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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 hollow cylinder representative of 'printed packaging' that would survive harsh environmental conditions. The printed packaging cylinder delineates printed potting for electronics packaging. An nScrypt 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 DW Master Bond 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 sintered Nylon 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 Nylon 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 Nylon printed packaging. Further studies are required to understand these failure modes in some of the LAPS Nylon samples and refine the process to address them.

Keywords: additive manufacturing, conductive ink, electronic packaging, harsh environmental testing, hybrid electronics, large area projection sintering, printed electronics

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1. Introduction

Hybrid digital manufacturing integrates additive manufacturing (AM) processes (e.g. thermoplastic extrusion, paste deposition, stereolithography, and material jetting) with other digital operations including: pick and place, milling, polishing, and laser machining/sintering within a multi-headed tool [1-5]. 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 [6-9]. Hybrid manufacturing can also decrease the device form factor by conforming electronics to the 3D structure [10, 11]. This unlocks unique devices and architectures that are impossible to fabricate with planar electronics manufacturing [12, 13]. However, the response of these systems when subjected to harsh environments is relatively unknown and limits the application space.

Printed functional electronics typically consists of multi-material systems that make up the substrate, conductive interconnects, and encapsulant used for potting. These processes can be used to create low-cost systems with integrated active and/or passive components including: RFID tags, sensors, and antennas [14-17]. 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, 18]. 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 [19-23]. 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 (two-material system) maintains resiliency when subjected to mechanical shocks normal to printed elements and thermal cycling [24]. The current work expands the literature by examining a broader range of testing criteria (thermal cycling, thermal shock, both normal and shear induced mechanical shock, and 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 'hollow cylinder, which represents printed potting for 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 packaging cylinders were fabricated using two different methods (direct write, projection sintering) from two different materials (Master Bond epoxy, Nylon 12). This work assesses the ability of printed electronic multi-material systems to meet harsh environmental conditions typical of qualification requirement in traditional electronics packaging by adapting existing standards to the printed electronic devices.

Methods and Materials

The electronic device consists of a cured conductive paste circuit (DuPont CB028) on a substrate and a packaging cylinder (printed potting) without a cap. An nScrypt SmartPump^{TM} was used to direct write (DW) both the CB028 for the conductive circuit and Master Bond (MB) SUP10HTND epoxy packaging cylinders while the subset of LAPS packaging cylinders were sintered with Nylon 12. Both CB028 and the MB epoxy were cured at 90ºC for one hour. The CB028 conductive paste circuit was cured prior to either directing writing or sintering the Master Bond or LAPS cylinders, respectively. 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 packaging cylinders 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 5ºC/min from ~30 to 165ºC, and a probe contact force of 0.01 N.

The inner and outer diameters of the MB packaging cylinders 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 Nylon packaging cylinders were sintered and measured to have inner and outer diameters of 2 and 4 mm, respectively. LAPS Nylon packaging cylinders are not subjected to the viscous effects of slumping like the direct write MB packaging cylinders; therefore, maintain the cylindrical shape and match designed dimensions with much greater accuracy than the MB packaging 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 Nylon packaging cylinders could be corrected by offsetting for shrinkage effects seen in these samples. All heights were close to 2 mm as designed. Figure 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 mΩ. During four-point probing, the sensing probes were placed immediately adjacent to either side of the cylinder (Figure 1) while the current supplying probes were placed 10 mm from the sensing probes on opposite ends of the conductive circuit.

1.1 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 [25, 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 [26-28]. Figure 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/cm^{2}was achieved. More details of the LAPS process can be found in the reference provided [25, 26].

1.2 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 1 mm/min as illustrated in Figure 3. Die shear strength indicates the bond strength of the die (i.e. the housing cylinder in this work) and substrate materials. Prior to testing, microscope images were captured to provide the inner and outer diameters for cylinder 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 cylinder area to evaluate the pass or fail criteria cited in the MIL STD.

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. Figure 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℃ respectively with a tolerance of 2°C. Figure 4b illustrates a single cycle of the test starting with the cold bath.

Mechanical shock testing of *MIL STD 883K 2002.5 F Mechanical Shock* (20,000 G's with a pulse duration of 0.2 ± 0.1 ms) determines the suitability of devices which may be subjected to moderately severe accelerations due to a sudden change in motion or applied forces. Figure 5a illustrates 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 ± 500 G's and produced a pulse duration of 0.14 ± 0.005 ms. Figure 6 shows a representative of the acceleration pulse imparted by the air cannon within the tolerance specified by the MIL STD.

The payload (device under test) is mounted with an adapter to the payload carriage that receives the mechanical shock event from the impact of the slug when fired. Each device type was tested in two orientations, subjecting them to both shear and normal accelerations. Shear accelerations induce traverse forces to shear the cylinder and/or conductive paste from the substrate, illustrated in Figure 5b. For normal accelerations, the cylinder 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 cylinder interference. The adapter allowed for clearance of the cylinder but the conductive paste was in contact with the face of the adapter. Figure 5c illustrates the tensile forces induced on the conductive paste and cylinder as the payload carriage is accelerating away from the air cannon barrel.

Results

Die Shear Testing

Figure 7a indicates the packaging cylinders fabricated by both methods exceed the requirements for die shear strengths. DW Master Bond epoxy packaging cylinders vastly surpass the failure criteria for die shear strength and Figure 7b 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 Figure 7b shows 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.

Figure 7a also indicates the shear forces are significantly less for the LAPS Nylon devices; however, this is expected since the contact area is much less than the DW epoxy devices. Even with the reduced area, the LAPS Nylon devices still significantly exceed the die shear failure criteria of Figure 7a. When taking contact area into account (Figure 7b), the LAPS Nylon 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 DW epoxy packaging cylinders. The increased die shear strength is likely due to the thermoplastic Nylon fusing to the substrate during the sintering process for better adhesion than just thermally curing thermoset epoxy materials. Furthermore, the increased die shear strength will remain evident for the LAPS devices if the area ratio of packaging cylinder to:substrate will remain constant.

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

We posit two possible mechanisms for the decreased resiliency of the LAPS Nylon 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 2. This is likely related to the high processing temperature in the LAPS process. The powder bed and substrate are preheated to ~170ºC, well above the curing temperature of the CB028 conductive paste (90ºC). 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 3). DW epoxy on Kapton® shows adequate resiliency to harsh temperature environments with resistance changes of only 0.5%. DW epoxy on FR4 decreases in resistance for both harsh temperature environments, which indicates a marginal curing effect and resilience to harsh environmental temperatures. Conversely, when the Nylon 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 ~ 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.

Mechanical Shock Testing

The mechanical shock testing results in Table 4 indicate the DW epoxy devices are resilient to exposure to high G's for all device types and orientations. The LAPS Nylon packaging cylinders 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 Nylon packaging cylinders and substrate compared to the DW epoxy packaging cylinders. A smaller contact area (~0.4x from the areas in Figure 7) creates much higher tensile stresses for the LAPS Nylon packaging cylinders. Increased tensile stresses may cause micro-cracking in the conductive ink, causing the resistance to increase. LAPS Nylon and DW epoxy packaging cylinders 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 LAPS Nylon packaging cylinders have 0.66x the mass of the DW epoxy packaging cylinders, which signifies the DW epoxy packaging cylinders 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 ratio of the area and mass difference indicates the conductive circuit under the LAPS Nylon packaging cylinders will experience about 60% more stress.

Conclusions

AM with hybrid processes to enable the fabrication of multi-layered functional printed electronics unlocks unique capabilities that were previously limited in traditional electronics manufacturing. For instance, printed electronics can permit conformal/structural electronics that can be printed on the fly and customized for specific applications with relatively low cost. One area that lacks attention in these emerging systems however is the resilience when subjected to harsh environments. In this work, simple electronic devices were fabricated with AM machines with a conductive paste circuit and a 'packaging cylinder' representative of printed potting for potential electronics packaging and exposed to harsh environmental conditions.

DW Master Bond epoxy devices show adequate bond shear strength and resilience to both harsh environmental temperatures and high acceleration on both Kapton® and FR4 substrates. Conversely, the viscous nature of epoxy allows slumping of the epoxy packaging cylinders that deviate from the designed dimensions although slumping of the epoxy may not be a concern for electronics packaging applications that do not require precise potting. On the other hand, LAPS Nylon devices show enhanced geometric accuracy and increased bond shear strength when compared to the DW epoxy 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 (~10x greater than the substrate materials and ~6x greater than the conductive paste in this work) 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.

For electronics packaging, DW processes depositing thermosetting epoxy for potting may be more robust and resilient to thermal loads; however, the viscous nature of the epoxy will have less accuracy. LAPS or other thermoplastic AM processes may be less resilient (especially when subject to thermal loads) but will have a greater accuracy that could be beneficial for high tolerance applications. The inability to reproduce the target geometry and the poor CTE mismatch of the epoxy and Nylon, respectively, may be adequate for applications in which encapsulation is the primary objective. However, future work can explore developing materials that have greater accuracy and closer CTE matching for improved resilience when exposed to harsh environments, for instance, using Nylon with an additive that reduces the CTE. Furthermore, an area for future work could include using AM processes to sinter Nylon substrates that eliminates the conventional circuit board materials and could improve resilience in a more complete hybrid AM process.

Funding

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References

[1] Church, K. H., Crane, N. B., Deffanbaugh, P. I., Ketterl, T. P., Neff, C. G., Nesbitt, P. B., *et al.*, 2017, "Multimaterial and multilayer direct digital manufacturing of 3D structural microwave electronics," *Proceedings of the IEEE,* vol. 105, pp. 688-701. doi: 10.1109/JPROC.2017.2653178

[2] Neff, C., Crane, N. B., Deffenbaugh, P. I., Zunino, J. L., Church, K. H., and Newton, M., 2016, "Digital Manufacturing and Performance Testing for Military Grade Application Specific Electronic Packaging (ASEP)," presented at the International Microelectronics Assembly and Packaging Society, Pasadena, CA. doi: 10.4071/isom-2016-WP13

[3] Rojas-Nastrucci, E. A., Tsang, H., Deffenbaugh, P. I., Ramirez, R. A., Hawatmeh, D., Ross, A., *et al.*, 2017, "Characterization and Modeling of K-Band Coplanar Waveguides Digitally Manufactured using Pulsed Picosecond Laser Machining of Thick-Film Conductive Paste," *IEEE Transaction on Microwave Theory and Techniques*. doi: 10.1109/TMTT.2017.2677447

[4] Saleh, E., Zhang, F., He, Y., Vaithilingam, J., Fernandez, J. L., Wildman, R., *et al.*, 2017, "3D Inkjet Printing of Electronics Using UV Conversion," *Advanced Materials Technologies,* vol. 2, p. 1700134, 2017/10/01. doi: 10.1002/admt.201700134

[5] Li, J., Wasley, T., Nguyen, T. T., Ta, V. D., Shephard, J. D., Stringer, J., *et al.*, 2016, "Hybrid additive manufacturing of 3D electronic systems," *Journal of Micromechanics and Microengineering,* vol. 26, p. 105005, 2016/08/23. doi: 10.1088/0960-1317/26/10/105005

[6] Bandyopadhyay, A., Gualtieri, T. P. L., and Bose, S., 2016, *Additive Manufacturing*. Boca Raton: CRC Press.

[7] Louis, M. J., Seymour, T., and Joyce, J., 2014, *3D oppportunity in the Department of Defense: Additive manufacturing fires up*: Deloitte University Press.

[8] Sachs, E., Cima, M., Williams, P., Brancazio, D., and Cornie, J., 1992, "Three Dimensional Printing: Rapid Tooling and Prototypes Directly from a CAD Model," *Journal of Engineering for Industry,* vol. 114, pp. 481-488. doi: 10.1115/1.2900701

[9] Schrand, A., 2016, "Additive Manufacturing: From Form to Function," *Strategic Studies Quarterly,* vol. 10, pp. 74-90.

[10] Macdonald, E., Salas, R., Espalin, D., Perez, M., Aguilera, E., Muse, D., *et al.*, 2014, "3D Printing for the Rapid Prototyping of Structural Electronics," *IEEE Access,* vol. 2, pp. 234-242. doi: 10.1109/ACCESS.2014.2311810

[11] Harrop, P. and Das, R., "Structural Electronics 2017-2027: Applications, Technologies, Forecasts," IDTechEx2017.

[12] Dickey, M. D., Cormier, D., and Parekh, D. P., 2015, *Additive Manufacturing: Ch.8 Multifunctional Printing: Incorporating Electronics into 3D Parts Made by Additive Manufacturing*. Boca Raton: CRC Press.

[13] Cui, Z., 2016, *Printed Electronics: Materials, Technologies, and Applications*. Singapore: John Wiley & Sons.

[14] Ketterl, T. P., Vega, Y., Arnal, N. C., Stratton, J. W. I., Rojas-Nastrucci, E. A., Cordoba-Erazo, M. F., *et al.*, 2015, "A 2.45 GHz Phased Array Antenna Unit Cell Fabricated Using 3-D Multi-Layer Direct Digital Manufacturing," *IEEE Transactions on Microwave Theory and Techniques,* vol. 63, pp. 4382-4394. doi: 10.1109/TMTT.2015.2496180

[15] Nassar, I., Tsang, H., and Weller, T. M., 2014, "3D printed wideband harmonic transceiver for embedded passive wireless monitoring," *Electronic Letter,* vol. 50, pp. 1609-1611. doi: 10.1049/el.2014.0769

[16] Ramirez, R. A., Rojas-Nastrucci, E. A., and Weller, T. M., 2017, "UHF RFID Tags for On-/Off-Metal Applications Fabricated Using Additive Manufacturing," *IEEE Antennas and Wireless Propagation Letters,* vol. 16. doi: 10.1109/LAWP.2017.2658599

[17] Hawatmeh, D., Rojas-Nastrucci, E., and Weller, T., 2016, "A multi-material 3D printing approach for conformal microwave antennas," in *International Workshop on Antenna Technology (iWAT)*, Cocoa Beach, FL, USA, pp. 7-10. doi: 10.1109/IWAT.2016.7434785

[18] Cunningham, V., 2015, "Navy additive manufacturing: adding parts, subtracting steps," Naval Postgraduate School, Monterey, California.

[19] Gilleo, K., 2004, *Area Arrary Packaging Materials: Adhesives, Pastes, and Lead-Free*. USA: McGraw-Hill.

[20] Lau, J., Wong, C. P., Prince, J. L., and Nakayama, W., 1998, *Electronic Packaging: Design, Materials, Process, and Reliability*: McGraw-Hill.

[21] Blackwell, G. R., 2000, *The Electronics Packaging Handbook*: CRC Press.

[22] Pecht, M. G., Agarwal, R., McCluskey, P., Dishongh, T., Javadpour, S., and Mahajan, R., 1999, *Electronics Packaging: Materials and Their Properties*. USA: CRC Press

[23] Chung, D. D. L., 1995 *Materials for Electronics Packaging*. Newton, MA, USA: Butterworth-Heinemann.

[24] Neff, C., Elston, E., Burfeindt, M., Crane, N., and Schrand, A., 2018, "A fundamental study of printed ink resiliency for harsh mechanical and thermal environmental applications," *Additive Manufacturing,* vol. 20, pp. 156-163. doi: 10.1016/j.addma.2018.01.009

[25] Nussbaum, J. and Crane, N., 2018, "Evaluation of Processing Variables in Polymer Projection Sintering," *Rapid Prototyping Journal*. doi: https://doi.org/10.1108/RPJ-04-2017-0070

[26] Craft, G., Nussbaum, J., Crane, N., and Harmon, J. P., 2018, "Impact of extended sintering times on mechanical properties in PA-12 parts produced by powderbed fusion processes," *Additive Manufacturing,* vol. 22, pp. 800-806, 2018/08/01/. doi: https://doi.org/10.1016/j.addma.2018.06.028

[27] Hamid, S. H., 2000, *Handbook of polymer degradation*, 2nd ed.: CRC Press.

[28] Duddleston, L., 2015, "Polyamide (Nylon) 12 Degradation during the Selective Laser Sintering (SLS) Process: A

Quantification for Recycling Optimization," Masters thesis, Mechanical engineering, University of Wisconsin-Madison.
[29] Military Standard 2016, "883K," in *Department of Defense, Test Method Standard, Microcircuits*, ed.
[30] DuPont Kapton Summary of Properties [Online]. Available: http://www.dupont.com/content/dam/dupont/products-and-services/membranes-and-films/polyimde-films/documents/DEC-Kapton-summary-of-properties.pdf
[31] FR4 Datasheet [Online]. Available: https://www.farnell.com/datasheets/1644697.pdf
[32] MasterBond Inc., Hackensack, NJ, email correspondence [Online].

List of Tables

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

Material	CTE (ppm/ºC)	Source
Kapton®	17 (30-100ºC)	Datasheet [30]
FR4	11-15 (in plane)	Datasheet [31]
CB028	~30 (30-75ºC)	Measured
Nylon (LAPS)	170 (30-165ºC)	Measured
MB epoxy	45-50 (@T_{room})	Personal communication [32]

Table 2. Change in Electrical Resistance during LAPS processing

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

Table 3. Change in Electrical Resistance when subjected to harsh environmental temperatures

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

[a]OC = open circuit created during testing

Table 4. Change in Electrical Resistance due to mechanical shock

Device Type	# of Samples	Orientation	ΔR after testing (mΩ)	ΔR (%)
DW epoxy -Kapton®	3	Shear	0 ± 8	0.0 ± 0.5
DW epoxy -Kapton®	3	Normal	-7 ± 26	-0.5 ± 2.1
DW epoxy -FR4	4	Shear	-5 ± 5	0.6 ± 0.6
DW epoxy -FR4	4	Normal	-20 ± 36	-0.5 ± 0.8
LAPS Nylon-FR4	4	Shear	0 ± 8	0.3 ± 1.5
LAPS Nylon-FR4	4	Normal	183 ± 98[a]	73 ± 30

List of Figures

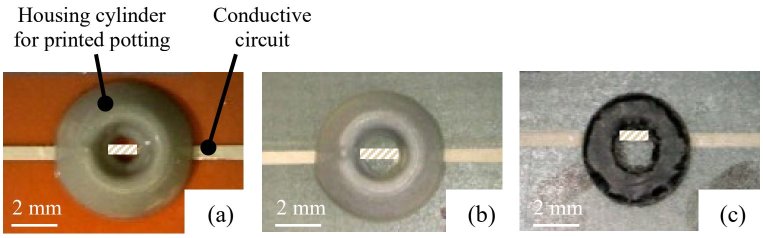

Figure 1. CB028 circuits and uncapped packaging cylinders: (a) DW Master Bond epoxy on Kapton®, (b) DW Master Bond epoxy on FR4, and (c) LAPS Nylon 12 on FR4. Note the conductive circuit is highlighted in the middle of the cylinder that connects the circuit underneath the cylinder. It is highlighted to increase the visibility of the conductive trace, otherwise it would be difficult to visualize with the current scale.

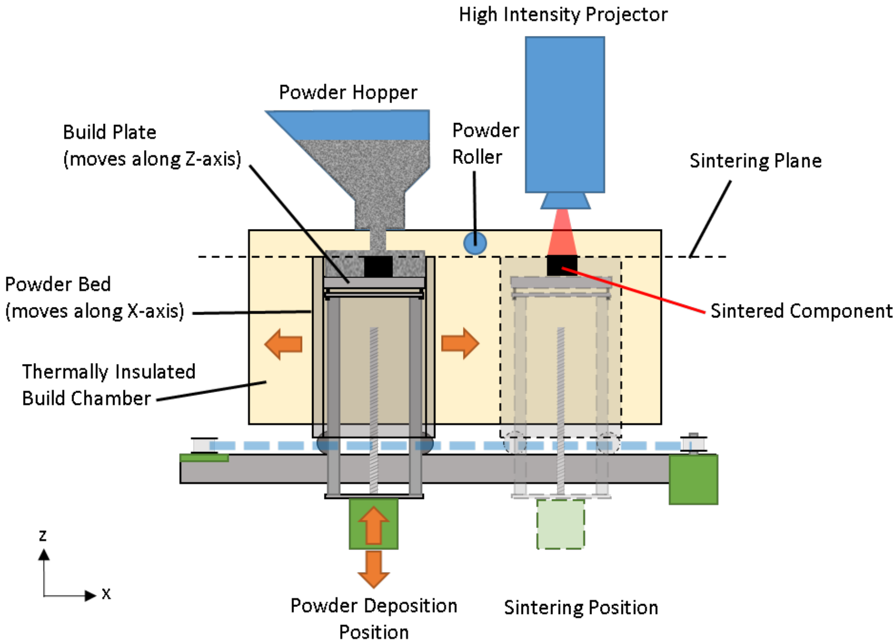

Figure 2. Large Area Projection Sintering (LAPS) system which fuses entire 2D cross sections with a single quick exposure. A powder hopper then deposits powder before a counter rotating roller levels a new uniform layer for sintering. The thermal camera which monitors the process is not shown here for clarity. [25]

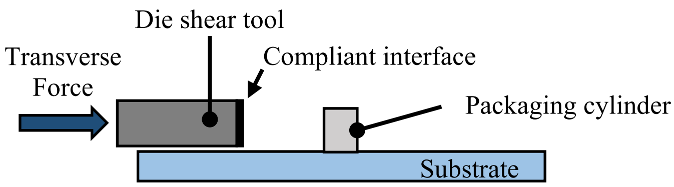

Figure 3. Die shear test schematic.

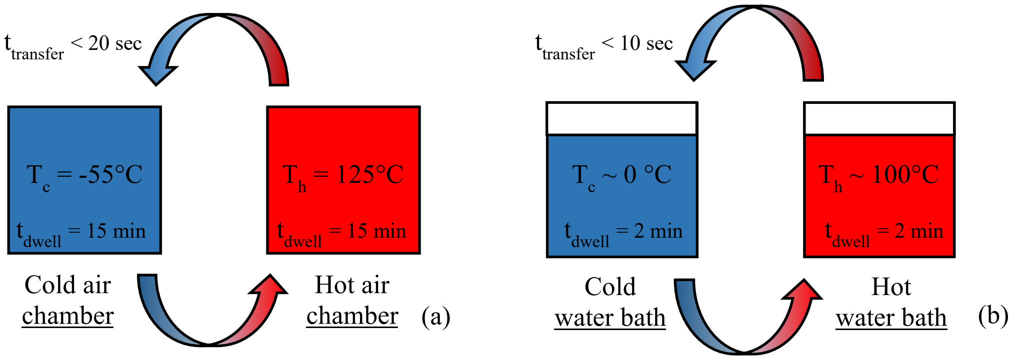

Figure 4. (a) Temperature cycling between cold and hot air chambers of MIL STD 883K 1010.9 B and (b) thermal shock testing between cold and hot water baths of MIL STD 883K 1011.9 A.

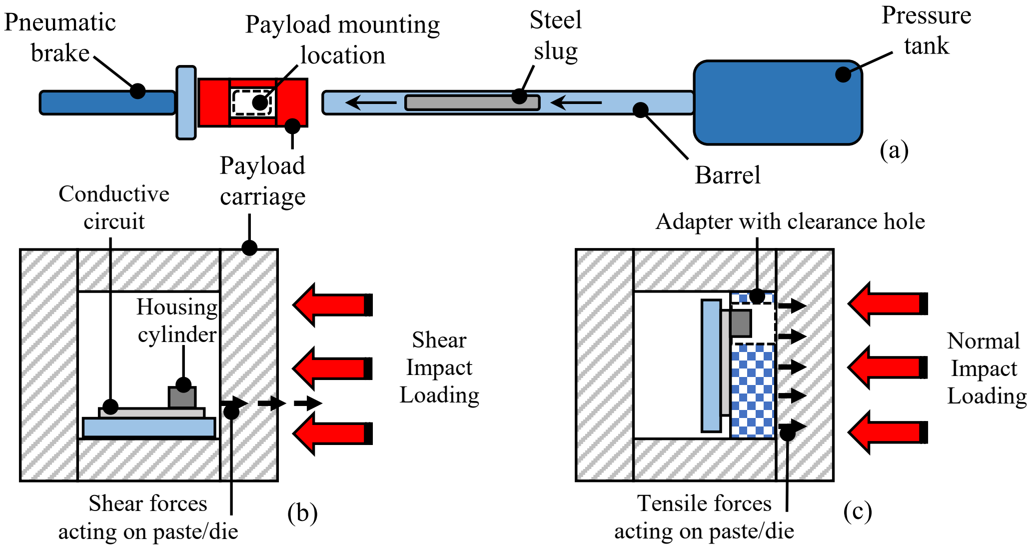

Figure 5. (a) Schematic of the pneumatic cannon, (b) shear forces acting when payload is oriented for shear, and (c) tensile forces acting when payload is oriented normal. Note: the packaging cylinder, conductive paste, and payload carriage labeled in (b) are the same in (c).

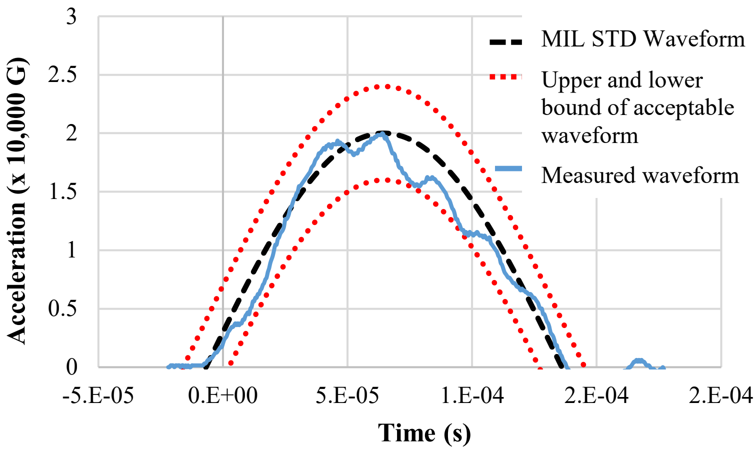

Figure 6. MIL STD 883K 2002.5 F Mechanical Shock acceleration pulse (20,000 G's with a pulse duration of 0.2 ± 0.1 ms) with upper and lower bounds of specified ±20%. The measured waveform is representative of the 20,400 ± 500 G's with a pulse duration of 0.14 ± 0.005 ms averaged from mechanical shock testing.

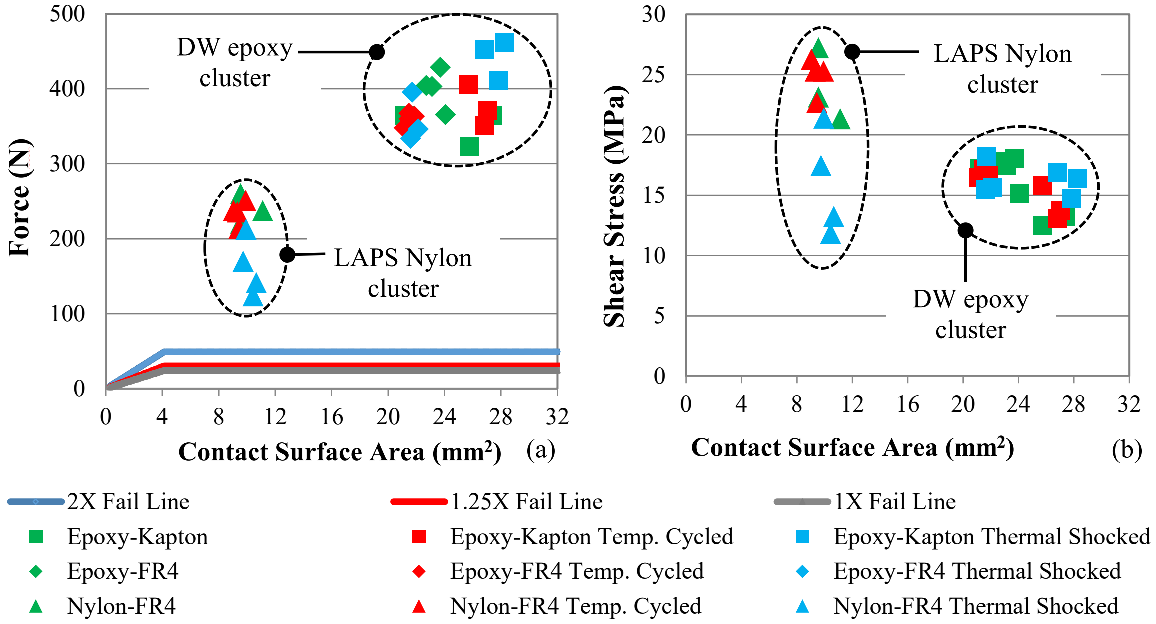

Figure 7. (a) MIL STD 883K die shear failure criteria and (b) Die shear strength vs. contact surface area for device packaging cylinders. DW Master Bond epoxy packaging cylinders show little variation due to the environmental exposures, but LAPS Nylon samples are weakened by the thermal shock. Note: the 2X, 1.25X, and 1X fail lines are specified by the MIL STD to indicate failure. When above the fail lines, the die shear strength is adequate for electronics packaging according to the MIL STD. The plots are presented in SI units to be consistent throughout this manuscript even though the MIL STD specifies the failure criteria in imperial units.