Metal Part Performance via Electroplated AM Plastic Parts

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What kind of metallic performance is needed?

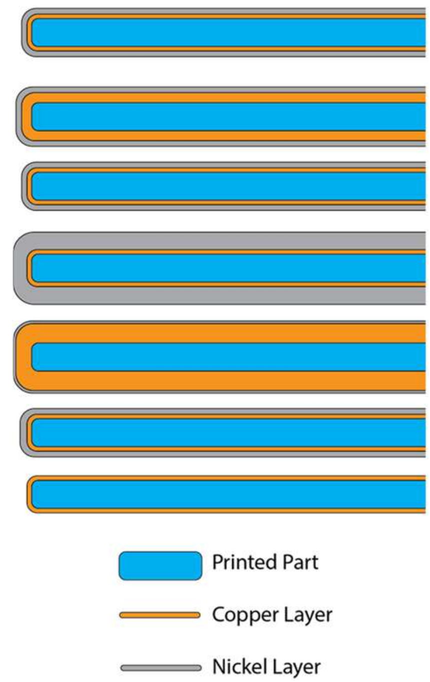
- Electrical conductivity
  - Metal resistivity is up 24 order of magnitude lower than resins or ceramics
- Thermal conductivity
  - Metal thermal conduction is up to 3 orders of magnitude higher than resins
- Metal use temperatures generally higher but range of each is broad
- Strength/Hardness – up to 2 orders of magnitude higher for metals
- Barrier coating
  - Prevent outgassing problems from resins sterile environments
  - Prevent environmental or chemical degradation of printed resins
- Reflectivity of electromagnetic radiation
- Why not just make parts from metal directly?
  - AM metal parts are 5-10x more expensive than resin AM parts, with high capital investment in machinery to make and post process parts

Design of Plating Sequences for Tailored Performance on AM parts

Funcionality vs. coating thickness and volume fraction

EMI	50 µm (nom.)	0.002 in	T
Cosmetic	125-200 µm	0.005-0.008 in	T*
Environmental Barrier	50-100 µm	0.002-0.004 in	T
Structural (Metal V_f)	25-400 µm	0.001-0.016 in	V
Heat conduction (Metal V_f)	25-300 µm	0.001-0.012 in	V
Abrasion resistance	50-75 µm	0.002-0.003 in	T
Electrical	5-100 µm	0.00025-0.004 in	T

(illustration, not to scale)



Electroplating Process for Molded or 3D Plastics Are Similar

- Review design for platability
- Ensure print method & materials are suitable for intended application

→ Build, clean & post process → Receive & inspect → Rack → Etch → Apply Conductive Layer → Plate 1st layer (Cu) → Sand/Polish → Plate 2nd layer (Ni) → Plate 3rd layer (?) → Inspect & Ship

- Are AM customers aware of the plating process requirements ?
- How to deal with the quality of 3D printed parts which are much more variable than molded parts, particularly surface finish
  - What QC checks needed prior to starting the plating process
- Extra process steps (sealing, sanding) may be needed for thermoplastic prints
- How is appropriate plating thickness determined?
- Dealing with low part count
- Need for Fast Turnaround

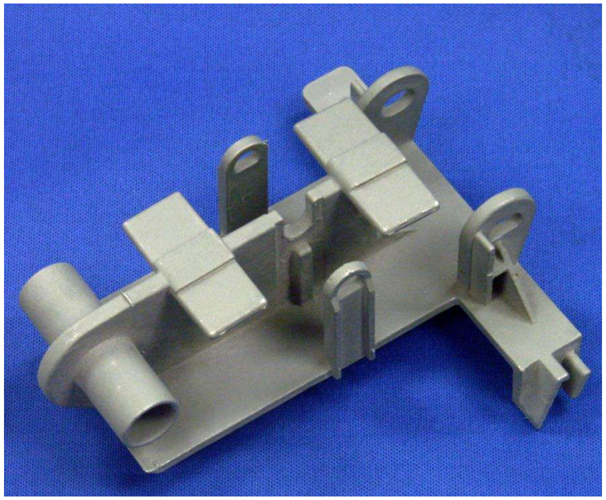
Adapting Printed Part Designs to the Process

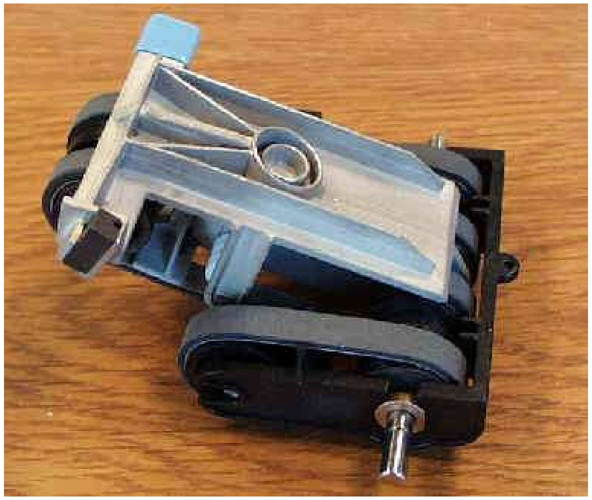
- Basic
  - Choosing appropriate print method and material
  - Make room for the coating
    - Apply surface offsets equal to coating thickness + 15%
      - **but how much needs to be applied?**
  - Design in assembly features
    - Install threaded inserts and Helicoils **PRIOR TO** electroplating (brass or SS only)
  - Add a radius to internal corners where possible
  - Remove/Modify un-platable features or mask them
- Intermediate
  - Consider thinner walls or hollowing part
  - Use of braces or fixtures to avoid distortion
- Advanced
  - Use unconventional DFAM design
    - Topology optimization for strength
    - Design modification to facilitate processing

Choosing the 3D Printing Process & Materials for Electroplating AM substrates

- Photopolymers- Best Finish, Isotropic, array of properties
  - Large Vat (expensive systems) vs. Shallow Tray (inexpensive) reshaped printer market
  - Inkjet photopolymer prints have support materials that impact plating process
  - Many photopolymer materials are temperature sensitive, some are water sensitive
- Powder Bed Fusion (PBF) Thermoplastic: SLS, MJF and SAF
  - Print density & surface permeability vary by machine and set up parameters
  - Surfaces are generally rougher but is improving in the last 4 years
  - More than 95% of prints are based on PA12 resin
- Filament Thermoplastic Prints (FDM)
  - Are the most widely used in the AM market but least use as electroplating substrates
  - Prints are porous and surface is permeable, so sealing is necessary
- **To make a good plated AM part a high quality AM print is essential**

Reversing Arm Assembly circa 2002 After the Fact RoM Analysis



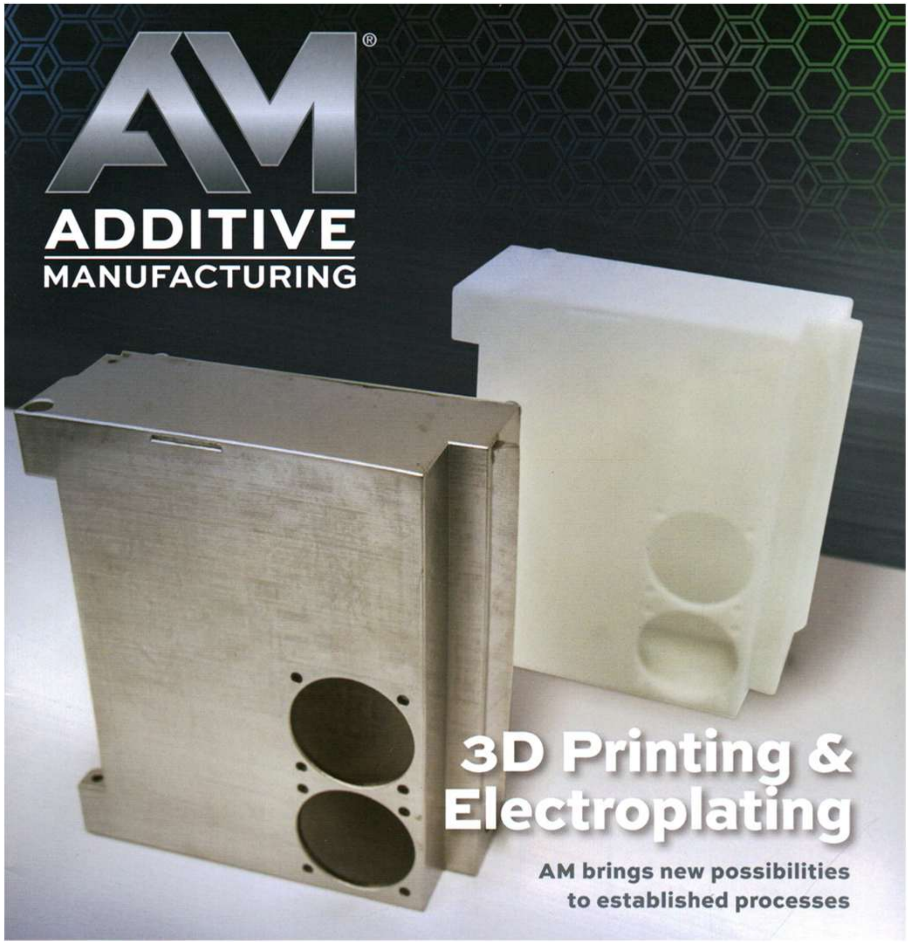


- SLA broke after ~**20K cycles**
  - 400K cycles needed for testing
  - Limited by lack of bending stiffness/strength
- Part file surfaces offset inward by 50 µm
- SLA plated with 50 µm Cu+Ni
- Plated SLA survived **400K cycles** w/o failure
  - **>20x durability improvement**

	Tensile Mod.	Tensile Strength	Flex Mod.	Flexural Strength
15% CF, 10% PTFE Polycarbonate	14.5 GPa 2.1 Mpsi	134 MPa 20 Kpsi	~14 Gpa ~2.0 Mpsi	~130 Mpa ~19 Mpsi
SLA Resin	3 GPa 0.44 Mpsi	60 MPa 9.4 Kpsi	2.8 GPa 0.41 Mpsi	100MPa 14.5 Kpsi
SLA Plated with 50 µm Cu+Ni	7 GPa 1 Mpsi	90 MPa 13 Kpsi	10 GPa 1.45 Mpsi	120 MPa 17.5 Kpsi

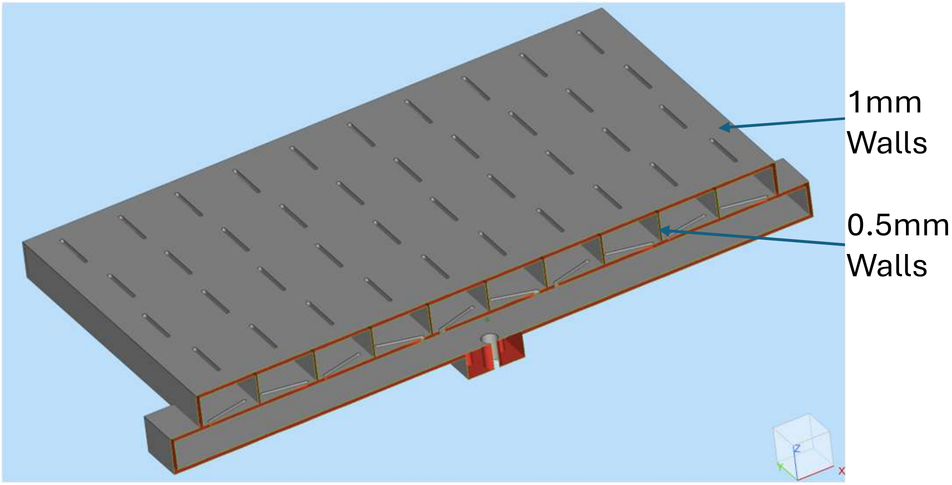
EMI Shielding

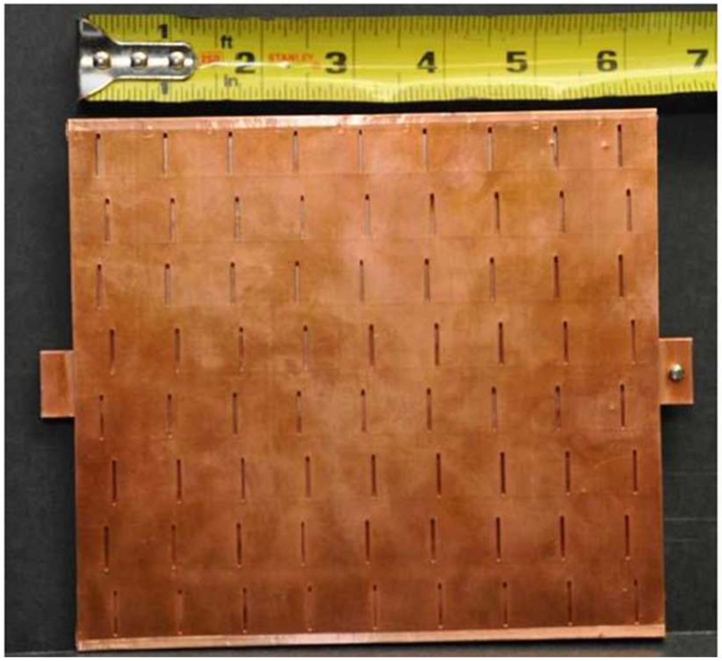
- EMI shielding of housings is a common electroplating application for AM parts
  - 38µm Cu+ 12µm Ni is sufficient form most high frequency EMI applications
  - High electrical conductivity copper is the performance layer, Ni prevents oxidation
- If the enclosure needs more strength, a thicker nickel deposit can be used
  - 25µm of Cu + 50µm Ni
    - Similar shielding
    - 2.5x the strength from coating
- Electroplating AM prints allows thinner walls, ~1 mm, saving weight
  - 30% lighter than 3mm thick print without plating

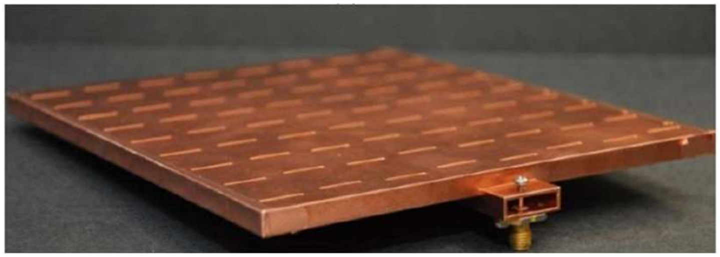


Slotted Wave Guide – Original Design

- Simple on the outside but the signal is carried in the internal chambers
  - Internal surfaces are ~60% of part total (865 cm^2), but slot access is only <10 cm^2
  - Limits ability to:
    - Completely clean
    - Completely cure internal surfaces
    - Etch
    - Apply a complete autocatalytic conductive layer
    - Electroplate internal cavities

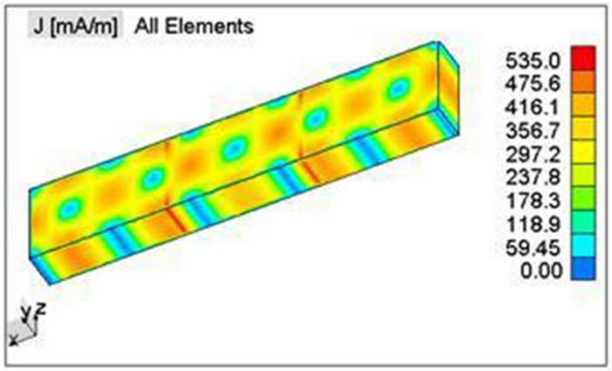






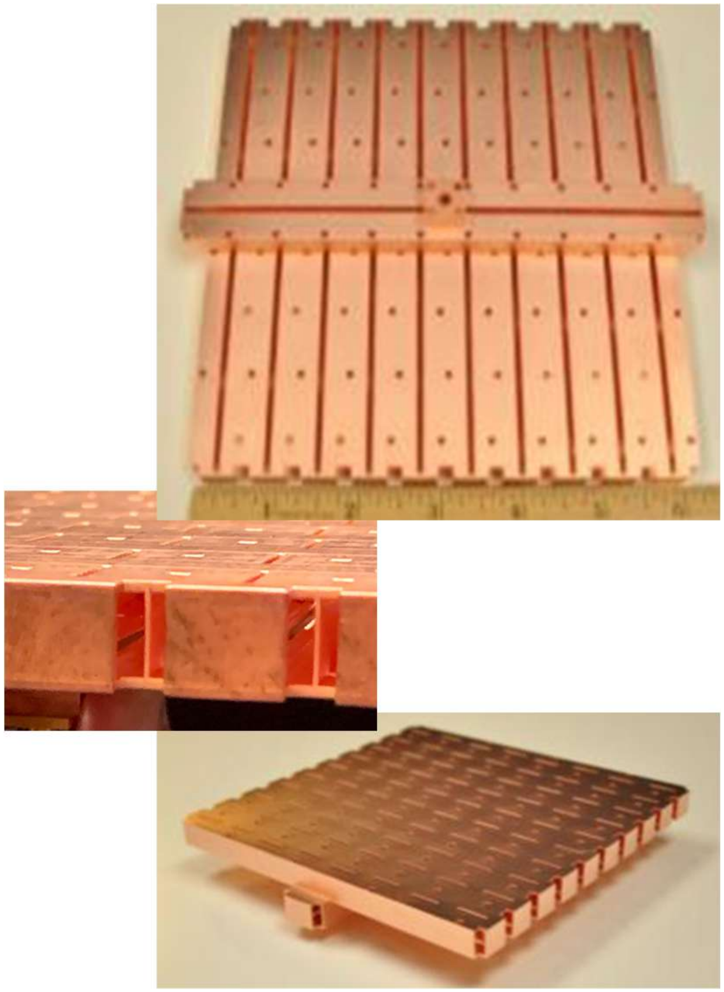
G. P. Le Sage: 3-D Printed Waveguide Slot Array Antennas
IEEE Access Vol. 4, p. 1259-1265, 2016

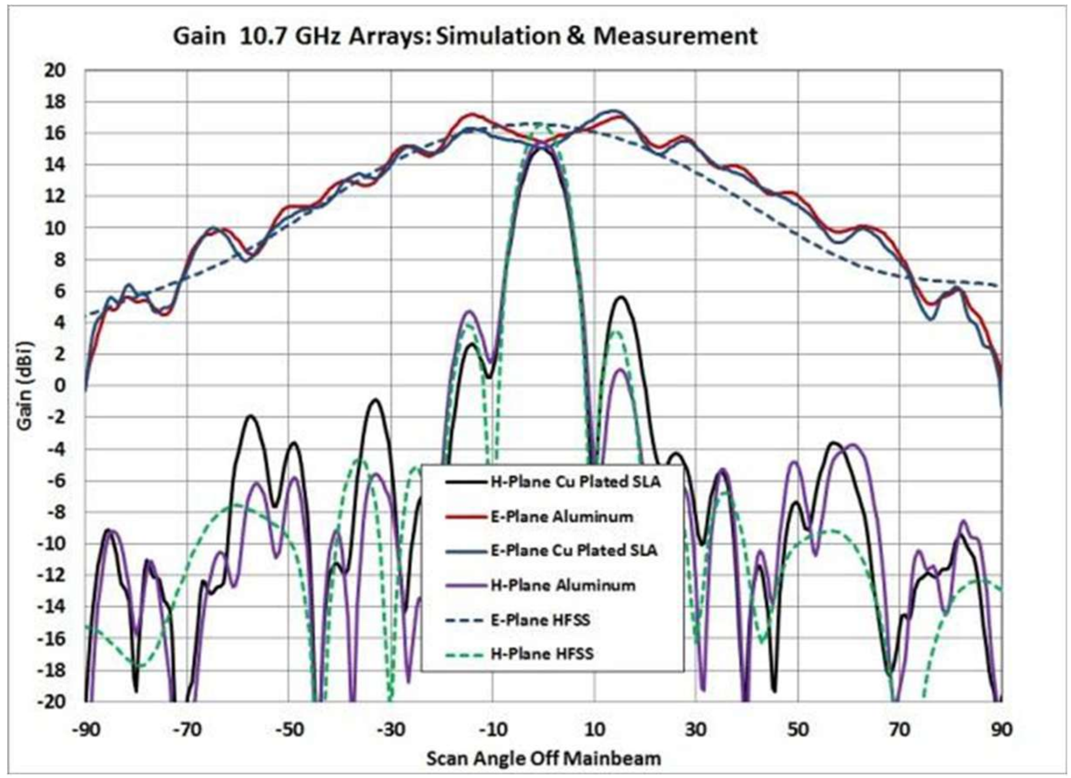
Antenna Signal Modeling Results in Process Simplification -Design for Additive Manufacturing in Antennas



- Performance modeling shows areas of high, in phase radiation (slots) and nodes
- Remove materials from nodes simplifies part printing and plating without compromising performance

Modeled & Measured Waveguide Performance



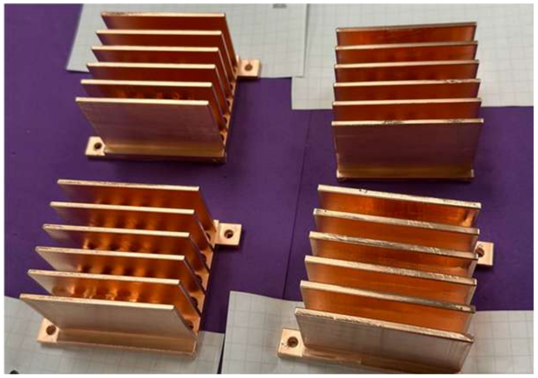


Heat Exchangers

- Heat Exchange collar patterned after those used on LED light bulbs
  - 200+ microns of Cu for heat conduction
  - 25 microns of Ni for corrosion protection
  - Tested solid and perforated collar cylinder around heat source.
  - Perforated cylinder provides continuous copper path to vanes.

Internal Heat Exchange Collar Test

USNA Capstone Project



Proposed: ASTM Reference Standard for use of Structural Plating to Reinforce AM Parts

- Key Element – Predictable, Reproducible Engineering properties
  - Based on the properties of the constituents and their volume proportions
  - Rule of Mixtures (RoM)

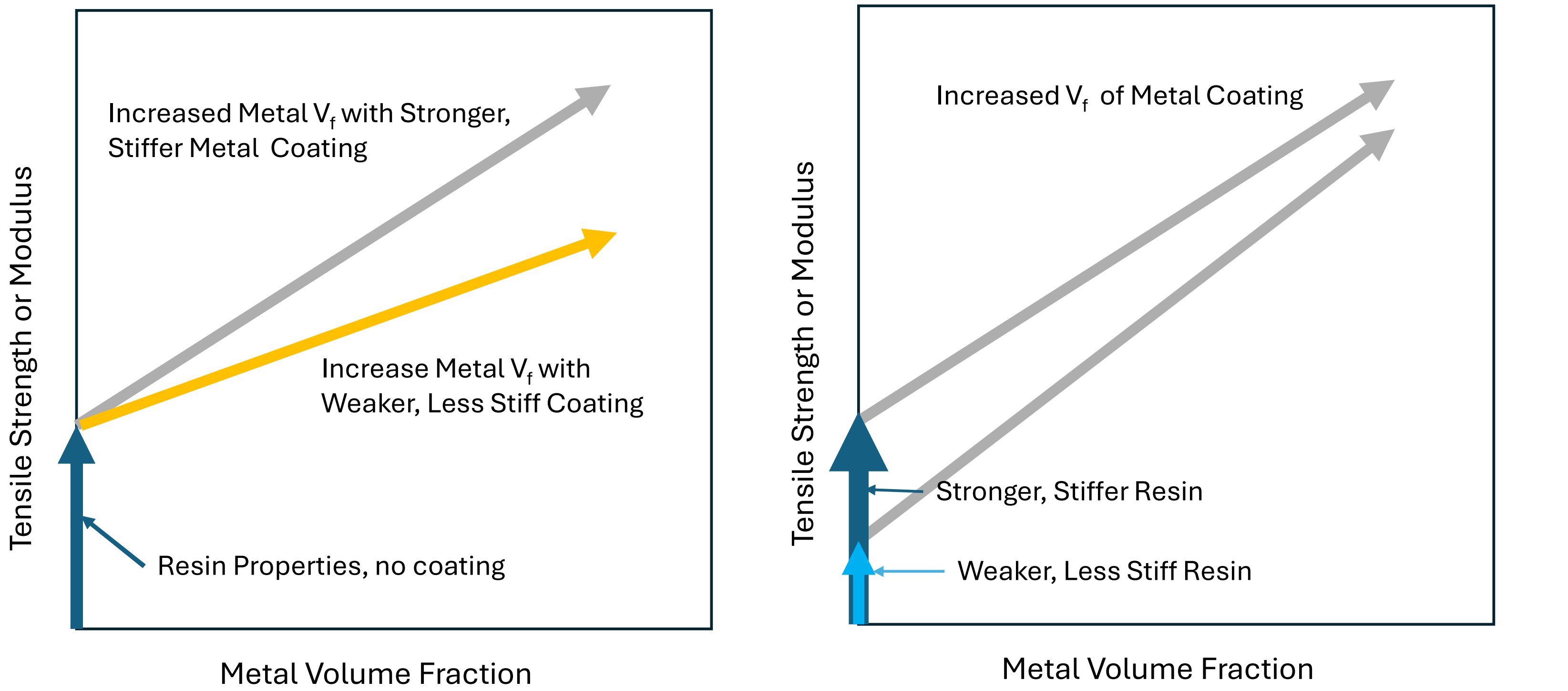
$$\sigma_c = \sigma_m * V_{fm} + \sigma_p * V_{fp} \text{ Strength}$$

$$E_c = E_m * V_{fm} + E_p * V_{fp} \text{ Stiffness}$$

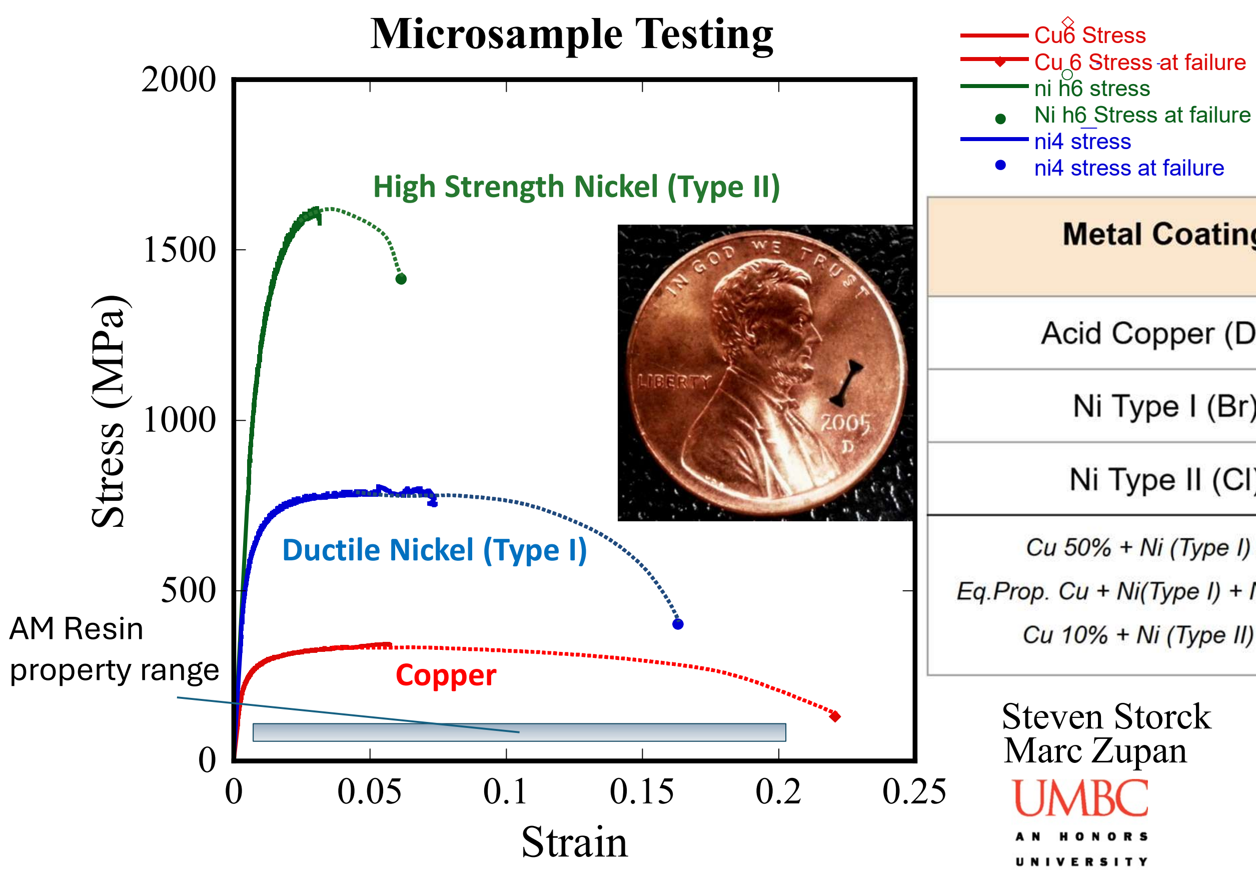
- Electroplating processes
  - Suitable for AM plastic & resin prints but are adapted for AM (temp and chem compatibility)
  - Surface Etching, Conductive Layer Application (bonding)
  - Mechanical Properties of Structural Electroplated Coatings (how to optimize/control)
  - Plating Rates, Controlling Metal Distribution, Coating Thicknesses (art of plating)
- Influence of AM printing processes & material properties for structural performance & process reliability

RoM Predictions of property trends with increasing metal volume fraction

Using Metal Coatings with Different Properties *Using Resin Substrates with different Properties*



Microsample Tensile Testing of Electroplated Cu & Ni coatings



Metal Coating	UTS (MPa)	YS (MPa)	Tens. E (GPa)
Acid Copper (DC)	370	264	90
Ni Type I (Br)	860	650	140
Ni Type II (Cl)	1558	1288	146
Cu 50% + Ni (Type I) 50%	*615*	***412***	***115***
Eq.Prop. Cu + Ni(Type I) + Ni (Type II))	*929*	***734***	***125***
Cu 10% + Ni (Type II) 90%	*1439*	***1185***	***140***

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Tensile and Flex Mechanical Testing Of SLA Resin Varying Substrate Properties, Same Plating Sequence

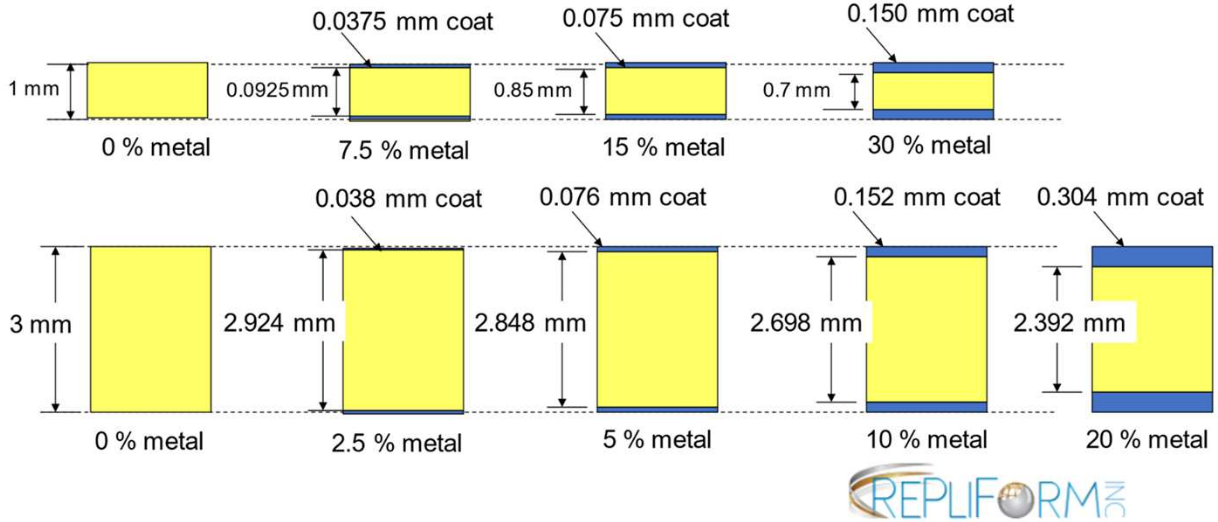
- D638 Tensile & D790 Flex Testing using samples where surface was offset by intended coating thickness prior to printing
- Resin Strength varied by <2x
- Resin Stiffness varied by nearly 5x
- Same metal proportions used on all samples while metal volume fraction (related to thickness) applied
  - Should Yield Strength or UTS of metal coating be used in RoM prediction
- In RoM analysis, is UTS or YS used in estimation?

Resin	UTS (MPa)	Tensile E (GPa)
Tough 2000	46	2.2
Clear	65	2.8
High Temp	51	3.6
Rigid 4000	69	4.1
Rigid 10K	80	10

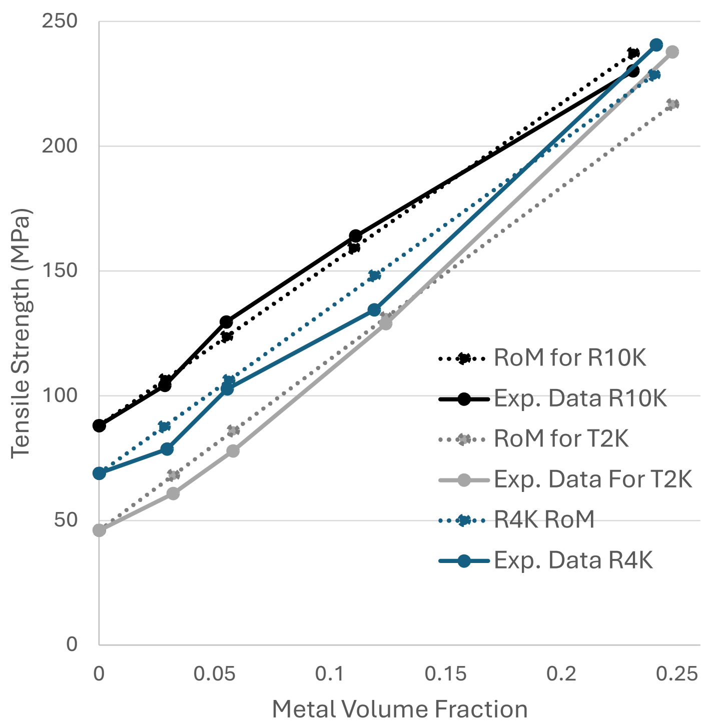
Metal Coating	UTS (MPa)	YS (MPa)	Tens. E (GPa)
Equal Proportions Cu(S) + Ni(D) + Ni (H)	*929*	***734***	***125***

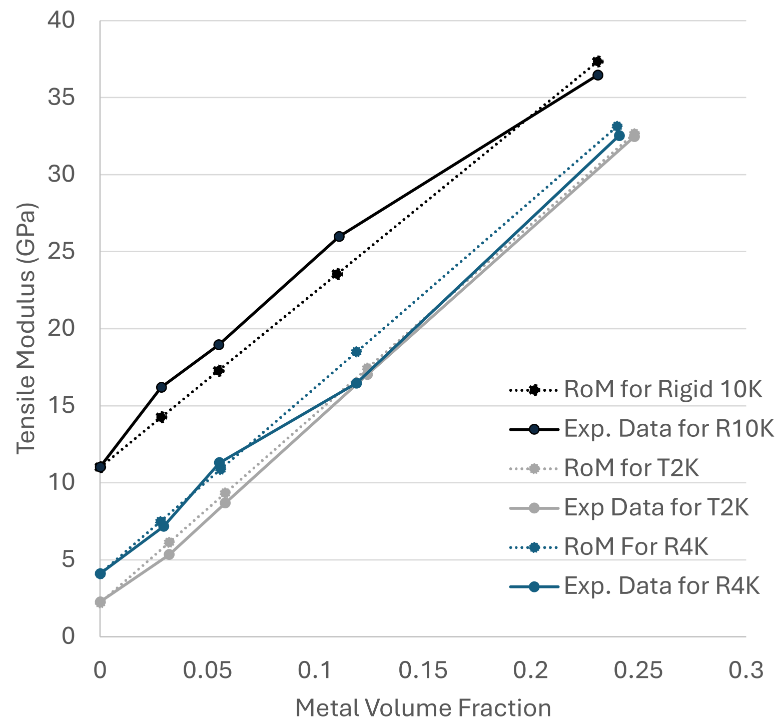
Plating Thickness and Volume Fraction Making Room for the Coating

- Composites are defined by the volume fraction of reinforcement in a specific matrix
- Coatings are defined by thickness
- To design for metal volume fraction,
  - determine metal proportion vs. the wall thickness and coating thickness
  - Offset file surfaces inwards to make room for plating **prior to** printing



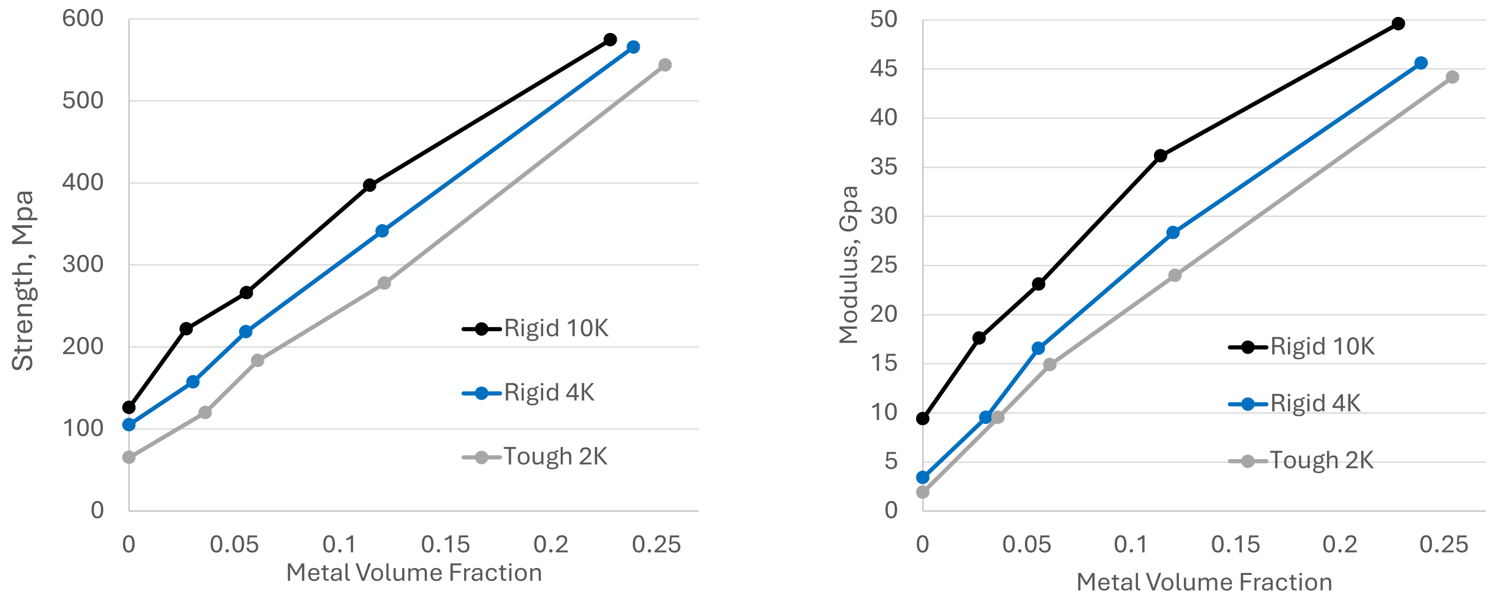
Tensile Strength and Modulus vs. RoM Predictions for Increasing Metal Volume Fractions





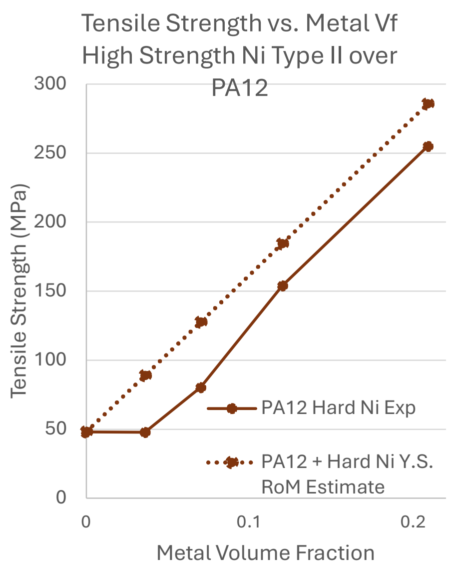
- RoM Prediction using Yield Strength vs. Exp. Data
- Experimental Strength values converged more at high metal V_f

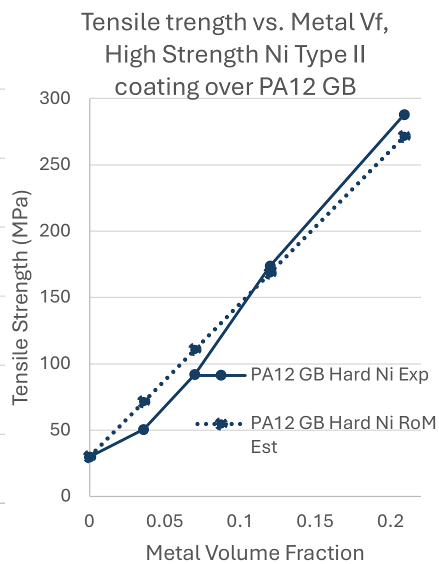
Flexure Strength and Stiffness

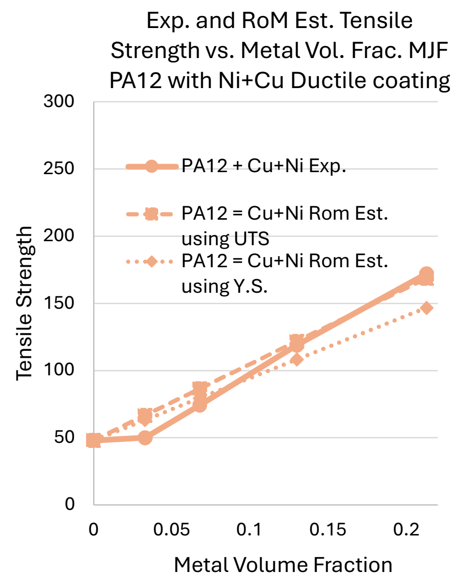


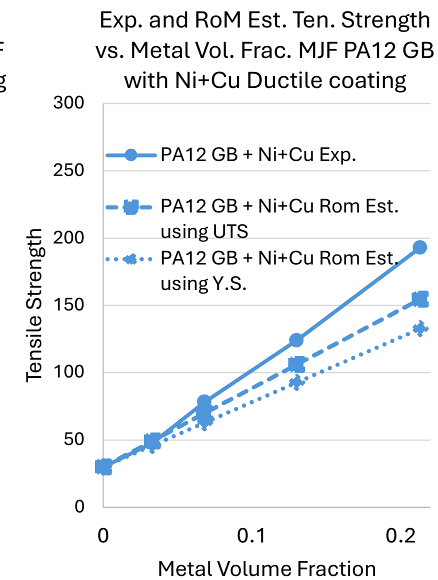
- Note that Flex Strength 2x faster than tensile strength with increasing metal Vf.
- Flex Modulus increased ~50% faster than the Tensile Modulus

Comparisons of Exp. Tensile Strength and RoM Tensile Strength predictions for PA12 and PA12 GB with a High Strength and a Ductile Metal Coating



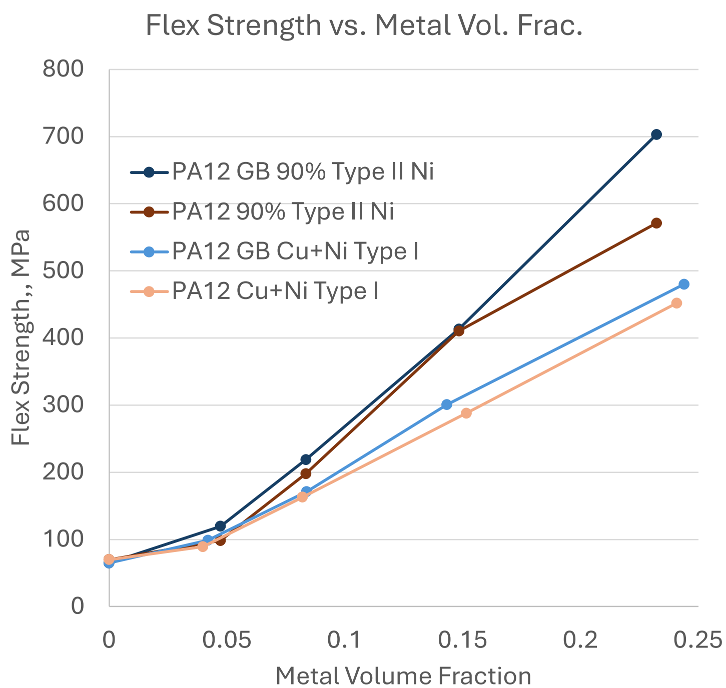


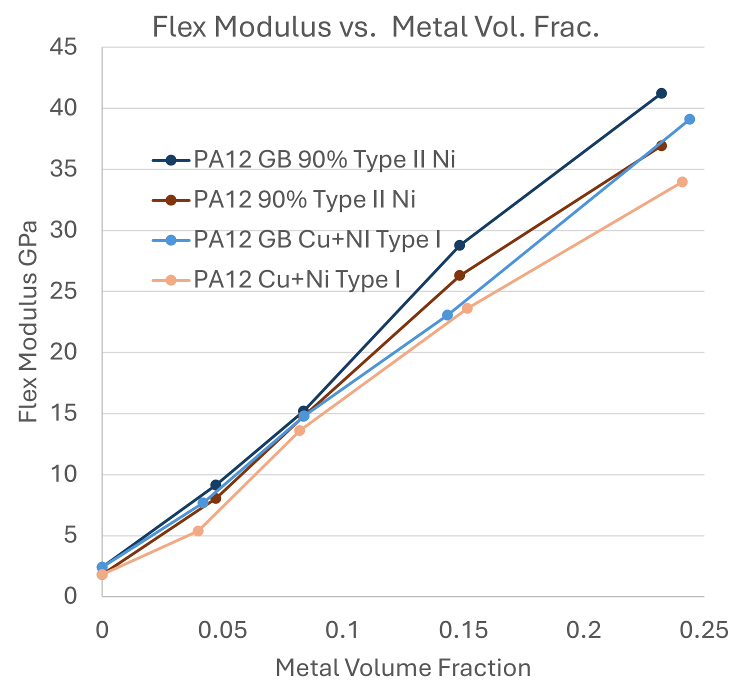




- Using the YS for the high strength coating overpredicts the strength through range of volume fractions form PA12 but does a decent job for the PA12 GB.
- Using either the YS or the UTS for the ductile coating gives a decent prediction for the PA12 but under predicts the strength for the PA12 GB

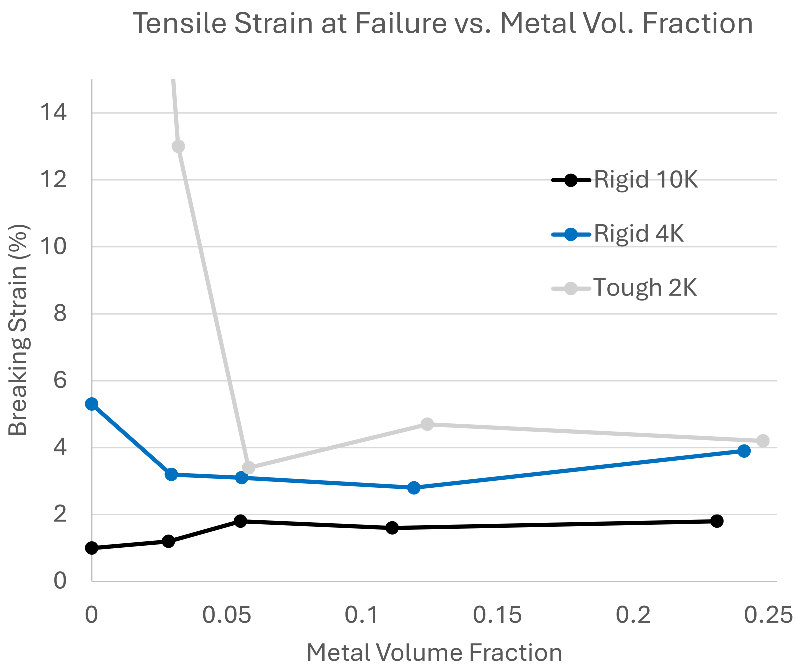
Flex test results of Electroplated MJF PA12 & PA12 GB

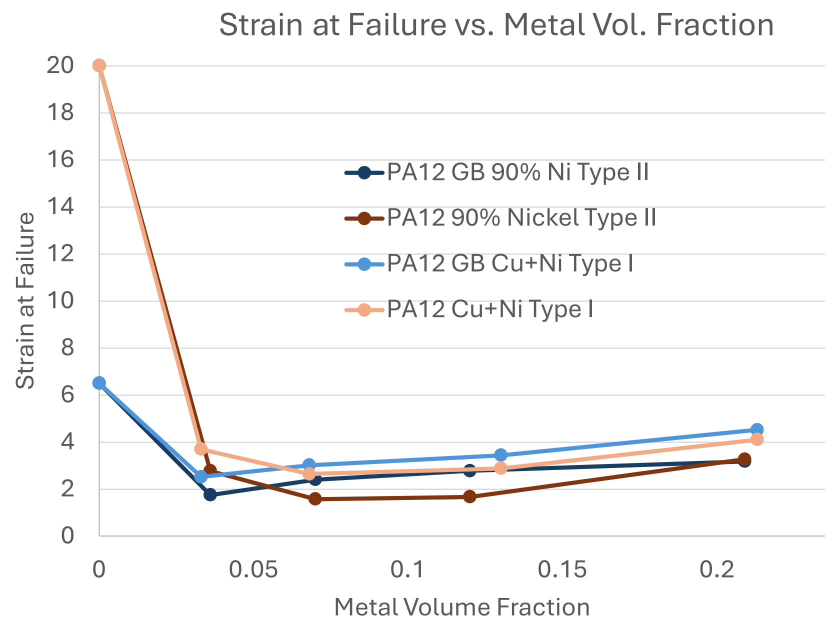




- Flex Strength increases at double the rate as the tensile strength
- Flex Modulus increases ~30 faster than the tensile modulus
- Very thin coatings, $V_f < 0.05$, do not reinforce as well as they should

Tensile Strain at Failure for SLA & SLS resins with different stiffnesses



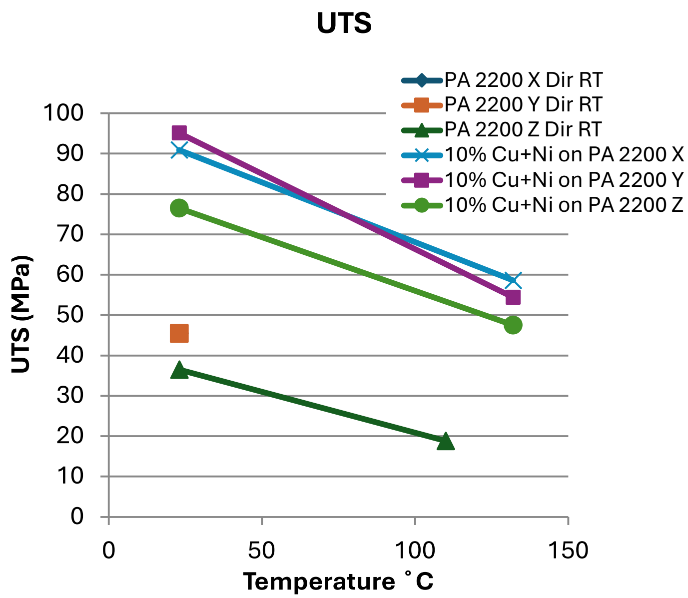


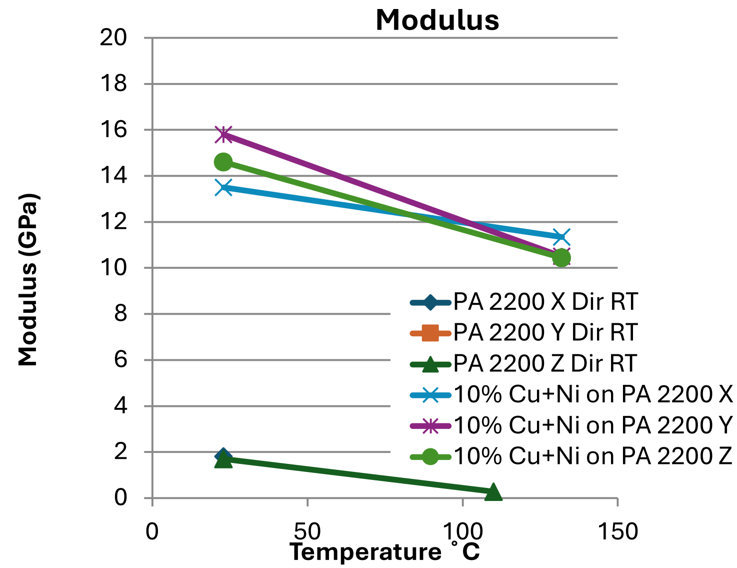
- For high strain resins, stain at failure declines after plating and converges at 3-4.5%
- For brittle resins, strain at failure modestly improves to 2-3%

Summary: Mechanical Testing of Electroplated AM parts

- Does the mechanical test data suggest predictable, reproducible properties can be made based on the properties of the constituents in the system and the proportions of each?
  - RoM estimates predicted experimental tensile strength and stiffness with reasonable accuracy
    - Flex strength is generally 2x Tens. strength
    - Flex stiffness is 1.2-1.5x tensile stiffness
- RePliForm has been using RoM predictions & mechanical test data to make informed decisions on resin selection, wall thickness and plating sequences for 2 decades.
- Where are the data gaps
  - Mechanical testing at elevated temperature
  - Creep
  - Fatigue
  - Others

Tensile Testing at Elevated Temperature-Electroplated SLS samples





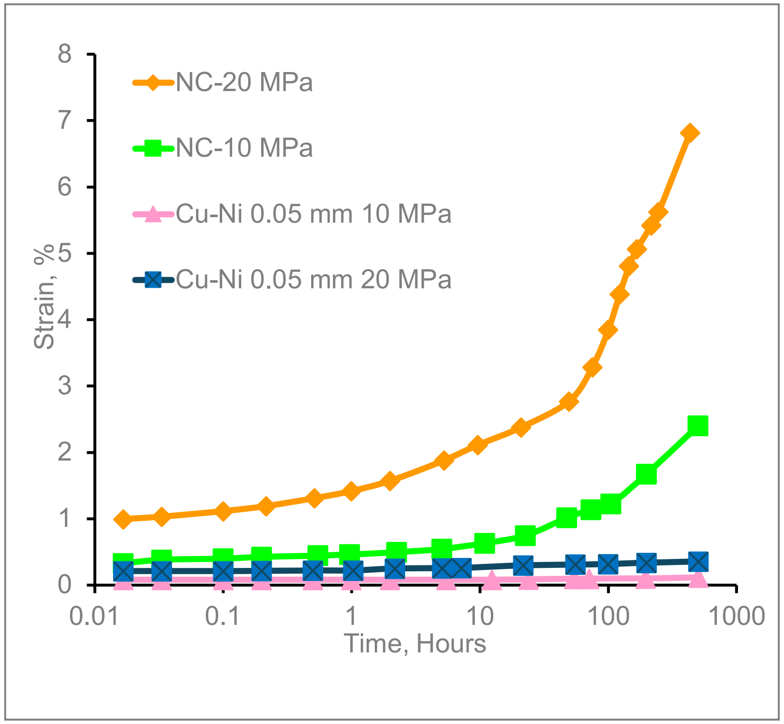
- Nearly 60% of metal coated PA12 strength is retained at 130C
  - Coated parts are still strong er than uncoated material at room temperature
- ~80% of the stiffness is retained in coated samples where 90% of the stiffness is lost in the uncoated PA12 SLS samples
  - At Room Temp., metal coating is 65x higher than substrate, at 130C its 460x higher

Flexural Creep Testing, D2990 using D790 samples

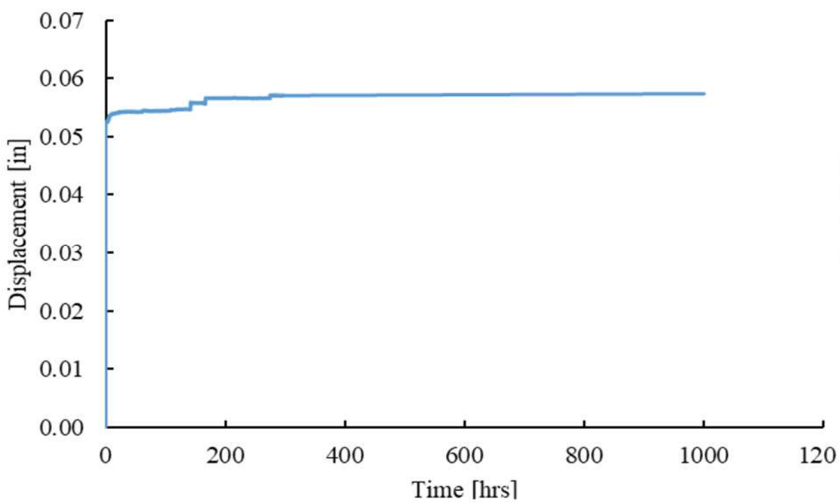
Sample	Load	Strain time-0	Strain Time 500 h
No Coating	20 MPa	0.99%	6.82%
50 µm Cu+Ni*	20 MPa	0.21%	0.35%
No Coating	10 MPa	0.32%	2.40%
50 µm Cu+Ni*	10 MPa	0.08%	0.11%

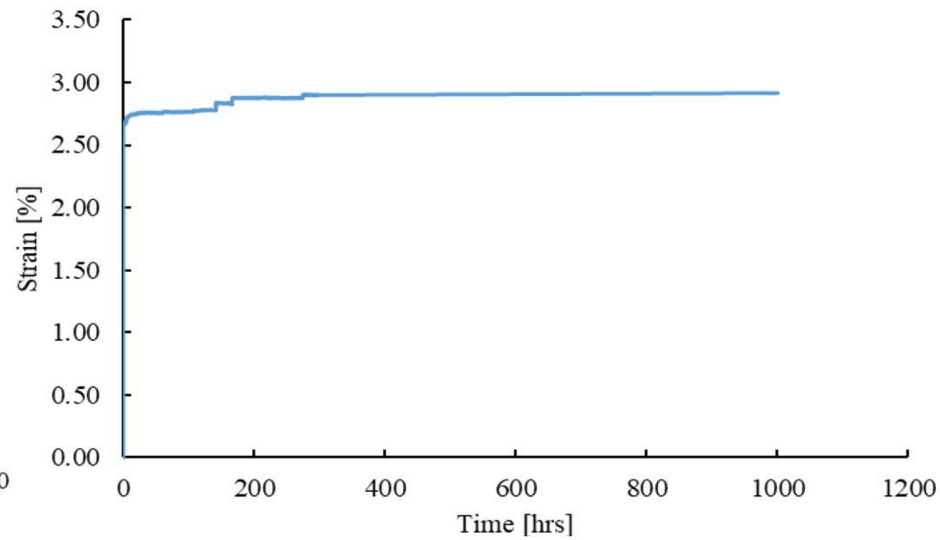
* 50 µm Cu+Ni on D790 flex sample, Metal V_f=0.04

- 20 MPa Load over 500 hours
  - 95% less Creep Strain, absolute
  - 97% less Creep Strain, Initial vs. final
- 10 MPa Load over 500 hours
  - 95% less Creep Strain , absolute
  - 98% Less Creep Strain, Initial vs. Final



D2990-17 Compression Creep Testing, MJF PA12



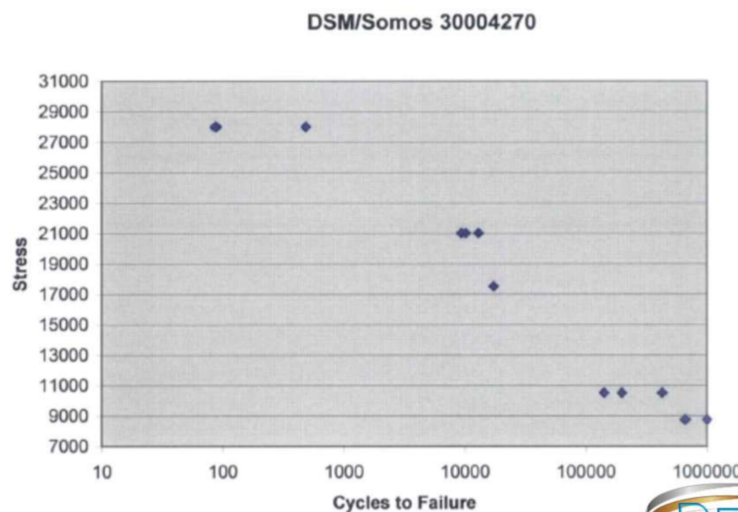


- Sample, 50 mm x 12.7 mm cylinder with 200 µm Cu+Ni (Type I) + Ni (Type II), Metal Volume Fraction = 0.06
  - Sustained 10 MPa Stress at 60C – Passed, 1000 hours
- Unplated 50 mm x 12.7 cylinder with no coating
  - Sustained 10 Mpa Stress at 60C failed <10 hours

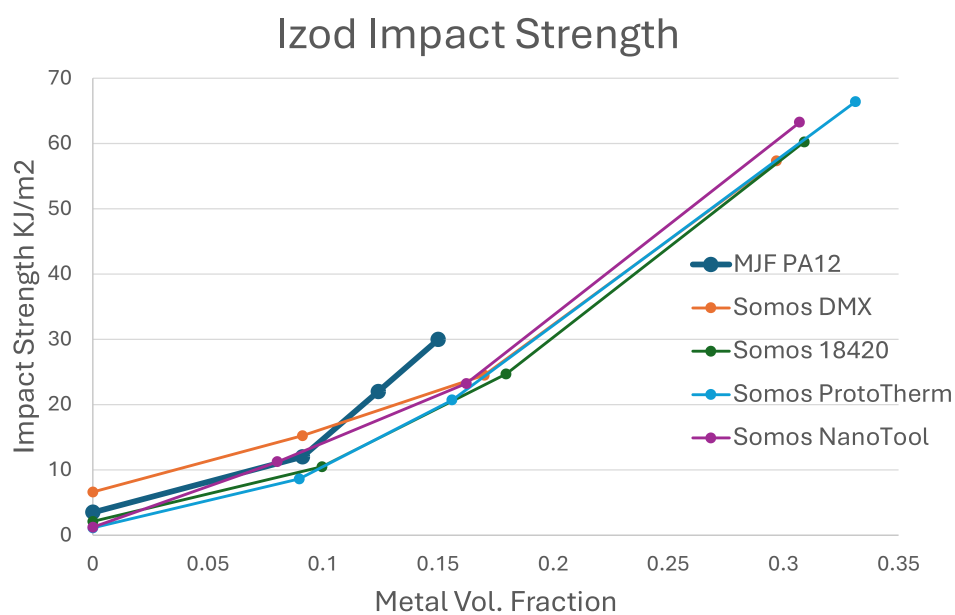
Fatigue Cycling of Cu-Ni coated NanoTool

- Boeing Internal Fatigue Cycle Testing (bending)
  - increased 250x with ProtoTool resin coated with metal V_f of 0.08.
- DSM – RePliForm Prelim. Tens. Fatigue Results
  - Cu+Ni (Type I) over NanoTool (current name PerForm), metal V_f=0.24

Stress	Cycles to Failure
21000	9311
21000	12917
21000	10134
28000	481
28000	85
28000	88
17500	17194
10500	197055
10500	424020
10500	140859
8750	653006
8750	1000000
8750	662630



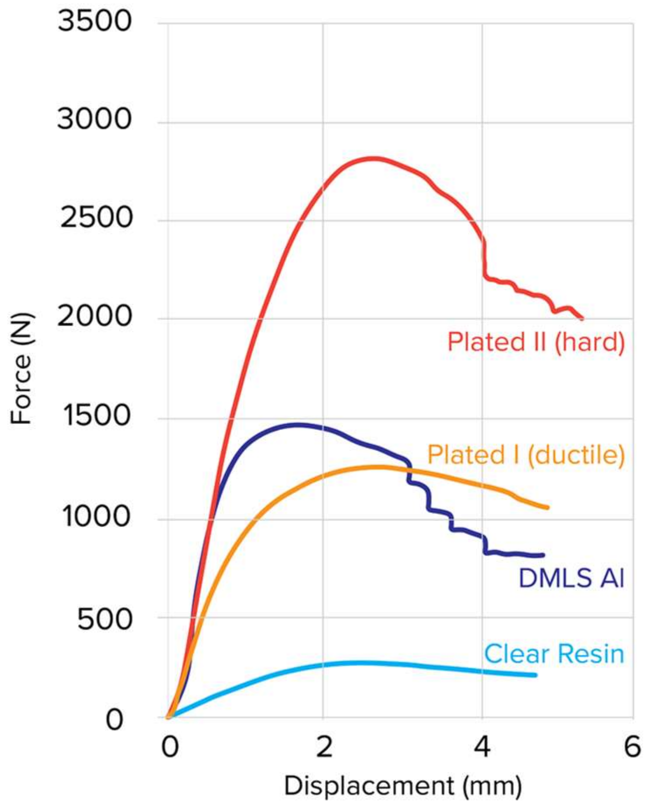
Impact Testing

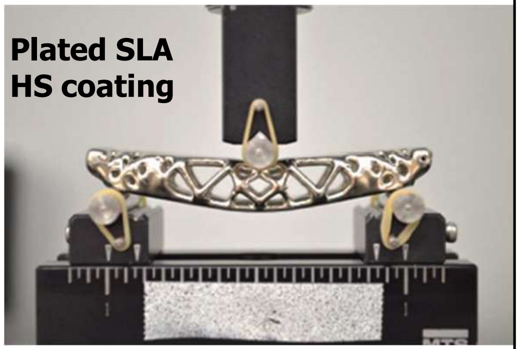


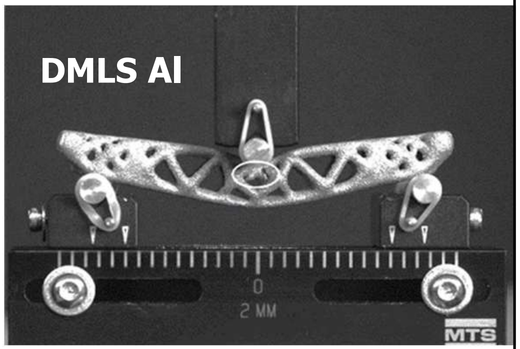
- Early impact data used Somos SLA resin coated with 50:50 Cu+Ni (Type I)
- MJF PA12 was tested recently using Cu+Ni(Type I)+NI (Type II) which is 1.5x stronger than the coating on the Somos resins.

Load-Deflection Exp with Topology Optimized Beams

- Could an electroplated resin be as strong as DMLS aluminum?
- DMLS AlSi10Mg Tensile Strength
    - ~460 MPa as built
    - ~320 MPa heat treated
- RoM estimate indicated that Vf of 0.32 with 90% Ni Type II coating would give 407 MPa UTS
    - Exp., 404 MPa Tens. strength
    - Exp., 980 Mpa Flex . strength
- nTopology topology optimized geometry selected,
    - surfaces offset in by 250 μm
    - Plated 25 μm of Cu followed by 225 μm of Type II Ni
- Breaking Loads
    - Clear Resin 270 N
    - DMLS AlSi10Mg 1480 N
    - 90% Ni plated resin 2800 N







*single representative test shown

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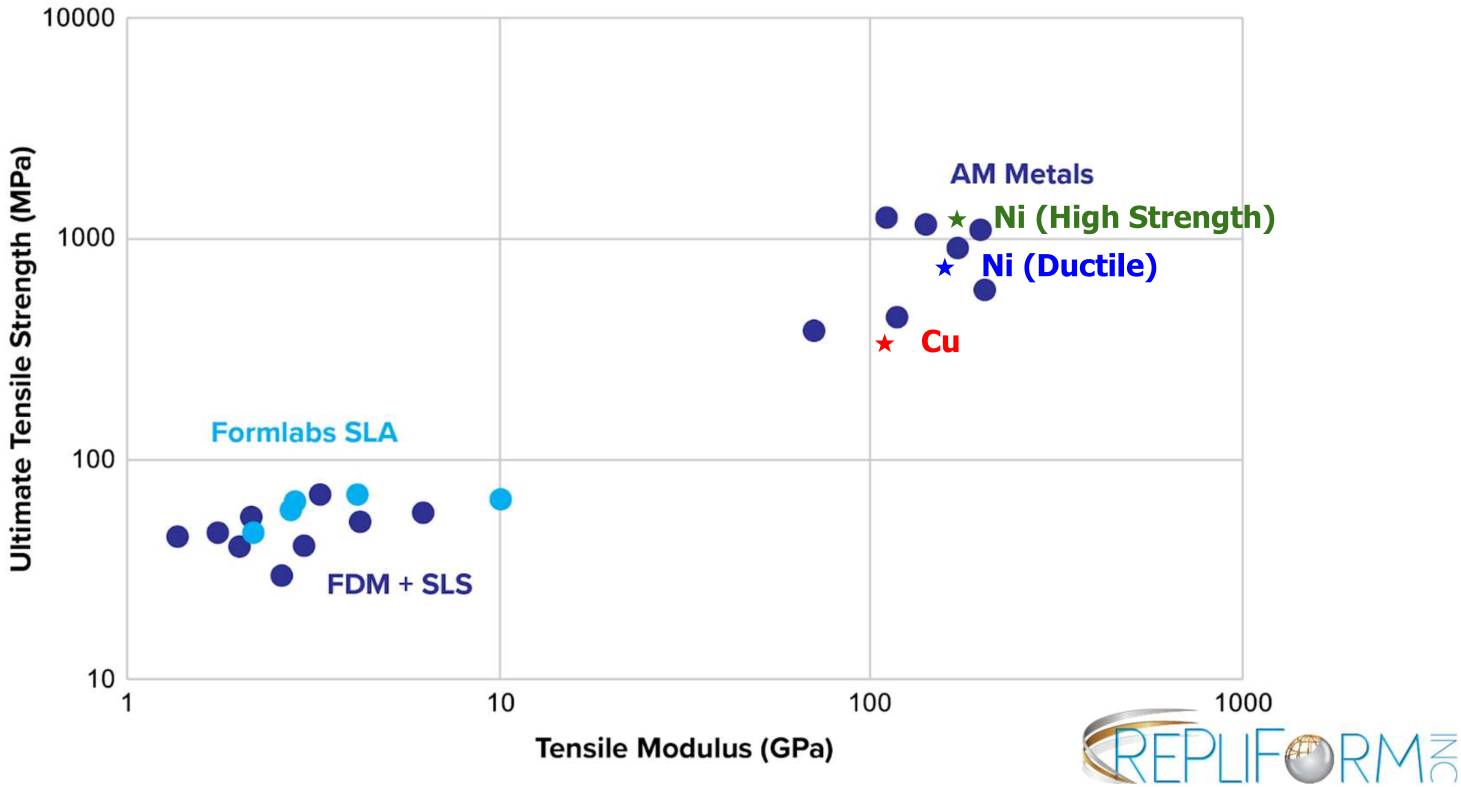
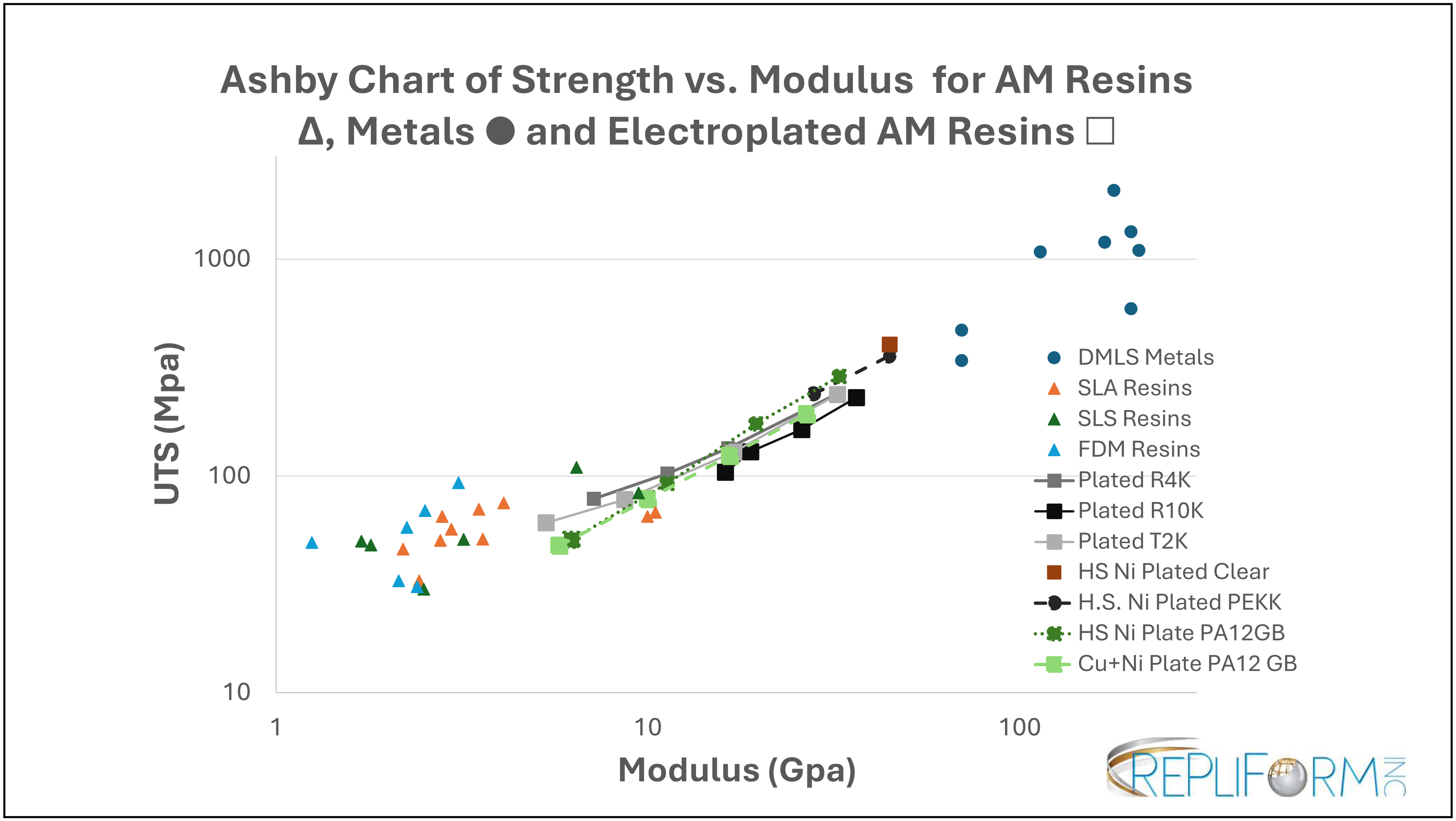
Metal Performance via Plating on AM Plastics

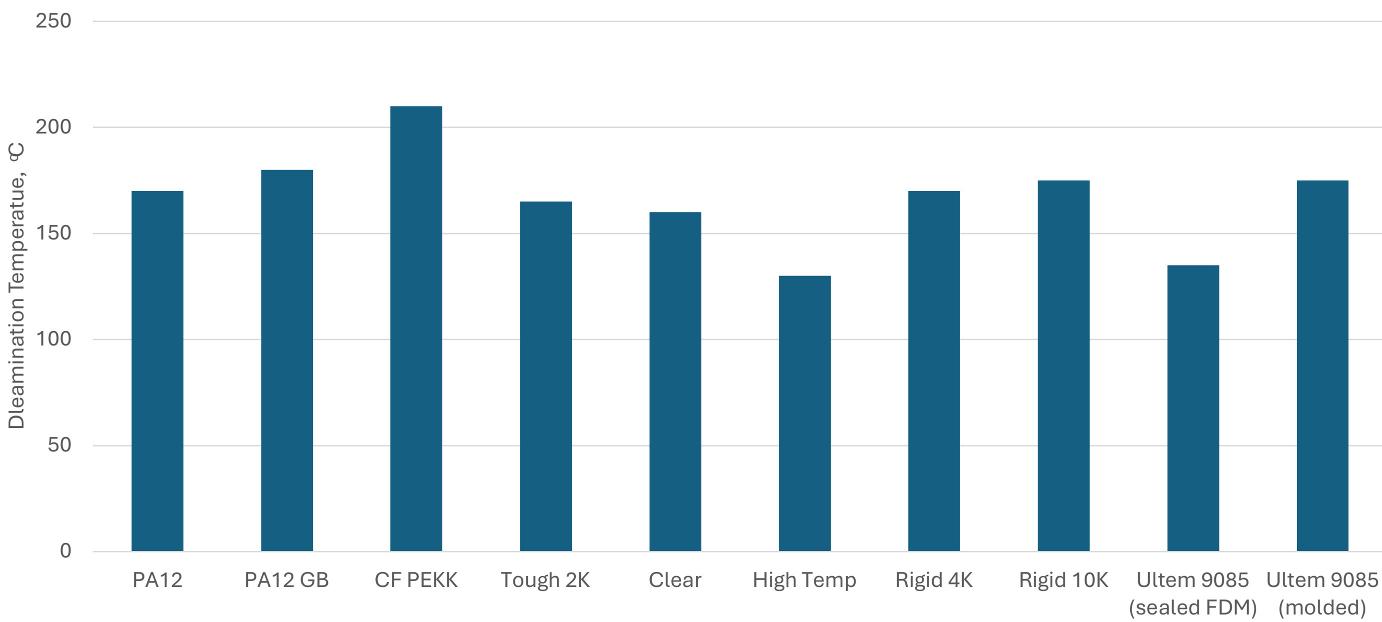
- Electroplated coatings are a great compliment to 3D printed resin parts
- AM gives tremendous design flexibility, plating adds functionality
  - Improve finish
  - Environmental Barrier
  - Abrasion resistant surfaces
  - Heat Conduction
  - EMI Shielding
  - Flammability resistance
  - Long term durability
  - Improve Strength & Stiffness (predictably)
- Collaboration with end customers is often a key to success
- RePliForm is working to establish an ASTM standard for reinforcing AM resin parts with electroplated coatings
  - Currently working with the ASTM F42 Sect. 05, 02 to do so
  - Without a standard, it’s hard to spec. use of electroplated coating for this use

Ult. Tens. Strength vs. Modulus for AM Resins & Metals vs. Electroplated Copper and Nickel




Ashby Chart of Strength vs. Modulus for AM Resins Δ, Metals ● and Electroplated AM Resins □
UTS (Mpa)
1000
100
10
1
10
100
Modulus (Gpa)
DMLS Metals
SLA Resins
SLS Resins
FDM Resins
Plated R4K
Plated R10K
Plated T2K
HS Ni Plated Clear
H.S. Ni Plated PEKK
HS Ni Plate PA12GB
Cu+Ni Plate PA12 GB
REPLIFORM INC

Stepwise Thermal Cycling Delamination Test



- Testing shown is for samples with wall thickness <6mm
- Samples with wall thickness >12mm often delaminate a lower temperatures unless resin CTE is low