina measurements. The two sigma variations (95%) on feature height were 30 μm and 26 μm for the 1016 μm and 762 μm laminae respectively, which is about 6.1% to 9.3% pre-bonding variation.

3.3.2. Cross-sectional Analysis

A five-layer G3.c device was cross-sectioned to assess the variation in channel height after bonding. The sample was cut in two regions providing four cross-section views (see Figure 21). It can be clearly observed that the sealing bosses were effective in constraining the adhesive in the desired areas, without compromising the channel active areas. After cross-section, the samples were inspected under a 100X optical microscope to determine the variation in channel size. Measurements were calibrated and the repeatability was determined to be 2 μm.

The results of the post-bonding channel height measurements are also summarized in Table 5. Analysis of variance (ANOVA) was performed on the post-bonding channel heights to determine significant effects of pre-bonding channel variation. The P-values for post-bonding channel heights were 0.000 and 0.008 for the 1016μm and 762μm thick lamina respectively, indicating that the post-bonding channel height was different from the pre-bonding height (see figure 22).

The post-bonded channel height variation decreases for the thicker lamina (lamina A) and increases slightly for lamina B. The overall standard deviation in the post-bonded samples ranged from 10 to 14 μm leading to a two-sigma distribution between 3.9 and 9.6% of channel depth. This is just below the 10% threshold established by Paul [1] and compares favorably with the 7 to 31% variation with stainless steel reported by Sharma et al. [3] for diffusion bonding and 21 to 37% with NiAl [11] for diffusion bonding. It is important to note that the channel height variability is approximately the same before and after bonding implying that the variation contributed from the bonding process is negligible.

Figure 23 shows the comparison of inter-channel heights within the device. The 5 channels across the device are shown in Figure 21 (bottom). No statistical difference was noted among similar laminae. Channels 1, 3 and 5 are statistically equivalent, while channels 2 and 4 are equivalent. Figure 23 shows that the inter-channel heights appear to be uniform and consistent within the device.

Results from Table 5 also show that the post-bonding channel height is approximately 12 to 13 μm higher than the pre-bonding height (see Figure 22). To investigate the potential causes of this height increase, a Tencor Instruments AlphaStep 200 profilometer was used to perform roughness measurements on the faying surfaces of extra laminae. Prior to measurements, the tester was calibrated using a known standard with a step value of 823Å. A 12 mg force stylus was used with a scan time of 40 seconds and a scan length of 2000 μm.

Roughness measurements were performed on both the front and back faying surfaces of random laminae. Peak-to-valley roughness readings are summarized in Table 6. It is apparent that Lamina B (762μm thick) is significantly rougher when compared to Lamina A. The largest peak-to-valley roughness values for the two laminae were 6.77 and 1.74 μm, respectively. Using the worst-case values from both laminae, the combined peak-to-valley roughness is approximately 8.5 μm. The post-bonding channel height is on average 12 to 13 μm higher (see figure 22) when compared to the pre-bonding measurements. These measurements indicate that surface roughness of the laminae could be a major contributor towards the observed difference in the channel height measurements. Measurement uncertainty and lamina warpage could be other contributors to the increase in post-bonding channel height. Figure 24 shows further evidence that surface roughness could contribute towards the observed increase in channel height after bonding.

In section 3.2, it was noted that fill ratios of 1.1 to 1.25 provide consistently good results with pressure testing. The increase in post-bonding channel height and the amount of surface roughness provides some explanation for the larger fill ratios required. Other factors affecting fill ratios could include the precise shape of fill cross-sections and the dimensional stability of the adhesive during curing.

Based on results from this study, it is expected that the adhesive bonding process is capable of producing microchannel arrays with channel heights ranging from approximately 100 to 2000 μm. Repeatable deposition of very small adhesive quantities is expected to be an issue at smaller channel heights. At the other end of the spectrum, cycles times for adhesive deposition get unacceptably long with very large adhesive quantities. There are also limits to the quantities of adhesive that can be deposited with stencil printing.

4. Conclusions

Adhesive bonding has been successfully demonstrated as a viable technique for producing microchannel arrays for low temperature applications. Sheet metal embossing and chemical etch patterning processes have been used to produce sealing bosses which control the channel critical dimension and ensure channel integrity. Sealing bosses reduce the number of laminae needed resulting in ~50% material savings. Optimal fill ratios were determined to be 1.1 to 1.25 for good performance. The need for excess adhesive was found due to patterning tolerances and faying surface roughness and may also be affected by the precise shape of fill cross-sections and the dimensional stability of the adhesive during curing. Bond strength characterization indicates that the adhesive bond strength is fairly robust relative to sample cleanliness. The effective shear bond strength on heat exchanger aluminum was found to be 5.5-8.5 MPa using a 3X safety factor applied to the results of a lap shear test.

Leakage and burst pressure testing on several samples has established confidence that adhesive bonding can produce leak-free joints. Operating pressures up to 413 kPa equivalent to tensile stresses of 1.9 MPa within bond joints, were successfully applied without leakage or failure. It is expected that higher

operating pressures can be accommodated by increasing the bond area of the device. While bond strength appeared to be insensitive to cleanliness, grease was found to inhibit hermetic bonds. Dimensional characterization revealed that the adhesive bonding process is capable of producing consistent dimensions with a two sigma post-bonded channel height tolerance under 10% after bonding. A considerable part of this variation was shown to be due to patterning tolerance. Surface roughness of the lamina faying surfaces was also found to influence the final post-bonded channel height.

The process was found adaptable to both aluminum and stainless steel bonding surfaces. The new process eliminates pre-fluxing and/or coatings prior to assembly, and does not require any flux removal or cleaning post assembly. These findings suggest that the application of surface mount adhesives to microlamination is a potentially cost effective method of producing low temperature microchannel arrays.

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