# Application of Controlled Thermal Expansion in Microlamination for the Economical Production of Bulk Microchannel Systems

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## Abstract

Diffusion bonding has been widely used within microlamination architectures for the fabrication of Micro Energy and Chemical Systems (MECS). MECS are microsystems with the ability to process bulk amounts of fluid within highly-parallel microchannel arrays capable of accelerated heat and mass transfer. Thus far, diffusion bonding of the microchannel arrays is commonly done in a vacuum hot press system. The use of the hot press greatly restricts the production rate due to vacuum pump-down time and heating-up and cool-down periods. Furthermore, larger substrates are gaining interest in the system design of MECS devices and it is not apparent that uniaxial pressing within a hydraulic vacuum hot press will provide the bonding pressure uniformity necessary for large substrate bonding. This paper presents a novel fabrication approach for the high-volume thermal bonding of MECS devices with the use of controlled thermal expansion. A thermal bonding fixture based on the principle of differential thermal expansion was developed with focus on controlling the bonding pressure magnitude, the pressure timing and its sensitivity. The application of such a fixture within a conveyorized furnace system could be the key to a continuous thermal bonding approach for the mass production of MECS devices.

## Introduction

Today, the function of many bulk microfluidic devices has been validated in the laboratory. Future development of bulk microfluidic devices will focus on the integration of different unit operations at low-cost and high production volume. The full commercial potential of bulk microfluidic systems will be realized through the integration of multiple, highly-paralleled unit operations into one single device. The innovative design of a thermal expansion bonding unit presented in this paper could be a key technology for the mass production and commercialization of microlaminated devices. The use of thermal expansion as a driving force for the pressure application during a microlamination approach was first suggested by Pacific Northwest National Laboratory (PNNL) in 1999.[0]

## Theoretical Concept and Pilot Study

The general concept of a bonding fixture based on the principle of differential thermal expansion for the application of bonding pressure consists primarily of a frame, two bonding platens and, in the simplest case, an expansion block interposed between them as visualized in Figure 1. The rigid frame is composed of a low thermal expansion material ($\alpha_{f1}$). The expansion block has a significantly higher coefficient of thermal expansion ($\alpha_{e4}$) than the frame of the fixture. All things being equal, the height of the expansion block is directly proportional to the amount of clamping pressure to be delivered. Between the expansion block and the frame are placed the bonding platens between which the laminae are aligned and stacked. In this case, the bonding platens serve to prevent solid state diffusion to the fixture parts and may be made of graphite or some other suitable material. As a guideline, the coefficients of thermal expansion (CTE) should preferably differ at least by a factor of two to guarantee functionality of the fixture.

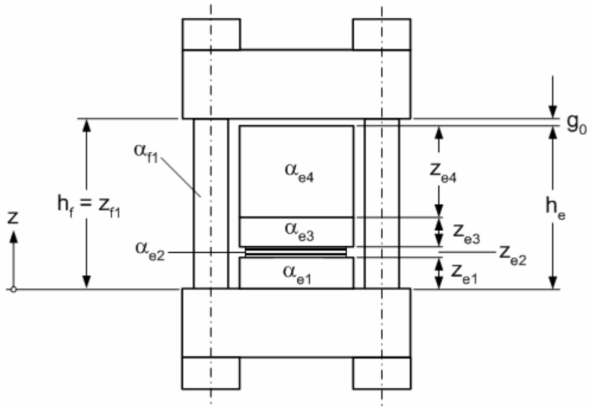

Figure 1: ΔCTE Fixture Concept

When the bonding unit is heated up to the bonding temperature, the expansion block and the platens inside the frame expand relatively to the frame by the difference in the sum of their coefficients of thermal expansion scaled by the product of the height of the expansion block and the change in temperature. An initial gap ($g_0$) can be designed into the fixture assembly to scale and time the application of the bonding pressure. As soon as the initial gap is consumed (i.e. inner parts come into contact with the frame), compression is applied to the laminae and increases with increasing temperature. An initial test fixture according to Figure 2 was developed to demonstrate the feasibility of bonding laminae by the use of differential thermal expansion. Prior to the experimental pilot test the generation of bonding pressure was quantified by a finite element model. The model has shown a bonding pressure of 7 MPa at a temperature of 800°C between the bonding platens. The expansion block was shaped conical to uniformly distribute the pressure to the graphite platens. Highly expanding stainless steel 321 was selected as a material for the expansion cone. The core piece was built of a lower expanding Inconel™ nickel-alloy.

Five donut-shaped copper (alloy 110) layers were bonded successfully with this test fixture and proved the feasibility of diffusion bonding with the use of thermal expansion.

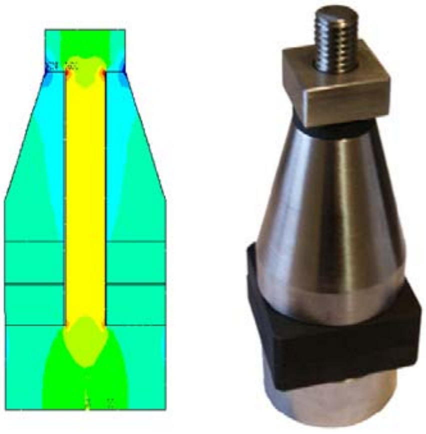

Figure 2: FE-Model and Initial Test Fixture for Bonding Pilots

## Novel Fixture Design to Control Bonding Conditions

Experimental and theoretical studies of ΔCTE-bonding fixtures have shown that a desired bonding pressure due to differential thermal expansion is rather difficult to control and a small change either in temperature or initial gap size can result in an enormous variation of bonding pressure (± 100%). This is due to the fact that the bonding pressure is regulated by the modulus of elasticity of the material. To avoid warpage leading to flow maldistribution within bulk microfluidic devices, it is necessary to: 1) dampen the amount of pressure caused by thermal expansion so to minimize pressure variations due to thermal fluctuations or gap adjustments; and 2) avoid putting pressure onto the stack until just before the bonding temperature. The second requirement extends from the difference in thermal expansion between the laminae and the bonding platen in the lateral dimension. One way to control the timing of applying bonding pressure, an initial gap adjustment is necessary to offset the point of contact until just before the final bonding temperature. However, to be effective, the pressure must be applied as a step function with low pressure sensitivity.

A more complex design of a thermal expansion bonding fixture claims the implementation of high-temperature spring elements to decrease the pressure sensitivity of the bonding fixture. The resulting bonding pressure is due to the amount of active spring compression related to the substrate area. By introducing spring elements into the fixture design, the amount of thermal expansion will always be consumed by the springs and the magnitude of the bonding pressure is no longer dependent on the material properties of the fixture platens. The application of disc springs is considered as favorable, since disc springs work with minimal compression by high load forces. Besides disc springs are available in various materials and alloys some of which, for instance, are capable of working at high temperatures. Taking this concept a step further, the spring elements can even be preloaded to the desired final pressure level as visualized in Figure 3. The springs are held by screws in the base plate of the bonding unit in the pre-compressed state. The appropriate amount of preload force can be applied with a hydraulic press and the screws snugged during the preload procedure to secure the amount of spring compression. During a bonding cycle, as soon as the expansion block comes in contact with the frame of the fixture, the preloaded force is transmitted into the laminae stack applying the pre-adjusted pressure. The timing of the force release can be controlled by a set screw in the fixture frame. The initial gap has to be compensated so that contact is made a few degrees below the final bonding temperature to guarantee release of the pre-loaded force to the laminae.

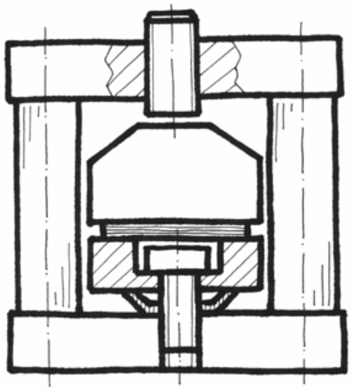

Figure 3 : ΔCTE Fixture Concept with Preload Mechanism

Fluctuations in temperature follow differential thermal expansion behavior of the fixture modulated by the spring constant which can be modified through the design of the spring. Consequently, a thermal expansion fixture with spring elements will yield minimal bonding pressure sensitivity. However, the presented concept involves some complications in the selection of appropriate materials and components to allow the fixture application at high temperatures without diffusion bonding structural components together or reaching limits of the maximal service temperature.

To provide a more fundamental understanding of this fixture concept, a finite element model was created in ANSYS as shown in Figure 4. The model was used to study theoretically the behavior of the differential thermal expansion unit and prove its feasibility. The theoretical assessment of the resulting bonding pressure, timing of the pressure and its sensitivity depending on changes in temperature was of interest to design and optimize a prototype fixture for experimental studies. The prototype fixture is composed of multiple high temperature materials selected depending on their thermal expansion potential. The base and the top of the thermal expansion fixture are made of molybdenum connected by four ceramic standoffs to guarantee a rigid and low expanding fixture frame. The test articles are placed between isotropic graphite ISO-63 bonding platens and aligned by three tungsten alignment pins. On top of the graphite bonding platen the engagement block is placed and centered. The engagement block is fabricated out of high temperature stainless steel 321 with a high coefficient of thermal expansion to drive the main displacement of the load cell sitting on top of it. The load cell consists of two molybdenum platens with four integrated Inconel$^{\text{TM}}$ high temperature disc springs. The device is held together by four high-temperature fasteners and is mainly responsible for controlling the magnitude of the bonding pressure. The initial gap between the load cell top and the fixture frame is adjusted with a fine threaded set screw in the top plate of the fixture frame to control the timing of the bonding pressure. The set screw is made of graphite to prevent diffusion bonding to the molybdenum top plate.

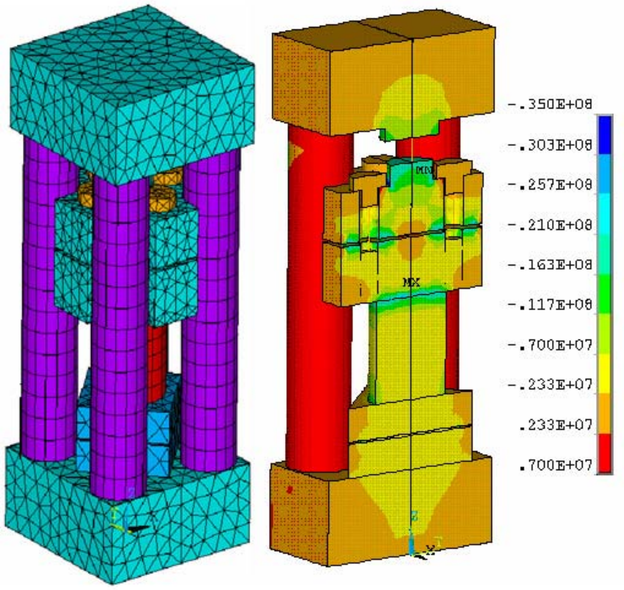

Figure 4 : FE-Model of the ΔCTE Fixture Prototype

The gap size can be adjusted by fitting a shim or assembly of shims according to the calculated gap size. Favorably is the use of a feeler gauge with a variety of precise shims for the adjustment of the initial gap and therefore for the timing of bonding pressure.

Based on the initial gap size the timing of the pressure can be controlled as shown in Figure 5. As soon as the load cell gets into contact with the fixture frame the bonding pressure kicks in with the pre-loaded force. The remaining portion of the target bonding pressure will be provided by the additional compression of the load cell depending on the difference between contact and bonding temperature. The slope of the additional pressure increase equals the pressure sensitivity of the fixture and is mainly dependent on the total spring constant of the load cell and the differential thermal expansion behavior. The finite element simulations reach a final pressure of 4.07 MPa which is only 1.75% off from the target bonding pressure of 4 MPa. The finite element model validated the concept of the ΔCTE fixture design. Consequently, a prototype fixture was built as shown in Figure 6.

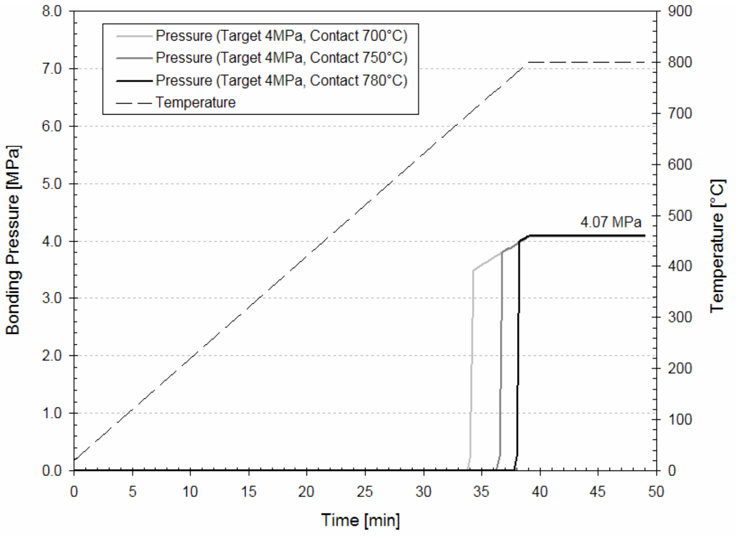

Figure 5 : Theoretical Pressure Engagement of FE-Model ΔCTE Fixture

Figure 6: ΔCTE Fixture Prototype

## Experimental Results

Different experiments have been conducted to validate the functionality of the proposed bonding fixture. Fuji pressure sensitive measurement film was used to evaluate pressure uniformity, magnitude and timing in the low temperature regime. The behavior of fin warpage was used as a reference for the calibration of the bonding fixture (pressure timing). The test articles (cross-section in Figure 7) were also used for the metallurgical assessment of the bond line. The void fractions of samples bonded in the ΔCTE fixture (Figure 8) were compared with samples bonded within the hot press (Figure 9) under similar conditions. Finally, an analysis of variance (ANOVA) was performed to compare samples bonded in the thermal expansion fixture and samples bonded within the hot press to determine if the differential thermal expansion fixture was capable and repeatable. After processing the 32 experimental runs the fin warpage was measured on the 64 test articles by scanning the channel fin with a Dektak$^3$ surface profiler. Since each test article had two fins a total of 128 measurements were taken. A multifactor analysis of variance (ANOVA) was performed to decompose the variability of the measured fin warpage into contributions due to the various factors (mode, temperature, pressure, time) and their interactions. The analysis of variance has shown that there is no statistical significant difference between samples processed in the hot press or within the fixture on the basis of a p-value of 0.92 for the experimental factor mode.

Figure 7: ΔCTE Bonded Sample Showing Minimal Fin Warpage

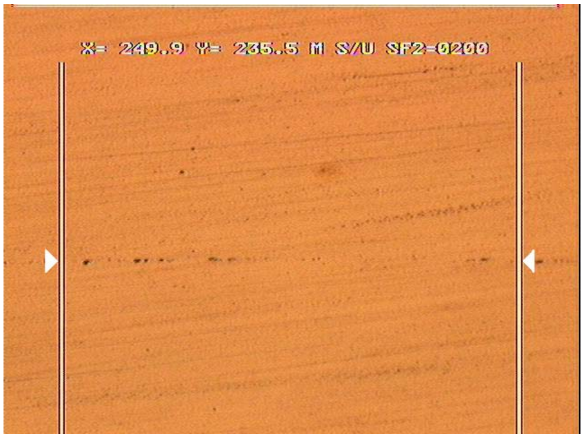

Figure 8: Bond Line ΔCTE Fixture (800°C/6MPa/30min)

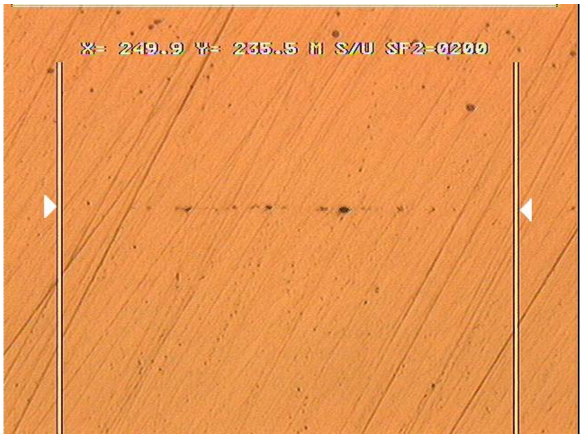

Figure 9: Bond Line Hot Press (800°C/6MPa/30min)

## Conclusions

A new and unique diffusion bonding fixture capable of operating within a continuous furnace has been presented in this paper. It was shown that the use of disc springs can significantly reduce the pressure sensitivity of the bonding fixture compared with prior efforts to simply put a highly expanding material between a lower expanding frame construction. The feasibility of the final device concept was theoretically validated by a finite element model. Experimental investigations with a fixture prototype have proven the functionality of the proposed bonding device. Based on this study it can be concluded that the diffusion bonding of devices within a ΔCTE fixture is not significantly different from processing devices in a hot press system. This is significant especially in light of the fact that the ΔCTE fixture has to engage prior to the bonding temperature which could lead to warpage.

The validation of a ΔCTE bonding fixture opens the possibility for the high-volume microlamination of MECS devices within a continuous furnace system which will reduce costs associated with diffusion bonding (or ultimately any thermal bonding) cycles. A major advantage of this fixture is the ability to decouple the pressure magnitude from the process temperature through the concept of preloading and force storage within a load cell. Initial gap settings are set independent of the pressure magnitude and, therefore, any level of bonding pressure can be applied at any level of bonding temperature by design. This flexibility makes the investigated ΔCTE bonding device not only interesting for diffusion bonding, but also for any thermal bonding process. Major advantages also exist for the use of a ΔCTE fixture over existing vacuum hot press platforms. In addition to better cycle times associated with continuous furnace processing, a second major advantage of the fixture is that it does not require dynamic loading at the bonding temperature. Loading of the bonding pressure in the ΔCTE fixture is more gradual. This may become important with heightened efforts to increase layer-to-layer registration precision and reduce fin warpage.

## References

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