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TR2022-104 September 17, 2022

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Solid Freeform Fabrication Symposium 2022

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ON-ORBIT FABRICATION OF SPACECRAFT STRUCTURES BY DIRECT SOLAR PHOTOPOLYMERIZATION

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June 2022

Abstract

One of the paradoxes of spacecraft design is that spacecraft are destined to operate in orbit where maneuvering thruster firings produce stresses below 0.01 G, but the spacecraft must be strong enough (and heavy enough) to survive the roughly 10 G's of linear acceleration and 50 G's of vibration in a rocket launch. In this paper, we develop and test an alternative: the post-launch freeform additive manufacture of a major communications satellite structural element in UV cured resin, using solar UV to trigger polymerization. This involves consideration of the chemistry of a UV cured liquid resin that not only has a very low (below our chamber limit of 0.2 kPa) vapor pressure post-degassing, but also is not dependent on oxygen presence to activate the thermal inhibitors that prevent premature polymerization. In tests, we successfully freeform 3D printed a small (60 mm) parabolic dish at chamber limit pressure using simulated solar UV flooding the chamber.

1 Introduction and Background

Since Sputnik 1 in 1957, spacecraft have been built in a very specific sequence: design, make parts, assemble the parts, test the assembly, launch, and (assuming all goes well) fly the mission. Unfortunately, this sequence implies that the assembled spacecraft be drastically overbuilt in order to survive launching. For example, NASA Goddard's prelaunch test procedure requires the assembled spacecraft survive a launch stress test of 10 G's (10 times earth gravitational acceleration) of linear acceleration and 50 G's of broadband vibration [1]. In comparison, a smallish satellite such as a Starlink unit, in orbit-raising mode, accelerates with around 100 micro-G's of acceleration¹.

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¹SpaceX does not publish their thruster data, but the spacecraft mass, the time to raise orbit and the orbital altitudes are available and so the overall acceleration may be inferred

This huge discrepancy between launch acceleration and orbital maneuvering acceleration is on the order of 1000 times. Even the comparatively large Space Shuttle OMS engines (burning monomethylhydrazine and dinitrogen tetroxide yielding 27 kN thrust per OMS x 2 OMS pods) pushing the 110,000 kg orbiter only generated 0.05 G's of acceleration at full throttle. Considering these huge discrepancies, it seems appropriate to consider other alternatives than overbuilding spacecraft structures to survive a 10-G / 50-G launch phase.

Concomitant with the launch stress issues is the desirability to create structures in orbit that are larger than the payload shroud of the launch vehicle. Most often, this is done by folding the structure along a few hinge lines [2, 3] or by spring deployment, such as Voyager 1 and 2 using a spring loaded mast 13 meters tall that compressed into a 0.66m tall canister (as stowed for launch) as the platform for the magnetometer instruments. [4].

One of the most common structures on a spacecraft (and one that must maintain it's shape) is the high gain antenna dish. Many spacecraft use a fixed antenna which must be overbuilt to survive the 50 G vibration of launch; for example, the Cassini mission's 4 meter antenna and mount weighed approximately 105 kg. An obvious workaround is a folded antenna that opens like an umbrella, but folded antennas are not without downsides either; the failure of Galileo's antenna is only one example of a folded structure failing to deploy [5, 6].

Folded structures are not the only option; if high precision is not required, it is also possible to use inflatable structures. One of the first communications satellites was ECHO-1, a 30-meter diameter inflatable sphere launched in 1960. Inflatable antenna dishes have seen use as recently as 1996 on the IAE (Inflatable Antenna Experiment), which was part of the SPARTAN-207 ISS experiment package [7, 8].

The upcoming NASA missions OSAM-1 and OSAM-2 are in part motivated by a desire to provide a technology test and demonstration of additive manufacturing on orbit and in vacuum [9–11]. These missions will test manufacturing and assembly with two well-understood technologies - melt-pultrusion of PEEK-carbon fiber composite, and classic fused-filament fabrication of a polyether-imide-polycarbonate blend. Unfortunately, the power required to maintain the printer hot end at the temperatures required for space-grade thermoplastics (< 340 degC for PEEK, 370 to 400 degC for polyetherimide) may limit the use of these technology to situations where several hundred watts of power is available continuously to maintain the extruder temperature even on the dark part of the orbit [12–14].

In this paper, we report continuing progress over our prior report [15], more specifically, success in developing and testing a greatly improved UV-cured liquid resin formulation that successfully prints at our chamber limit pressure of 0.2 kPa (100 kPa is roughly sea-level atmospheric pressure; 0.2 kPa is 1/5000 of sea-level pressure) and may be suitable for use in the environment of space. This new liquid resin enables a new method of on-orbit, outside-the-airlock additive manufacturing, with a goal of avoiding the overbuilding satellite structures. The benefits of this include reducing the vehicle launch weight as well as creating a method to construct large and very large structures in orbit, including structures that greatly exceed the size of the deployed satellite and the size of the launch vehicle payload shroud.

The proposed method even allows the spacecraft to be launched before some parts of the spacecraft are designed, let alone built or assembled. This method employs outside-of-spacecraft 3D freeform fabrication in vacuum, using this new resin and employing solar ultraviolet to supply the necessary energy to trigger the generation of free radicals in the fluid resin, triggering crosslinking and hardening the liquid resin into a tough, heat resistant solid. As there is no FFF hot-end nor any need for a UV source other than the sun, the process is inherently low power (we estimate 10 to 30 watts of power).

For a video visualization of this process, please see <https://youtu.be/MmencoxoSvc>, and for a generalized overview, please see <https://www.youtube.com/watch?v=ebZqaOBZApE>.

2 Requirements For A Space-Rated Additive Manufacturing Resin

The requirements for a liquid resin for on-orbit manufacturing can be stated succinctly: Smells like water; Flows like honey; Sticks like glue; Hardens like rock.

“Smells like water” - a liquid resin to be used in outside-the-airlock environments must have very low volatility, far less than water (which boils at approximately 2.3 kPa at room temperature). This requirement includes any dissolved gases, including dissolved oxygen. Oxygen in particular is problematic, because most additive manufacturing resins use thermal inhibitors that require the presence of oxygen to function. Without an effective thermal inhibitor, the thermodynamically rare event of free radical formation triggering local polymerization causes the resin to begin hardening within a few days of degassing, even in the absence of UV. Similarly, all of the other components - resin, plasticizer, photoinitiator, thermal inhibitor, defoamer, and any other additive must be vacuum compatible to avoid creating a cloud of contaminating vapor in orbit.

For this reason, our candidate liquid resin contains no monomers (single-unit molecules that can chain together to form the hardened resin). Instead, the candidate resin uses only oligomers (medium-length prelinked chains of molecules, the result of partial polymerization). Such molecules are physically very long and heavy, so they have extremely low vapor pressures. Because these molecules do not enter the gas phase, they have essentially no smell.

“Flows like honey” - the liquid resin needs to have a low enough viscosity to flow from the resin tank through the piping, valves, and nozzle of the 3D printer, but high enough to keep the extruded resin in position until cured. Until the resin cures the only thing holding the resin in position is surface tension and viscosity.

“Sticks like glue” - the resin must bond readily to previously deposited and fully hardened layers. This precludes the use of some families of polymers with otherwise excellent characteristics such as silicone adhesives, many of which self-bond to prior fully hardened material poorly.

“Hardens like rock” - the cured resin must be tough and rigid, preferably within a few seconds of exposure to solar UV. Although the completed structure will be used in zero-G, the structure

must be stiff enough to stay in position under the forces of motion during the print phase including the force of the viscous material being extruded from the nozzle. The cured material must also be tough enough and vibrationally “lossy” enough to not succumb to undamped vibrations during stationkeeping, attitude control thruster firing, or beam steering actions. There are many photoinitiators available, thanks to the efforts of chemists to come up with the best possible materials for durable dental filling composites [16]; we have found that one of these - BAPO (bisacylphosphine oxide) - works well for our needs.

3 Resin Recipe

We have developed a good candidate recipe for an on-orbit 3D printing resin. This recipe provides an existence proof that on-orbit, in-vacuum freeform additive manufacturing is possible.

The starting base material is a polyphenyl ether vacuum oil; this functions both as an aid to mixing and as the plasticizer in the final hardened structure. We use Santovac 9, which is a five-ringed polyphenyl ether. The bulky size and nonreactive nature of this molecule serves to separate the long chains and crosslink sites, trading rigidity for toughness and elasticity. We have found that candidate resin formulas with too little (or no) plasticizing agent were very stiff and rigid, but prone to spontaneous cracking from internal stresses and therefore not satisfactory.

Conversely, with too much plasticizing agent (above 40 to 50% by weight), the matrix of crosslinked polymer chains is insufficient to encapsulate and retain the oil molecules, so the surface of the completed structure feels oily to the touch (even after an isopropanol solvent bath) and surface adhesion is poor. Our preferred candidate recipe is 20% by weight vacuum oil, which maintains a dry surface but is also slightly flexible and tough.

Additionally, our candidate resin contains no monomers, as monomers tend to be small molecules with high volatilities even at room pressure and temperature. Instead, our candidate resin uses only urethane acrylate oligomers, which have essentially zero vapor pressure. The downside to this is that the oligomer feedstocks are extremely viscous and difficult to mix without heating, so it is necessary to add the thermal inhibitor as early in the process as feasible to minimize thermal polymerization.

Further, to avoid prematurely “burning through” the thermal inhibitor, the mixing, degassing, and storage of the candidate resin should be carried out in a UV- and blue-light-free environment, similar to a red safelight as used in darkroom photography.

To produce this new resin, a weight of Santovac 9 vacuum oil equal to 20% of the desired final weight of resin is warmed to about 60 degC. With mild stirring to minimize bubble entrainment and gas absorption, about 0.84% by final weight of the photoinitiator and 0.14% by final weight of a thermal inhibitor is added and dissolved. The preferred photoinitiator is BAPO - bis-acylphosphine oxide, which is usually obtained in the form of a solid powder². The preferred thermal inhibitor is

²BAPO is used as the photoinitiator in common dental bluelight-cure filling materials

phenothiazine (PTZ)³, a greenish yellow flake material. A small amount (0.3 % by final weight) of BYK-088 (a long-chain alkane defoamer) is added to the warmed mixture as well and the mixture gently stirred until both the BAPO and PTZ are dissolved.

The mixture and all three oligomers are now warmed to about 100 degC and the oligomers are added with gentle stirring to avoid bubble entrainment, from least viscous to most viscous. The first oligomer added is commercially available as Sartomer CN968 (viscosity 3500 CPS, and with six functional groups⁴), about 50% by final weight. The second oligomer is Sartomer CN991 (viscosity 7000 cps, two functional groups) is added, about 15% by final weight, and with gentle stirring.

The third and final oligomer is Sartomer CN9013 (viscosity 180000 cps, nine functional groups), adding about 15% by final weight, with gentle stirring. The CN9013 is extremely viscous (it is essentially a solid at room temperature) and so some patience is required.

The final step is degassing. With the resin at held at 70 to 100 degC on a hotplate inside a vacuum chamber, the resin is degassed at a pressure lower than 5 kPa for several hours. This removes the vast majority of both dissolved gases and entrained gas bubbles.

After degassing, the resin is ready for use. It is recommended to store the unused resin in brown glass (UV-blocking) containers, and store those containers in an opaque outer container. Samples of this recipe were stored in the dark brown bottles in an office environment at room temperature for over a year without premature hardening. Depending on the 3D printer, it may be useful to degas the resin again after the resin is loaded into the 3D printer reservoir.

4 The Printing Apparatus

The freeform 3D printing apparatus is shown in Figure 1.

The on-orbit 3D printer is intentionally designed to be as lightweight as possible, and to allow reuse of most of the significant parts through the entire lifetime of the spacecraft. The linear telescoping boom and one of the rotary axes would be needed in any case to deploy a prebuilt antenna, so there is no weight penalty associated with linear boom or the tilt rotary axis. The dish axial rotation motor would be used only in antennas with an asymmetrical beam pattern.

Several issues and points bearing special attention should be noted when designing a freeform printer for solar UV curing:

- In direct sunlight, the time-to-cure for the resin can be less than the time for the resin to exit the nozzle and adhere to the partially completed part, causing a failure-to-adhere and eventually a print failure. Rather than under-cure the resin by adding an excess of thermal inhibitor

³Phenothiazine is also the starting chemical for numerous antipsychotic drugs, including Thorazine and Triflurin.

⁴Each functional group is roughly one crosslink bond site

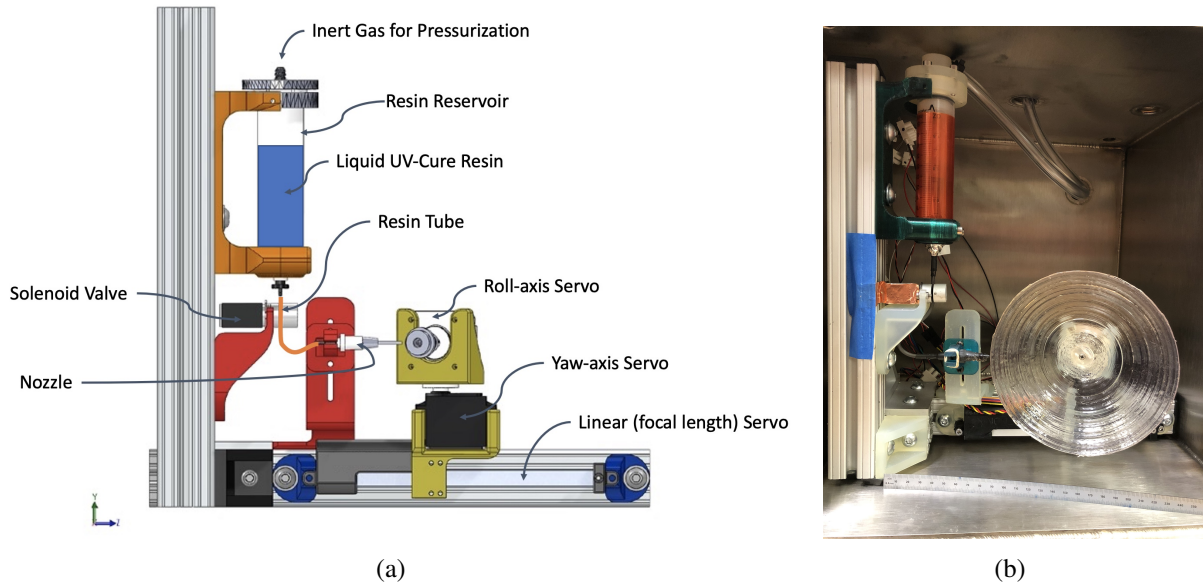


Figure 1: Front view: (a) CAD model, (b) Test article of the freeform 3D UV resin printer, inside the vacuum chamber.

or an insufficient amount of photoinitiator, a simple sunshade to block direct sunlight and allow only a controlled amount of solar UV works well.

- Even though the resin is degassed, the use of a PWM solenoid valve can induce microbubbles. Interestingly, these microbubbles do not expand without limit but are stable at the size where the internal pressure equals the surface tension of the fluid resin surrounding the gas phase. This is because the internal pressure goes down as the bubble's volume expands with a factor of $1/r^3$ while the surface tension of the bubble, acting as a hoop stress (causing compression) is linear with the circumference, so it is possible for a microbubble to be stable inside a fluid in a space-grade vacuum [17].

Intentionally induced (and controlled) foaming can be beneficial to final strength, as the foaming increases the structural cross-section's moment of inertia without increasing the mass of the structure. This may be beneficial in some applications such as on-orbit construction of very large structures. Foaming does increase the surface roughness, so it has a negative impact on the maximum operating frequency of a dish antenna (as discussed below).

- Resin pressurization with a servo-driven ram compressing a conventional syringe, and closing the pressure loop with a MEMS pressure sensor will work, but mechanical hysteresis causes significant variation in resin flow even with closed-loop operation. Resin flow was more uniform when the resin reservoir was pressurized with an external gas. In our 1-G experiments at our 0.2kPa chamber limit, we simply pressurized the headspace of the syringe with about 0.1 bar of overpressure compared to the nozzle, but a zero-G implementation would require a separating membrane or bladder. We have considered but not yet tested the use of a small progressive cavity pump as an alternative. Because the progressive cavity pump is a positive displacement device it would also replace the resin flow control solenoid valve.

5 Fabrication and Testing

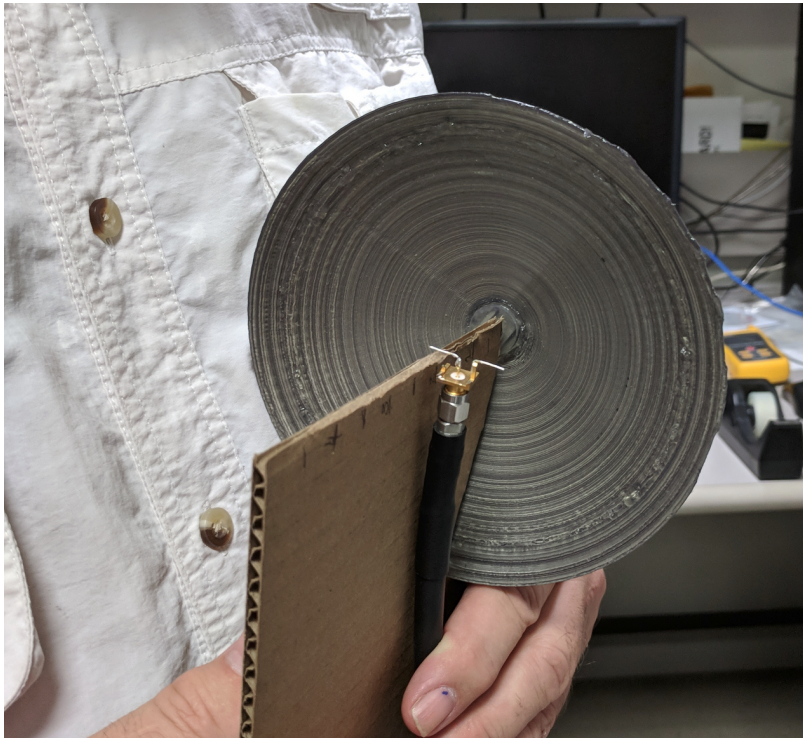
To validate that this resin can produce a structure that would have actual value if produced on-orbit, we fabricated several paraboloid dish antennas and tested the performance of these antennas. Our test paraboloids were fabricated on the freeform apparatus shown in Figure 1. Our UV light source delivered about $5 \text{ mW} / \text{cm}^2$ of 405nm near UV (comparable to the solar near-UV energy in low earth orbit) to the resin disk. The process was intentionally interrupted and shown to be capable of restarting after a pauses of up to 60 minutes with potential of longer intervals if desired. This shows that "forced pauses" due to orbital day/night cycles are not an issue.

After an antenna paraboloid has been 3D-printed and well cured by the solar UV, it must be metallized- that is, coated in a conductive material (preferably a metal) in order to reflect the microwave-band communication signals. Fortunately, being in a space environment makes metallization very easy - a few grams of aluminium, heated with a tungsten filament, will easily boil away into the vacuum of space and plate out on the paraboloid surface. This vacuum aluminization process is well known and used commercially to render potato chip bags opaque and impermeable to oxygen. Metallization does not necessarily require the use of aluminium; lower melting point metals such as potassium, sodium, or calcium will also function in a vacuum environment.

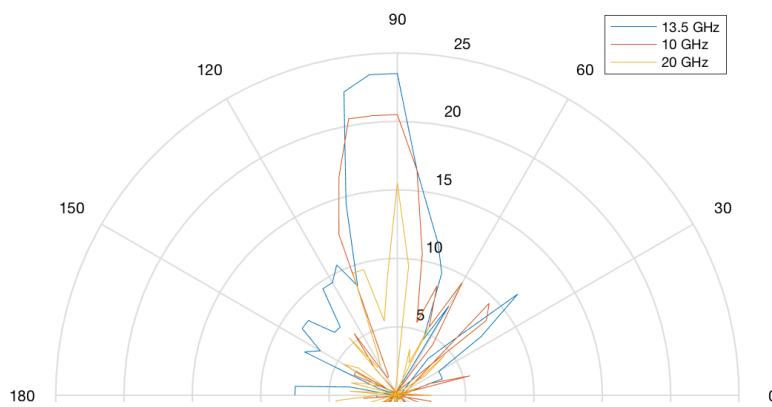
Rather than set up a high-level vacuum chamber for vacuum metallization, we used a commercially available metallization spray (MG SuperShield) to make an analogous metallization effect. Our performance test article was a 165mm parabolic reflector of about $f/1$ focal ratio. printed in air. The test microwave feed antenna and test receive antennas were simple dipoles, resonating at about 10 GHz, and the S-parameters determined with an Agilent N5230A network analyzer. The testing showed that the in-air 3D-printed test article had a gain of 23.5 dB at 13.5 GHz (Ka band).

In radio communication the surface roughness determines the highest usable operating frequency for a dish antenna; typically this is taken to correspond (for wavelength λ) to a maximum surface deviation of $\pm\lambda/4$. Of course, this is not a hard criterion; improvements in surface roughness to better accuracy yield somewhat better beam patterns and selectivity up to the theoretical angular resolution limit (in radians) of a circular aperture of diameter d at $1.22\lambda/d$, beyond this limit, no improvement is possible. We tested both the in-air and in-vacuum dishes for surface roughness and found that the in-air, non-foamed dish had a surface roughness of $\pm 0.25\text{mm}$, corresponding to a maximum operating frequency of 300 GHz. The in-vacuum test article was printed at our vacuum chamber limit pressure of 0.2 kPa (far lower than the pressure on the surface of Mars at nominally 0.6 kPa). This sample was intentionally foamed and so had a much rougher surface, measured to be approximately $\pm 1.0\text{mm}$, thus allowing for a maximum operating frequency of 75 GHz. Clearly these are not optical quality surface finishes, but they are more than adequate for radio and microwave use.

We also carried out a heat exposure resistance test. A cured sample of this resin was subjected to a 400 degC temperature-controlled heat source, creating and maintaining a 10mm diameter molten deposit of rosin-fluxed 60/40 Pb/Sn solder for several minutes. After allowing the test piece to cool, we removed the non-adherent solder blob and flux, and examined the sample under a microscope. We found no trace of any change to the crosslinked resin. There was no charring,



(a)



(b)

Figure 2: (a) The metallized 165mm test article, with the 10GHz dipole at approximately the focal point. (b) The resulting antenna gain plot, for 10, 13.5, and 20 GHz.

dissolution, softening (depolymerization), etching, or other damage detected at all. We therefore surmise that the resin is probably sufficiently heat resistant for orbital use.

6 Discussion and Conclusions

The resin described above serves to eliminate a “big IF” in on-orbit manufacturing, by demonstrating the existence of at least one vacuum-safe UV-set resin. This is an enabling technology, not only for parabolic antennas, but it also enables the on-orbit production of other large and very large structures on-orbit. For example, the structural truss for a very large solar photovoltaic array could be 3D-printed on-orbit and as-needed. As different sequences for the additive manufacturing system can be uploaded post launch, it becomes possible to have significant parts of the spacecraft to be designed *after* the spacecraft launch, such as custom antenna footprints uploaded to an on-orbit spare spacecraft.

Of course, our tests were carried out in 1 G and not at LEO vacuum levels, but at our chamber limit, which is a vacuum three times better than the surface of Mars (nominally about 0.6 kPa). This places the entire concept to at least TRL 4 to possibly 5 on the NASA Technology Readiness Level evaluation scale.

The resin can also serve as a consolidating and structuralizing agent for the construction and shielding of off-Earth shelters and facilities from regolith. In an informal test, the resin and common quartz sand (procured locally) was mixed, in the proportions 10% by weight resin and 90% by weight sand. The composite mixture was consolidated manually and then exposed to our UV light source for several hours. The result was a relatively strong layer of resin/quartz composite approximately 2 to 3 millimeters thick, effectively shielding the interior 4-6 mm of yet-uncured resin-quartz mixture.

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