Presented here is a redacted report generated for aerospace qualification of polySpectra's COR Alpha 10 resin. Since then, there have been several changes to the resin formulation and the currently available resin is polySpectra COR Alpha 20. The general performance of the new resin should be close to that reported herein and the observed trends should also be maintained.

Executive Summary

polySpectra is an advanced materials company that makes additive manufacturing (AM) polymers for challenging applications where current additive solutions are not effective. polySpectra has developed a new family of photopolymers, termed Cyclic Olefin Resin (COR). COR Alpha is our first product line of materials that demonstrate a unique combination of high toughness, impact resistance, chemical tolerance and temperature resistance competitive with molded engineering polymers.

COR materials can enable challenging applications in a wide variety of industrial and consumer sectors because they are derived from a fundamentally new class of chemistry for AM and therefore have the potential to solve or mitigate the typical weaknesses of both additive resins and additive polymer parts more generally.

This project's purpose was to understand the benefits and current applicability of a printed COR Alpha 10 material to aerospace and defense applications. Using widely accepted standardized tests, this report summarizes a baseline for our COR Alpha 10 material performance and highlights both benefits and areas for improvement to help direct ongoing resin development. An expert third-party assessment of this report is included in the project to provide an objective view of the results within the context of aerospace applications.

Description of the Current Product

The Current Product is an array of additively manufactured (AM) parts using polySpectra's rugged COR Alpha 10 product. Currently these parts are being printed and processed in polySpectra facilities and then shipped to customers for testing, qualification, and end use. We are building out our capacity to process larger numbers of parts for situations where outsourcing printed parts is feasible. For situations where customers need to print at their own site, the next offering from polySpectra will be a turnkey and complete on-site customer solution that packages materials, 3D printing, post-processing, training, and customer support. For this on-site solution, polySpectra will supply the materials, and we have partnered with a number of leading additive manufacturing printer suppliers to deliver the qualified hardware and software needed for customers to build the desired parts.

The key feature that makes polySpectra's COR materials tougher and more temperature resistant than any other light-activated resin for AM arises from the inherent properties of their fundamental chemical structure. polySpectra's chemistry platform is enabled by a history of chemical innovation in olefin metathesis starting with the Nobel Prize-winning research of Dr. Robert Grubbs at Caltech, and specifically built on a discovery in Dr. Grubbs' lab by polySpectra's founder and CEO, Dr. Raymond Weitekamp. This patented and published discovery enables 3D printable resins that make polymer components capable of production-grade properties.

Our current manufacturing process is similar to any resin printing process for end-use parts. First, liquid resin is brought into a 3D printer. We use Digital Light Processing (DLP) printers for our current product which are based on the proven stereolithography (SLA) printing that started the AM industry. Second, the 3D printer prints by curing thin layers of liquid resin into solid via UV light, building layer on layer to produce the complete part. Printed parts are then removed from the printer and cleaned with a solvent to remove excess resin. Next, cleaned parts are post-cured in an industrial oven for less than 2 hours to reach full properties. If needed, the parts are finished for the application and then are ready to be used. Typically, we expect this entire process to take less than 12 hours.

Description of Tests

The following are families of tests we have had performed that give a baseline for our COR Alpha 10 material. We also include in this report a table describing each specific test using the corresponding numbering system below.

Within the current product results shown here, there is plenty of room to optimize for specific behavior. For example, we currently do not use performance-enhancing additives for aging, UV protection, reduced flammability, or fillers like glass fiber for stiffness and enhanced temperature resistance. Adding components like these is a clear path to making improvements as needed for specific applications.

Families of tests:

1.01 – Tensile testing at range of temperatures.

> Significant performance maintained across temperatures.

1.02 – Impact strength testing at a range of temperatures.

> Most of COR Alpha's impressive impact performance was retained throughout the extreme temperatures tested, maintaining more than 80% of impact strength even at -53.9 C (-65 F).

1.03 - Compression

> Compression strength is roughly three times higher than tensile.

1.04 - Coefficient of thermal expansion (CTE)

> Expected results for this type of material and exhibits virtually linear expansion across a wide range of temperatures.

1.05 – Flammability

> With no added flame retardants, flammability results were poor as expected. As with many plastics, this can be solved with appropriate additives for applications where flammability is a key concern.

1.06 - Water absorption

> Very low water absorption. For comparison, Alpha absorbs significantly less than molded PEEK.

1.07 - Chemical compatibility

> Good resistance to water, sea water, and chemicals tested--resistance that the COR chemistry is known for.

1.08 - Accelerated weathering (UV)

Similar results to other aging-related tests: strength and modulus are relatively unaffected though elongation and impact is decreased. This can be solved with additives that resist the aging and weathering process, none of which have been included in this baseline resin.

1.09 – Thermal aging.

Similar results to other aging-related tests. Results can be significantly improved with additives.

1.10 – Dielectric

COR Alpha acts as an impressive dielectric, with a low dielectric constant around 2.5 and a low dissipation factor at low frequencies.

1.11 – Hardness

COR Alpha is a hard plastic which helps resist damage.

1.12 – Flexural

Flexural strength is roughly three times higher than tensile.

1.13 – Heat deflection temperature

COR Alpha demonstrates a unique combination of high temperature performance and high impact strength for additive manufacturing.

1.14 – Outgassing.

COR Alpha Meets NASA requirements for a low-outgassing material for on-orbit or vacuum testing use.

1.15 – Ionizing radiation exposure.

Similar results to other aging-related tests. Results can be significantly improved with additives.

1.16 – Shear

Shear strength results on par with tensile.

1.17 - Bearing

Bearing strength is roughly four times higher than tensile.

Test Results

Key results are summarized in plots below. Full results of the test plan are summarized in the table below.

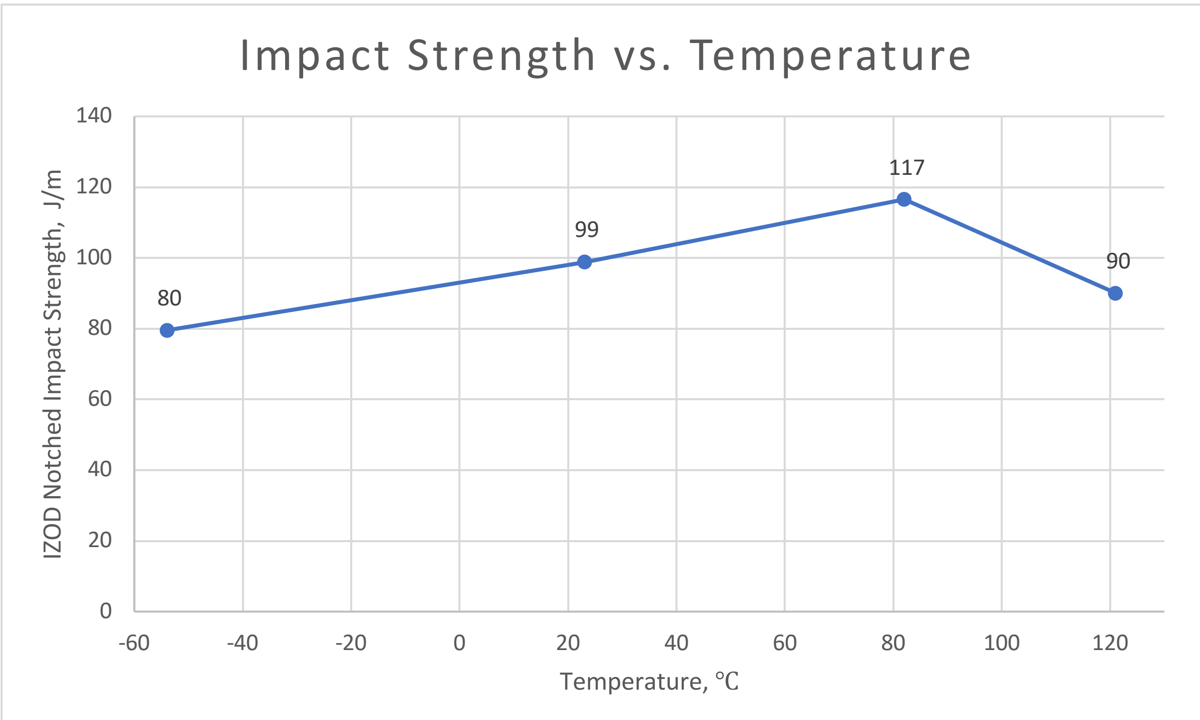

Figure 1. Most of COR Alpha's impressive impact performance was retained throughout the extreme temperatures tested, maintaining more than 80% of impact strength even at -53.9 C (-65 F).

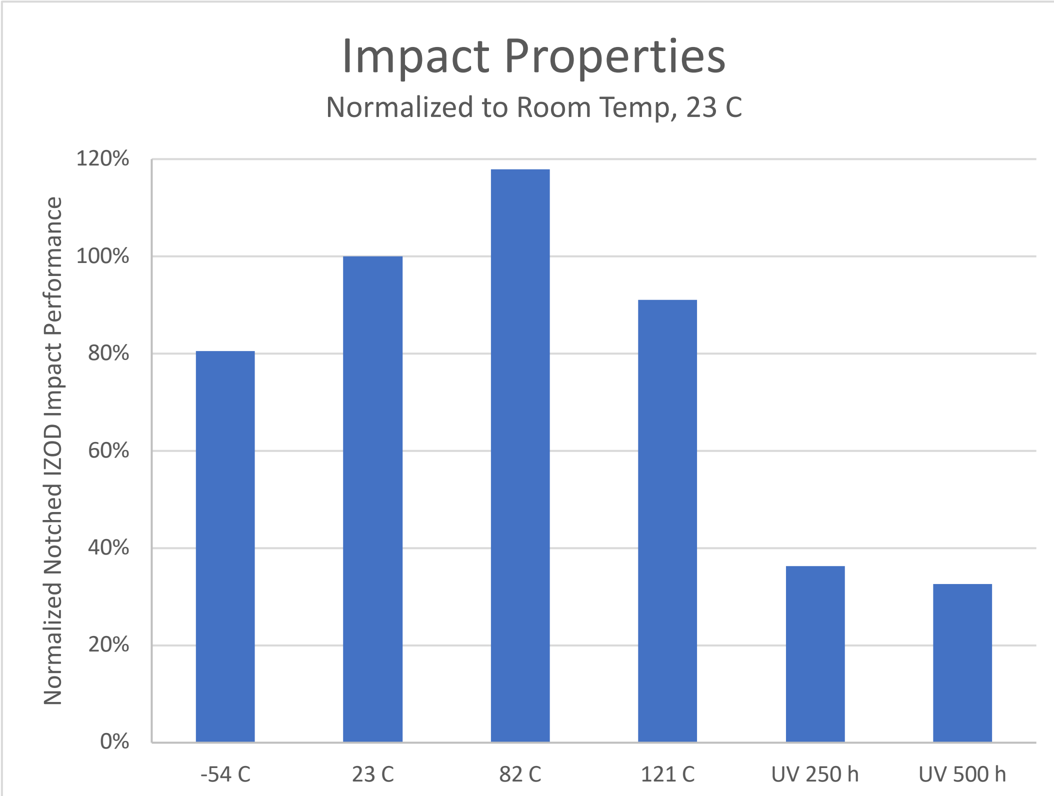

Figure 2. As in Figure 1, high impact strength is retained across temperatures. UV stability of printed COR parts can be improved to match as-printed properties with additives.

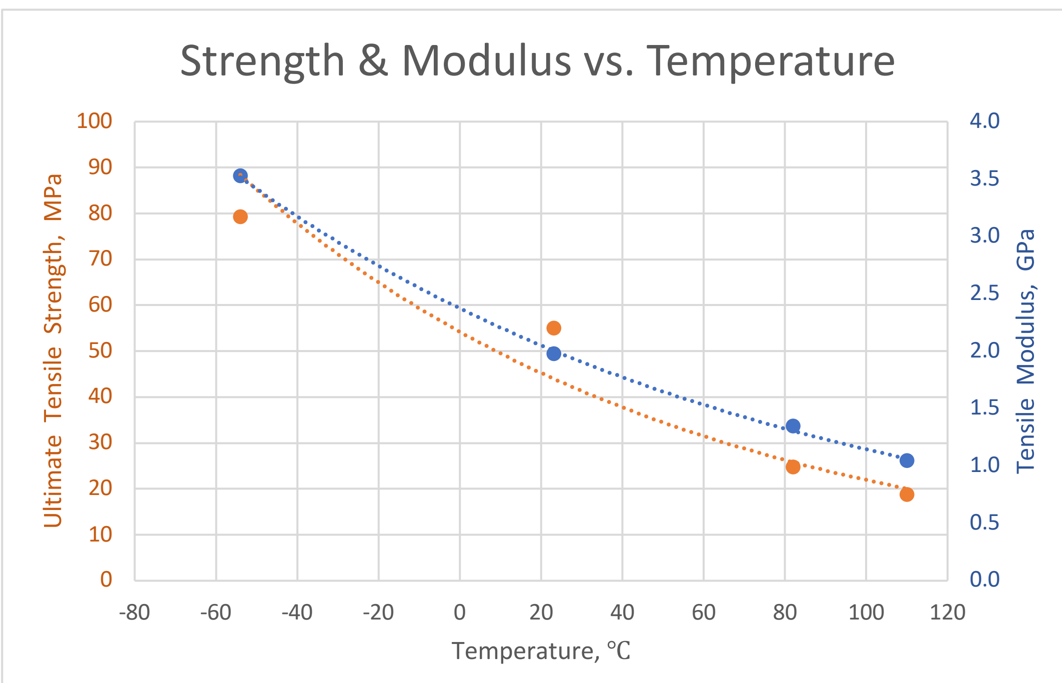

Figure 3. Significant properties are retained across a wide range of continuous temperatures. If needed, this performance can be further improved with additives such as fiber fills.

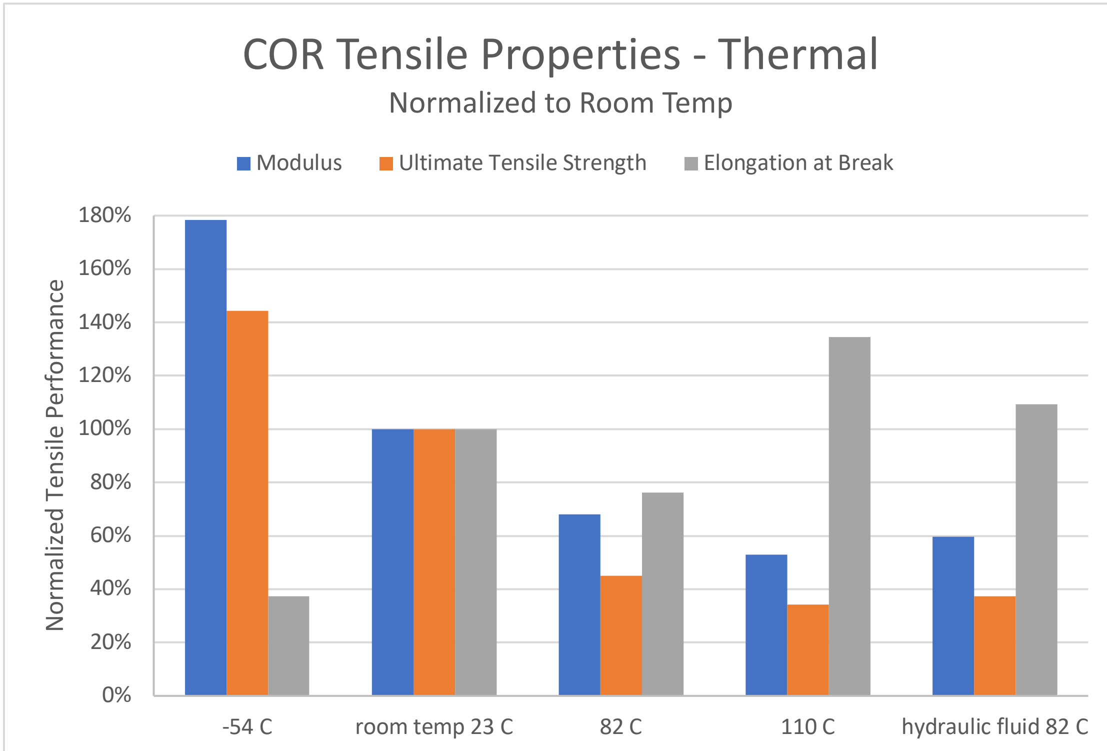

Figure 4. Another way to visualize thermal COR Alpha performance as normalized to room temperature properties.

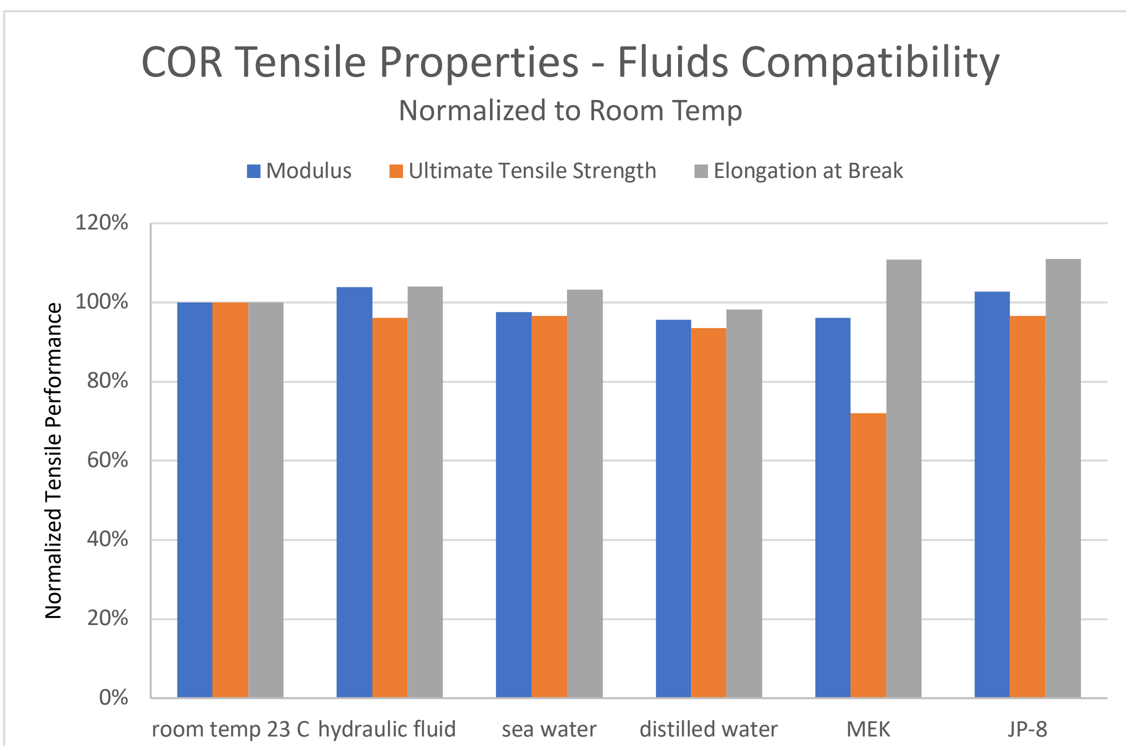

Figure 5. COR Alpha performs well with the tested fluids with the only significant performance difference being a UTS of about 75% of baseline in MEK exposure.

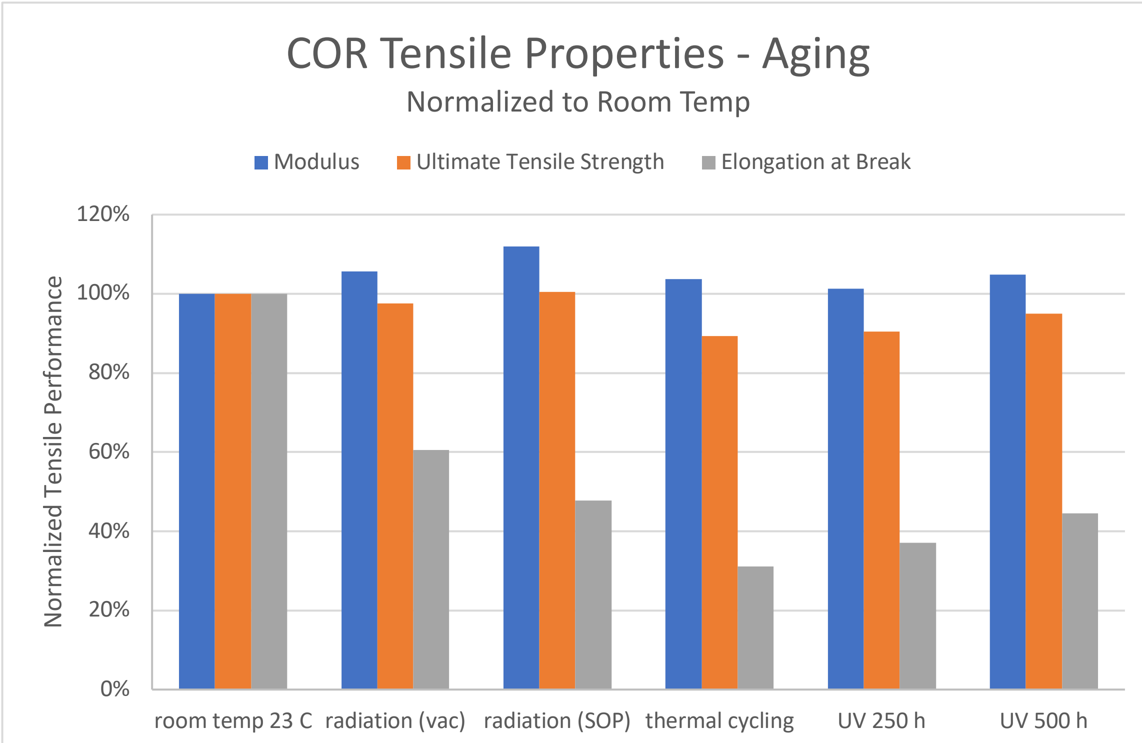

Figure 6. Various kinds of aging and cycling including ionizing and UV radiation exposure. For all tests, modulus and strength were relatively maintained, while elongation suffered. Additives can improve the elongation performance for final part use.

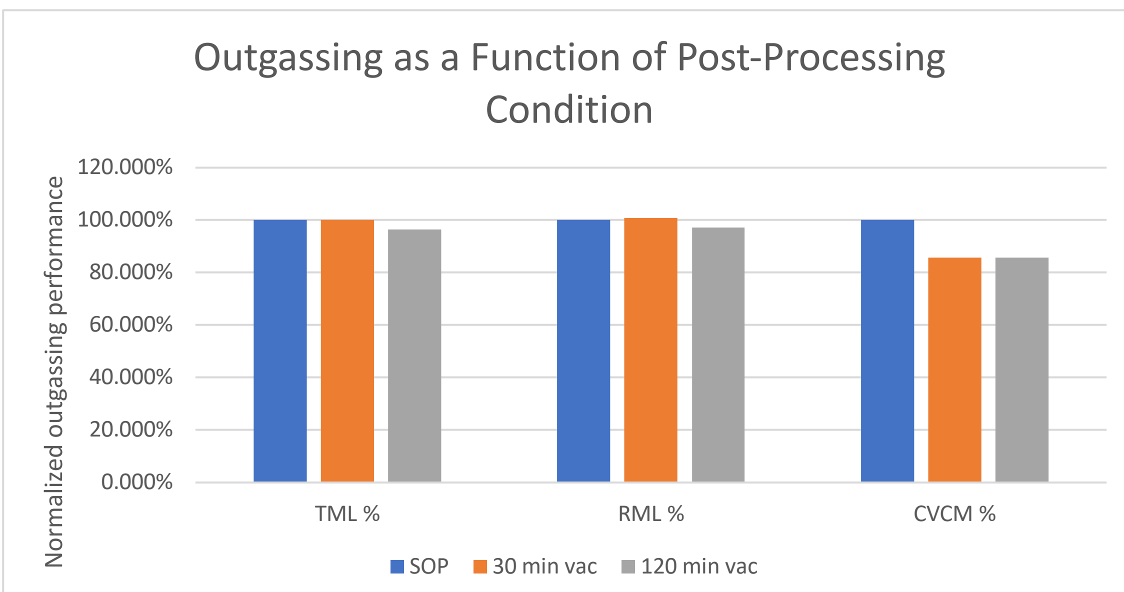

Figure 7. % Total Mass Loss (TML), % Recovered Mass Loss (RML), and % Collected Volatile Condensable Material (CVCM) for samples processed with the standard post-printing procedure (SOP), SOP +30 min vacuum bake, and SOP +120 min vacuum bake. These results show that there is little impact on mass loss from the addition of a vacuum bake step and a small decrease in CVCM for both samples that were processed with a vacuum bake step. All of the conditions fell within the "low outgassing" limits of RML < 1.00% and CVCM <0.1%. The 30 minute vacuum bake process was chosen for the other samples in this work program, except where otherwise noted.

ID #	Description	Specifications	Procedure	Result 1 +/- one std dev	Result 2 +/- one std dev	Result 3 +/- one std dev
1.01.0	Tensile properties	-	ASTM D638	Young's Modulus (E): 1.97 +/- 0.05 GPa	Ultimate Tensile Strength (UTS): 55 +/- 1 MPa	Elongation at break (EAB): 10.9% +/- 1.3%
1.01.1	Tensile properties at elevated temperature	Temp 110 C (230 F)	ASTM D638	E: 1.05 +/- 0.12 GPa	UTS: 19 +/- 2 MPa	EAB: 14.6% +/- 5.6%
1.01.2	Tensile properties at low temperatures	Temp -53.9 C (-65 F)	ASTM D638	E: 3.52 +/- 0.79 GPa	UTS: 79 +/- 12 MPa	EAB: 4.0% +/- 0.9%
1.01.3	Tensile properties at elevated temperature	Temp 82.2 C (180 F)	ASTM D638	E: 1.35 +/- 0.20 GPa	UTS: 25 +/- 8 MPa	EAB: 8.3% +/- 2.4%
1.02.0	Izod notched impact	-	ASTM D256	Impact Strength: 99 +/- 27 J/m		
1.02.1	Izod notched impact at elevated temperature	Temp 121.1 C (250 F)	ASTM D256	Impact Strength: 90 +/- 14 J/m		
1.02.2	Izod notched impact at low temperatures	Temp -53.9 C (-65 F)	ASTM D256	Impact Strength: 80 +/- 18 J/m		
1.02.3	Izod notched impact at elevated temperature	Temp 82.2 C (180 F)	ASTM D256	Impact Strength: 117 +/- 20 J/m		
1.02.4	Izod un-notched impact	-	ASTM D4812	Impact Strength: 1027 +/- 454 J/m		
1.03.0	Compression	-	ASTM D695	Modulus: 1.78 +/- 0.02 MPa	Peak strength: 155 +/- 32 MPa	
1.04.0	Coefficient of thermal expansion	Temp range - 53.9 C - 121.1 C (-65 F - 250 F)	ASTM E831	Linear Coefficient of Thermal Expansion (ppm/C): 105 +/- 3 C		

1.05.0	Flammability (UL94 V), ambient conditioning	-	UL94	Does not meet requirements for UL 94		
1.05.1	Flammability (UL94 HB), ambient conditioning	-	UL94	Does not meet requirements for UL 94		
1.06.0	24 hour water absorption	-	ASTM D570	Percent water absorption by weight: 0.079%		
1.06.1	Water absorption - longer duration	-	ASTM D570	Percent water absorption at saturation: 0.191%		
1.07.0	Chemical compatibility	Hydraulic fluid MIL-PRF 83282 (ambient) Practice A, Procedure II 168 hr, immersion, no strain	ASTM D543	E: 2.05 +/- 0.09 GPa	UTS: 53 +/- 1 MPa	EAB: 11.3% +/- 0.9%
1.07.1	Chemical compatibility	Hydraulic fluid MIL-PRF 83282 (at 82.2 C (180 F)) Practice A, Procedure II 168 hr, immersion, no strain	ASTM D543	E: 1.18 +/- 0.22 GPa	UTS: 21 +/- 6 MPa	EAB: 11.8% +/- 5.0%
1.07.2	Chemical compatibility	Seawater Practice A, Procedure II 168 hr, immersion, no strain	ASTM D543	E: 1.93 +/- 0.06 GPa	UTS: 53 +/- 1 MPa	EAB: 11.2% +/- 2.0%
1.07.3	Chemical compatibility	Distilled water Practice A, Procedure II 168 hr, immersion, no strain	ASTM D543	E: 1.89 +/- 0.09 GPa	UTS: 51 +/- 1 MPa	EAB: 10.6% +/- 2.1%
1.07.4	Chemical compatibility	MEK washing fluid Practice A, Procedure II	ASTM D543 (ASTM D740?)	E: 1.90 +/- 0.09 GPa	UTS: 40 +/- 2 MPa	EAB: 12.0% +/- 0.2%

		168 hr, immersion, no strain				
1.07.5	Chemical compatibility	JP8 jet fuel Practice A, Procedure II 168 hr, immersion, no strain	ASTM D543 (ASTM D740?)	E: 2.03 +/- 0.1 GPa	UTS: 53 +/- 1 MPa	EAB: 12.0% +/- 0.1
01.08.0	Accelerated weathering - 250 hr midread	QUV light source Cycle I, 250 hr	ASTM G154	E: 2.00 +/- 0.08 GPa	UTS: 50 +/- 3 MPa	EAB: 4.0% +/- 0.7%
1.08.1	Accelerated weathering - 500 hr full test	QUV light source Cycle I, 500 hr	ASTM G154	E: 2.07 +/- 0.13 GPa	UTS: 52 +/- 1 MPa	EAB: 4.8% +/- 0.9%
1.08.2	Accelerated weathering - 250 hr midread	QUV light source Cycle I, 250 hr	ASTM G154	Impact Strength: 36 +/- 2 J/m		
1.08.3	Accelerated weathering - 500 hr full test	QUV light source Cycle I, 500 hr	ASTM G154	Impact Strength: 32 +/- 1 J/m		
1.09.0	Aging via thermal cycling	Temp range: - 53.9 C - 121.1 C (-65 F to 250 F) 13.9-16.7 C/min (25-30 F/min) ramp rate with 15 min hold at temperature extremes 100 cycles	MIL-STD-810G	E: 2.05 +/- 0.03 GPa	UTS: 49 +/- 1 MPa	EAB: 3.4 +/- 0.2%
1.10.0	Dielectric constant and dissipation factor - high-frequency	1 MHz	ASTM D150	Dielectric constant: 2.66 +/- 0.03	Dissipation Factor: 0.0058 +/- 0.0004	
1.10.1	Dielectric constant and dissipation factor - low-frequency	1 kHz	ASTM D150	Dielectric constant: 2.81 +/- 0.03	Dissipation Factor: 0.03 +/- 0.000	
1.11.0	Shore hardness	-	ASTM D2240	Shore D Hardness: 84 +/- 2		
1.12.0	Flexural properties	-	ASTM D790	Flexural modulus: 2.99 +/- 0.24 GPa	Peak strength: 153 +/- 11 MPa	

1.13.0	Heat deflection temperature	Method A (1.82 MPa)	ASTM D648	140 +/- 3 C		
1.14.0	Outgassing	pS SOP	ASTM E595	Collected Volatile Condensable Material (CVCM): 0.005%	Total Mass Loss (TML): 0.723%	Recovered Mass Loss (RML): 0.623%
1.14.2	Outgassing	pS Procedure 3 - +30 min vac	ASTM E595	CVCM: 0.004%	TML: 0.725%	RML: 0.628%
1.14.3	Outgassing	pS Procedure 4 - +120 min vac	ASTM E595	CVCM: 0.004%	TML: 0.698%	RML: 0.606%
1.15.0	Effects of ionizing radiation	10Mrad at 1.8Mrad/h with steps of 0, 4.5, 7.5, and 10 Mrad pS Procedure 3 - +30 min vac	IEC 60544-2	E: 2.09 +/- 0.10 GPa	UTS: 54 +/- 1 MPa	EAB: 6.6% +/- 0.6%
1.15.1	Effects of ionizing radiation	10Mrad at 1.8Mrad/h with steps of 0, 4.5, 7.5, and 10 Mrad pS SOP	IEC 60544-2	E: 2.21 +/- 0.07 GPa	UTS: 55 +/- 1 MPa	EAB: 5.2% +/- 0.6%
1.16.0	Shear	-	ASTM D732	Shear strength: 59.5 +/- 2.2 MPa		
1.17.0	Bearing	Procedure A (tensile)	ASTM D953	Bearing strength: 198.9 +/- 7.4 MPa		

Third-party Assessment

The following is a third-party assessment by the *The Barnes Group* on COR materials' near-term applicability to the aerospace sector and relevant likely applications.

THE BARNES GROUP
ADVISORS

6 November 2019

Michele Guide
Product Development Director
PolySpectra, Inc.
626 Bancroft Way
Berkeley, CA 94710

Dear Michele,

The data generated under this test program confirms that COR Alpha 10 has very compelling material properties relevant to incumbent Additively Manufactured (AM) material systems.

Stereolithography (SLA) or Vat Photopolymerization is the oldest additive manufacturing (AM) technology, but the process has found limited application for end-use components due to poor mechanical performance. Legacy photo-curable polymer systems were characterized by low toughness and were most commonly used for specialty applications requiring high accuracy and smooth surface finish. By comparison, Material Extrusion (ME), originally known as FDM, and Powder Bed Fusion (PBF), originally SLS, could produce tough, durable parts that were suitable for flight hardware. As a result, the earliest aerospace implementation of AM made use of flame-resistant Nylons produced via PBF. Material Extrusion has also been widely implemented using durable thermoplastics like ULTEM™ Polyetherimide (PEI).

These two material systems are especially relevant because the America Makes organization recently released design databases for Nylon 12 produced by PBF as well as ULTEM™ 9085 produced by ME. AM adoption has been limited to large design organizations that can afford very expensive testing campaigns to produce design values with a statistical basis. Now that this data is available, COR Alpha 10 would need to show a significant performance advantage over these materials to justify adoption by an existing user or program.

In the hierarchy of materials available across the polymer AM processes, COR Alpha 10 exhibits strength and stiffness comparable to legacy AM materials, but appears to possess exceptionally high toughness as shown by the Izod impact testing results. The impact energies measured during testing are comparable to injection molded PEEK and are well in excess of values reported for ME PEI and PBF PA12. The material response to solvent and environmental exposure is fairly typical, and doesn't appear to preclude it from any of the current applications of polymer AM. Likewise, the material retains reasonable ductility at low temperatures and useful strength at 250F.

THE BARNES GROUP ADVISORS
526 COCHRAN ST | SEWICKLEY, PA 15143

COR Alpha 10 represents a general improvement in performance that could replace many Nylon 11 and 12 material variants produced with the PBF process. The test data collected shows that relative to unfilled or typical Flame Resistant (FR) grades of Nylon 11 and 12, COR Alpha 10 exhibits superior mechanical properties in nearly every property, especially toughness, while potentially increasing the range of application due to a higher maximum service temperature. Compared to ME PEI (ULTEM™ 9085), COR Alpha 10 represents a slight reduction in strength and stiffness in exchange for approximately 2-3x higher toughness. In addition to the mechanical property improvements, there are likely additional parts that could be converted to AM based on the typical benefits of the Vat Photopolymerization process relative to PBF and ME, specifically, mechanical isotropy, improved surface finish and higher dimensional accuracy.

PBF processes typically suffer from relatively expensive hardware, and limited material recyclability. ME processes are often limited by the cost of building (and subsequently removing) support structures during printing. As VP processes typically don't face these limitations, COR Alpha 10 may also provide a lower unit cost for many printed parts, further increasing potential applicability.

Although there are many parts on unmanned platforms that could see performance benefits from adopting COR Alpha 10, additional applications in commercial and military aircraft would be possible with additives to improve flame resistance or to provide electrical conductivity for ESD applications. The toughness of this material system is well suited for a variety of micro to medium sized UAVs, but widespread adoption in this class of vehicles may require development of UV inhibitors or a standard surface treatment recommendation for exterior service. Further improvements in mechanical performance (tensile strength and stiffness) from glass or carbon fiber reinforcement while maintaining toughness could further increase COR Alpha's value proposition.

Aerospace application of polymer AM has been applied in two main areas. Initially, the primary application was producing non-critical structures on larger aircraft using AM as a cost avoidance to eliminate labor-intensive parts like formed and welded environmental control system ducts. The second application matured as smaller airframes for Unmanned Aerial Vehicles (UAVs) or single-use airframes became more pervasive. In this space, polymer AM has been used to design very efficient, unitized, multifunctional structures to save cost (relative to traditional composites) and to reduce weight (by eliminating joints, optimizing geometry). The aerospace industry has long sought to use AM technology to create durable parts with predictable and isotropic mechanical properties with no tooling investment. Incumbent polymer AM systems still suffer from relatively high costs, poor surface finishes, and anisotropic mechanical properties. This test data suggests that COR Alpha and the VP process can provide a significant improvement over these incumbent systems for many applications.

Sincerely,

Christopher Aldridge
Senior Advisor