

Mechanical and Temperature Resilience of Multi-Material Systems for Printed Electronics Packaging

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ABSTRACT

In this work, two AM technologies were utilized to compare the effectiveness of fabricating a simple electronic device with a conductive trace and die that would survive harsh environmental conditions. An nScript direct write (DW) system was the primary manufacturing system but a developing technology—coined large area projection sintering (LAPS)—manufactured a subset of samples for comparison. The tests follow Military Standard (MIL STD) 883K and include resiliency evaluation for die shear strength, temperature cycling, thermal shock, and high G loading by mechanical shock. Results indicate Master Bond (MB) epoxy devices show resilience to extreme temperatures, thermal shock, and mechanical shocks while also surpassing the die shear strength failure criteria specified by the MIL STD. LAPS devices also show mechanical resilience to thermal shock and surpass the die shear strength failure criteria. However, there were some open circuits, increases in resistance, and delamination when LAPS devices were subjected to extreme temperatures and 20,000 G shock loading normal to the substrate. The thermal effects are likely due to the thermal expansion mismatch between Nylon and the conductive paste while the mechanical shock effects may be attributed to the geometry differences of the LAPS dies. Further studies are required to understand these failure modes in some of the LAPS samples and refine the process to address them.

INTRODUCTION

Hybrid digital manufacturing integrates additive manufacturing (AM) processes (thermoplastic extrusion and/or paste deposition) with other digital operations including: pick and place, milling, polishing, and laser machining within a multi-headed tool [1-3]. This enables fabrication of printed functional electronics without the need for sophisticated electronics manufacturing processes (i.e. photolithography). This further shifts inventory from physical off-the-shelf components to raw materials that can be fabricated on demand [4-7]. Hybrid manufacturing can also decrease the device form factor by conforming electronics to the 3D structure [8, 9]. This unlocks unique devices and architectures that are impossible to fabricate with planar electronics manufacturing [10, 11].

Printed functional electronics typically consists of multi-material systems that make up the substrate, conductive interconnects, and die/encapsulant. These processes can be used to create low-cost systems with integrated active and/or passive components including: RFID tags, sensors, and antennas [12-15]. However, combining multiple materials introduces several challenges that must be overcome to yield an effective electronic package and there is significant variability in the performance levels of devices produced using these methods [2, 16]. An effective electronics package must be structurally robust to protect the encapsulated materials, have adequate adhesion to the substrate to maintain function during operation, be resilient to withstand operating temperatures, and resist thermo-mechanical stresses upon thermal cycling [17-21]. Minimizing differences in coefficient of thermal expansion (CTE) is critical to minimizing these stresses.

Previous work shows CB028 conductive paste deposited on poly-ether-ether-ketone (PEEK) substrates maintains resiliency when subjected to harsh mechanical and thermal environmental conditions [22]. The current work examines a broader range of testing criteria. This is the Accepted Manuscript version of an article accepted for publication in IOP Science. IOP Publishing Ltd is not responsible for any errors or omissions in this version of the manuscript or any version derived from it. The Version of Record is available online at <https://iopscience.iop.org/article/10.1088/2058-8585/ab38e9/meta>.

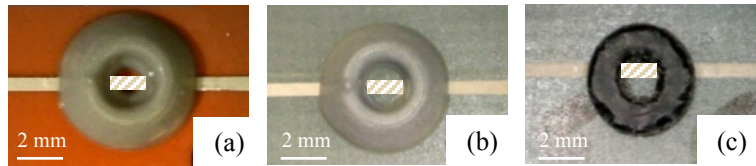
(temperature, mechanical shock, shear forces) on a simple electrical component consisting of three materials. The selected component has a conductive trace micro-dispensed onto a substrate with a printed 'die', which represents packaging of conductive elements and electronic components for encapsulation/protection. The simple electronic devices were fabricated on two different substrates (FR4, Kapton® film) and the dies were fabricated using two different methods (paste deposition, projection sintering) from two different materials (Master Bond epoxy, Nylon 12). This work elucidates the robustness of printed electronic multi-material systems when subjected to harsh environmental conditions and demonstrates how existing standard can be applied to qualifying these materials.

METHODS AND MATERIALS

The electronic device consists of a cured conductive paste circuit (DuPont CB028) on a substrate and a housing cylinder (or 'die') without a cap. An nScrypt SmartPump™ was used to dispense both the CB028 for the conductive circuit and Master Bond (MB) SUP10HTND epoxy dies while the subset of LAPS dies were sintered with Nylon 12. Both CB028 and the MB epoxy were cured at 90°C for one hour. Kapton® and FR4 were chosen as substrate materials since they are both commonly used in the electronics industry and provide a flexible and rigid substrate, respectively. LAPS Nylon 12 dies were only printed on FR4. Table 1 lists the coefficient of thermal expansions (CTE) for the materials utilized in this work. Note the significantly higher CTE of Nylon. The measured CTE values utilized a TA Instruments Q400 Thermo-mechanical Analyzer (TMA) with sensitivity of ± 15 nm, a ramp rate of 5°C/min from ~30 to 165°C, and a probe contact force of 0.01 N.

Table 1 Coefficient of thermal expansion (CTE) for materials studied

| Material | CTE (ppm/°C) | Source |
|--------------|-----------------------------|-----------------------------|
| Kapton® | 17 (30-100°C) | Datasheet [23] |
| FR4 | 11-15 (in plane) | Datasheet [24] |
| CB028 | ~30 (30-75°C) | Measured |
| Nylon (LAPS) | 170 (30-165°C) | Measured |
| MB epoxy | 45-50 (@T _{room}) | Personal communication [25] |



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Fig. 1: CB028 circuits and dies: (a) MB on Kapton®, (b) MB on FR4, and (c) LAPS Nylon 12 on FR4. Note the conductive strip is highlighted in the middle of the cup that connects the circuit underneath the cup.

The inner and outer diameters of the MB dies were designed for 3 and 4 mm, respectively; however, the MB tends to slump after deposition and actually has more of a trapezoidal cross section with inner and outer diameters closer to 1-1.6 and 6 mm, respectively. The LAPS dies were sintered and measured to have inner and outer diameters of 2 and 4 mm, respectively. LAPS dies are not subjected to the viscous effects of slumping like the MB dies therefore maintain the cylindrical shape and match designed dimensions with much greater accuracy than the MB cylinders. For applications requiring tight tolerances, the MB viscous effects would need to be adjusted with design offsets to compensate for slumping. The smaller than designed *ID* of the LAPS dies could be corrected by offsetting for shrinkage effects seen in these samples. All heights were close to 2 mm as designed. Fig. 1 illustrates the varying samples types.

The resistance of the conductive circuit was characterized with four-point probe measurements immediately before and after each test regime. Measurement error was found to be ± 3 m Ω . During four-point probing, the sensing probes were placed immediately adjacent to either side of the die (Fig. 1) while the current supplying probes were placed 10 mm from the sensing probes on opposite ends of the conductive circuit.

Large Area Projection Sintering (LAPS)

The LAPS technology developed at the University of South Florida is a powder bed fusion technology which utilizes a high intensity projector to selectively heat and fuse an entire cross section with a single exposure [26]. This provides the ability to extend sintering times without extending overall build time. Extended sintering times allows the material to fully densify without the need for high peak temperatures (as in laser sintering processes) which can degrade the material and is well suited for sintering temperature sensitive materials [27, 28]. Fig. 2 presents a schematic of the LAPS system. Utilizing an inexpensive off-the-shelf projector a 20 μm pixel resolution on the powder bed with an optical power density of 2 W/cm² was achieved. More details of the LAPS process can be found in the reference provided [26].

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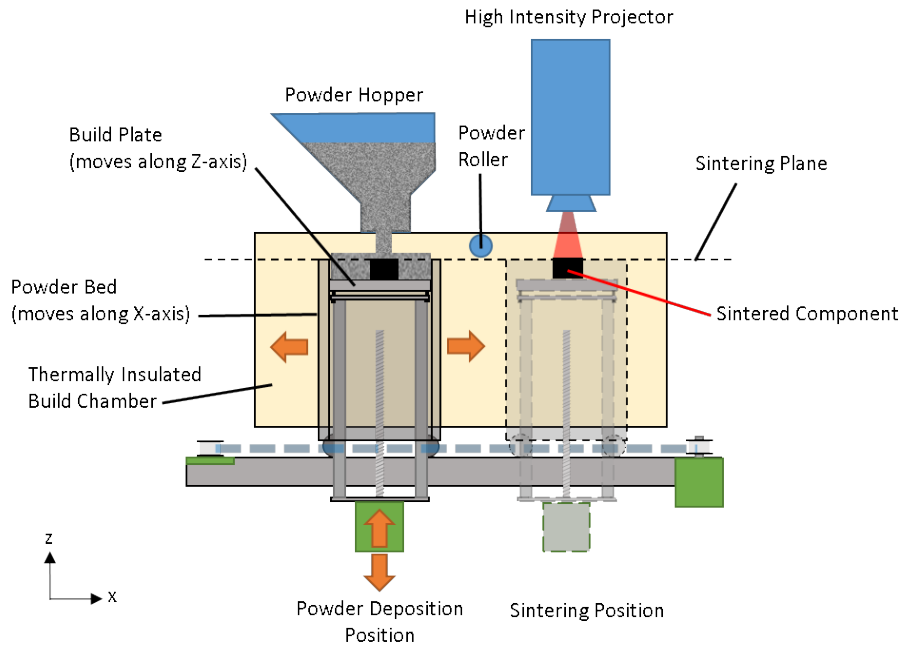
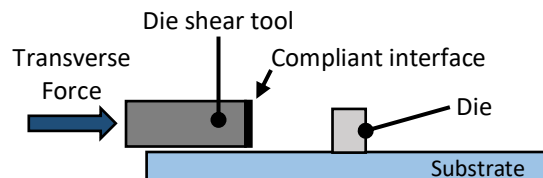


Fig. 2 Large Area Projection Sintering (LAPS) system which fuses entire 2D cross sections with a single quick exposure. A powder hopper then deposits powder before a counter rotating roller levels a new uniform layer for sintering. The thermal camera which monitors the process is not shown here for clarity. [26]

Harsh Environmental Testing

All harsh environmental testing was performed in accordance to Military Standard (MIL STD) 883K, which is the department of defense standard for qualifying military electronics for reliable and repeatable operation [29]. Die shear testing was performed following the procedures of *MIL STD 883K 2019.9 - Die Shear Strength* with a hydraulic MTS 858 Table Top system with a die shear tool velocity of 1mm/min as illustrated in Fig. 3. Die shear strength indicates the bond strength of the die and substrate materials. Prior to testing, microscope images were captured to provide the inner and outer diameters for cylindrical die area calculations and identified any surface defects before testing. Per MIL STD 883K 2019.9, the maximum force was recorded for each test and plotted against the measured die area to evaluate the pass or fail criteria cited in the MIL STD.



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Fig. 3 Die shear test schematic.

Temperature cycling of *MIL STD 883K 1010.9 B Temperature Cycling* evaluates resistance to extremes of alternating high and low temperatures in air chambers. The standard specifies temperature of the cold and hot air chambers be -55°C and 125°C respectively for condition B, a transfer time between chambers of less than 1 minute, a minimum of 10 cycles, and a minimum dwell time of 10 minutes. Fig. 4a illustrates a single cycle of the test starting with the cold chamber.

Thermal shock testing of *MIL STD 883K 1011.9 A Thermal Shock* determines the resistance of devices to sudden exposure of extreme temperatures with sharp temperature gradients and the effect of repeated exposures to these conditions. To induce thermal shock, the standard prescribes using a fluid bath. Condition A prescribes using water as the fluid medium and therefore establishes the temperatures of the cold and hot baths, 0°C and 100°C respectively with a tolerance of 2°C . Fig. 4b illustrates a single cycle of the test starting with the cold bath.

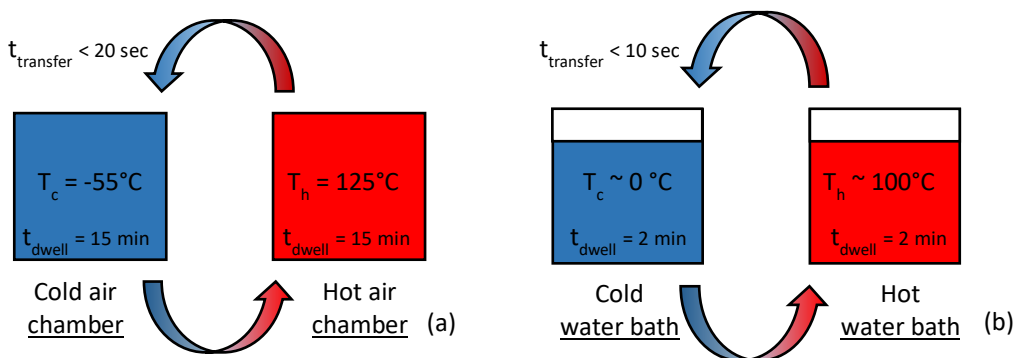


Fig. 4 (a) Temperature cycling between cold and hot air chambers of MIL STD 883K 1010.9 B and (b) thermal shock testing between cold and hot water baths of MIL STD 883K 1011.9 A.

Mechanical shock testing of *MIL STD 883K 2002.5 F Mechanical Shock* (20,000 G's with a pulse duration of $0.2 \pm 0.1 \text{ ms}$) determines the suitability of devices which may be subjected to moderately severe accelerations due to a sudden change in motion or applied forces. Fig. 6a illustrate a pneumatic air cannon utilized to impart a repeatable mechanical shock to an individual device per test that is configured to apply accelerations of $20,400 \pm 500 \text{ G's}$ and produced a pulse duration of $0.14 \pm 0.005 \text{ ms}$.

The payload (device under test) is mounted with an adapter to the payload. Each device type was tested in two orientations, subjecting them to both shear and normal accelerations. Shear accelerations induce traverse forces to shear the die and/or conductive paste from the substrate, illustrated in Fig. 5b. For normal accelerations, the die was positioned in an adapter facing the steel slug with a clearance hole to allow the substrate to be mounted flat against the payload carriage without die interference. The adapter allowed for clearance of the die but the conductive paste was in contact with the face of the adapter. Fig. 5c illustrates the tensile forces. This is the Accepted Manuscript version of an article accepted for publication in IOP Science. IOP Publishing Ltd is not responsible for any errors or omissions in this version of the manuscript or any version derived from it. The Version of Record is available online at <https://iopscience.iop.org/article/10.1088/2058-8585/ab38e9/meta>.

induced on the conductive paste and die as the payload carriage is accelerating away from the air cannon barrel.

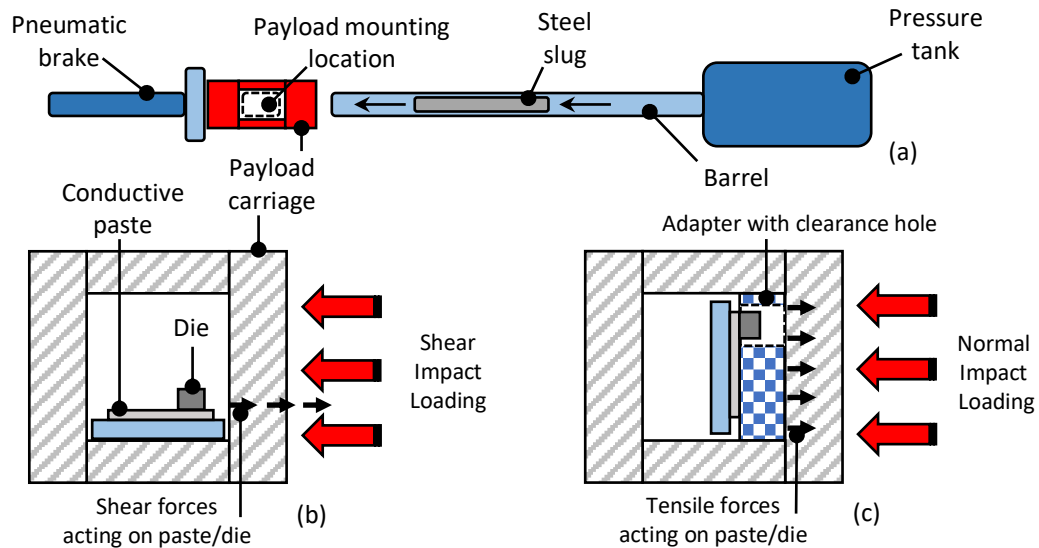


Fig 5 (a) Schematic of the pneumatic cannon, (b) shear forces acting when payload is oriented for shear, and (c) tensile forces acting when payload is oriented normal. Note: the die, conductive paste, and payload carriage labeled in (b) are the same in (c).

RESULTS

Die Shear Testing

Fig. 6a indicates the dies fabricated by both methods exceed the requirements for die shear strengths. MB dies vastly surpass the failure criteria for die shear strength and Fig. 6b further indicates that die shear strength is not a critical concern when exposed to harsh temperature environments. The die shear stresses are normalized by area and Fig. 6b show that the results have overlapping standard deviations between testing conditions, which signifies harsh temperature environments do not have a significant effect on die shear strength. Fig. 6a also indicates the shear forces are significantly less for the LAPS devices; however, this is expected since the contact area is much less than the MB devices. Even with the reduced area, the LAPS devices still significantly exceed the die shear failure criteria of Fig. 6a. When taking contact area into account (Fig. 6b), the LAPS devices actually show 40 – 60% higher die shear strength (Force/Area) except when subjected to thermal shock, in which case it is similar to the MB dies. Temperature cycling between air chambers of MIL STD 883K 1010.9 B doesn't have a severe effect on die shear strength in any of the sample types. On the other hand, thermally shocking the LAPS

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devices in a fluid bath decreases die shear strength but shear stress at failure is still similar to the MB samples.

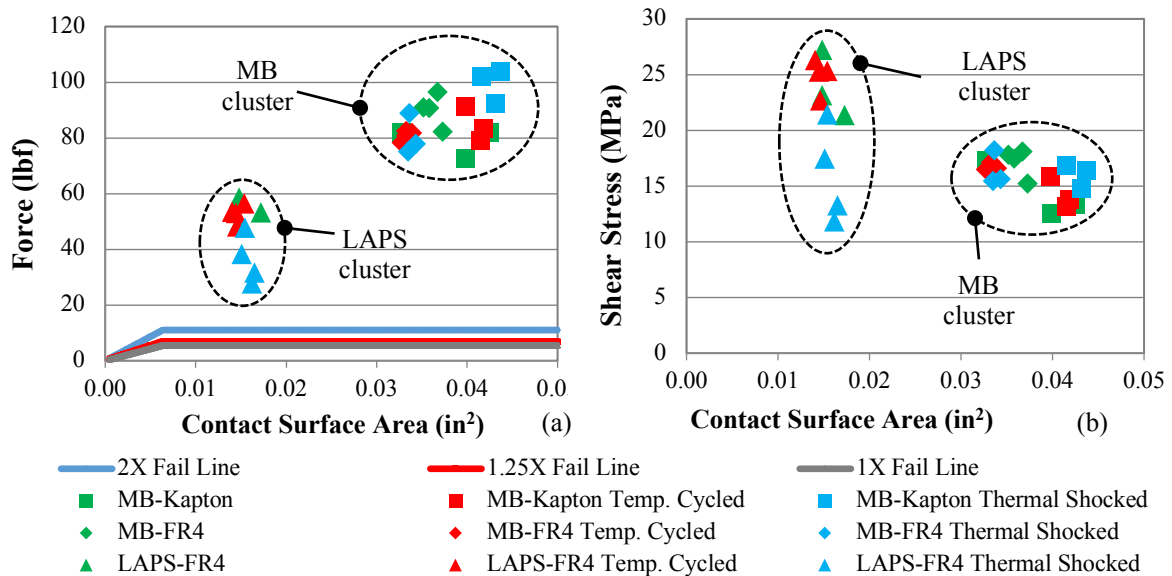


Fig 6 (a) MIL STD 883K die shear failure criteria and (b) Die shear strength vs. contact surface area for device dies. Master Bond dies show little variation due to the environmental exposures, but LAPS samples are weakened by the thermal shock.

We posit two possible mechanisms for the decreased resiliency of the LAPS die shear strength when thermally shocked. Nylon 12 is slightly hydrophilic and may be absorbing a small amount of water during submersion in the fluid bath, this could explain the decreased die shear performance. Even more likely is the coefficient of thermal expansion (CTE) mismatch between materials (Table 1). Nylon as a thermoplastic has a characteristically larger CTE than that of thermosetting materials like Kapton[®], FR4, and epoxies. Large CTEs will cause greater stress at the substrate interface that may cause localized delamination and/or cracking.

Thermal Cycling

Resistance of the conductors on the LAPS parts decreases as seen in Table 3. This is likely related to the high processing temperature in the LAPS process. The powder bed and substrate are preheated to ~170°C, well above the curing temperature of the CB028 paste (90°C). The high processing temperature decreases the resistance of the already cured conductive circuit.

The impact of temperature exposures on the resistance is highly dependent on the materials (Table 4). MB on Kapton[®] shows adequate resiliency to harsh temperature environments with resistance changes of only 0.5%. MB on FR4 decreases in resistance for both

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harsh temperature environments, which indicates a marginal curing effect and resilience to harsh environmental temperatures. Conversely, when the devices made with the LAPS process were temperature cycled, three of the four devices resulted in open circuits while thermal shocking lead to increased resistance. The CTE mismatch between the Nylon and substrate/ink combination is likely the mechanism of failure here. Nylon has a much larger CTE than the other materials and specifically $\sim 6x$ higher than the CTE CB028 (Table 1). This creates significant interfacial stress that could damage the conductive paths and increase resistance. Repeated expansions and contractions from the thermal cycling regimes could expand the defects.

Table 3 Change in Electrical Resistance during LAPS processing

| Device Type | # of Samples | ΔR after testing (m Ω) | ΔR (%) |
|-------------|--------------|--|----------------|
| LAPS-FR4 | 10 | -140 ± 98 | -19 ± 7.34 |

Table 4 Change in Electrical Resistance when subjected to harsh environmental temperatures

| Device Type | # of Samples | ΔR after testing (m Ω) | ΔR (%) |
|--|--------------|--|----------------|
| MB-Kapton [®] Temp. Cycled | 3 | 8 ± 22 | 0.5 ± 1.4 |
| MB-Kapton [®] Thermal Shocked | 3 | -6 ± 15 | -0.5 ± 1.2 |
| MB-FR4 Temp. Cycled | 4 | -9 ± 19 | -0.6 ± 1.5 |
| MB-FR4 Thermal Shocked | 4 | -50 ± 30 | -4 ± 0.6 |
| LAPS-FR4 Temp. Cycled | 4 | 280 (3 of 4 OC ^a) | 40 (3 of 4 OC) |
| LAPS-FR4 Thermal Shocked | 4 | 20 ± 11 | 5 ± 2 |

^aOC = open circuit created during testing

Mechanical Shock Testing

The mechanical shock testing results in Table 5 indicate the MB devices are resilient to exposure to high G's for all device types and orientations. The LAPS dies on FR4 substrates were resilient to mechanical shock in shear, but one of four samples delaminated while the other three samples experienced a significant increase in resistance when subject to acceleration normal to the substrate. This is likely related to the significantly smaller contact area between LAPS dies and substrate compared to the MB dies. A smaller contact area ($\sim 0.4x$ from the areas in Table 2) creates much higher tensile stresses for the LAPS dies. Increased tensile stresses may cause micro-cracking in the conductive ink, causing the resistance to increase. LAPS and MB dies have a mass of 0.023 ± 0.0003 and 0.035 ± 0.0010 [grams], respectively, which is another important consideration in mechanical shock testing. The nylon LAPS dies have $0.66x$ the mass of the MB dies, which signifies the MB dies will experience greater forces for a given acceleration ($F=m \cdot a$). However, since the area difference is more severe, it is the dominating mechanism. Taking the This is the Accepted Manuscript version of an article accepted for publication in IOP Science. IOP Publishing Ltd is not responsible for any errors or omissions in this version of the manuscript or any version derived from it. The Version of Record is available online at <https://iopscience.iop.org/article/10.1088/2058-8585/ab38e9/meta>.

ratio of the area and mass difference indicates the conductive circuit under the LAPS dies will experience about 60% more stress.

Table 5 Change in Electrical Resistance due to mechanical shock

| Device Type | # of Samples | Orientation | ΔR after testing (m Ω) | ΔR (%) |
|------------------------|--------------|-------------|--|----------------|
| MB-Kapton [®] | 3 | Shear | 0 \pm 8 | 0.0 \pm 0.5 |
| MB-Kapton [®] | 3 | Normal | -7 \pm 26 | -0.5 \pm 2.1 |
| MB-FR4 | 4 | Shear | -5 \pm 5 | 0.6 \pm 0.6 |
| MB-FR4 | 4 | Normal | -20 \pm 36 | -0.5 \pm 0.8 |
| LAPS-FR4 | 4 | Shear | 0 \pm 8 | 0.3 \pm 1.5 |
| LAPS-FR4 | 4 | Normal | 183 \pm 98 ^a | 73 \pm 30 |

CONCLUSIONS

In this work, simple electronic devices were fabricated with AM machines with a conductive paste circuit and a 'die' for potential electronics packaging. MB devices show adequate bond shear strength and resilience to both harsh environmental temperatures and high acceleration on both Kapton[®] and FR4 substrates. LAPS devices show enhanced geometric accuracy and increased bond shear strength when compared to the MB samples while also showing adequate resilience to thermal shock and high G loading in the shear direction. However, the Nylon 12 used in the LAPS process may become a concern when subjected to extreme temperature cycling and high accelerations when in a normal-tension loading orientation as some failure was seen in normal mechanical shocks and electrical changes (open circuits, resistance changes) were seen in temperature cycling. The CTE mismatch between the thermoplastic Nylon 12 causes greater interfacial stress upon heating than the rest of the thermosetting materials. This expansion may be inducing micro-cracks in the conductive paste to increase resistance. Water absorption may also be a contributing factor to compromise the resiliency during harsh environmental testing of the LAPS devices since Nylon 12 has a tendency to absorb moisture.

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