Preliminary Study of Additive Manufacturing Processes for Copper Alloys

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To support Wieland's efforts to manufacture commercially viable additivity manufactured copper, our team was asked to develop postprocessing techniques and characterize mechanical and electrical properties of Direct Metal Laser Sintered (DMLS) and Binder Jet printed samples. Tensile testing proved that heat treating DMLS samples is an effective way to increase yield strength. Sintering studies with Binder Jet printed samples showed effective binder burnout and incomplete sintering.

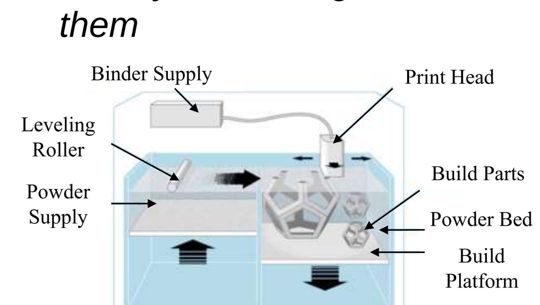
This work is sponsored by Wieland Rolled Products North America, East Alton, IL

Project Background

- Additive manufacturing (AM) is very attractive for the design flexibility it allows but has not been explored for copper and copper alloys
- Two methods examined in this study are outlined below:

Binder Jet Printing

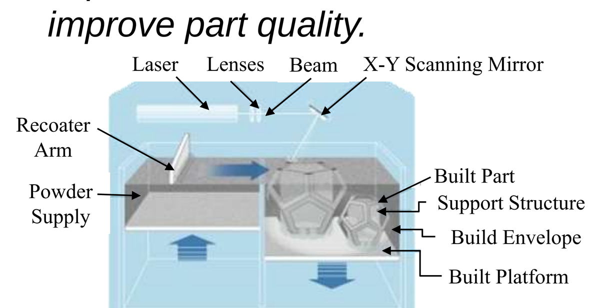
- *Uses a binder as adhesive to hold metal particles together forming shapes called green parts.*
- *Green parts undergo postprocessing including de-binding and sintering to densify and strengthen them*



https://www.3dnatives.com/en/powder-binding100420174/

Direct Metal Laser Sintering (DMLS)

- *Uses a high-power laser to heat metal powder particles in a small area, fusing the particles together in successive layers.*
- *Laser power, speed, scan patterns, particle size, and layer depth can all be altered to improve part quality.*



https://www.additively.com/en/

Problem Statement

- How do the mechanical and electrical properties of parts manufactured via DMLS and binder jet printing compare to part manufactured via traditional casting and wrought processing?
- Goal: Characterize DMLS printed C18150, conduct heat treat studies to improve mechanical properties, and determine sintering procedure for C102

Table 1: Compositions of alloys of interest

Alloy	Cr (wt%)	Zr (wt%)	Cu (wt%)
C18150	0.5 - 1.5	0.02 - 0.20	Balance
C102	-	-	99.95 min

Experimental Procedure

Heat Treat Studies on DMLS Printed C18150

- Samples heated to 950°C and held for 1hr
- Samples water quenched to room temp
- Samples heated to 450°C for 1-4hr or 500 °C for 1-2hr and air cooled to room temp

Sintering Studies on Binder Jet Printed C102

- Samples heated to 450 °C for various isothermal holds to burn out binder
- Samples sintered for 6 to 22 hours at 900-1050°C
- Sintering conducted under forming gas atmosphere (5% H_2, 95% N_2) in tube furnace

Density Measurements

- Archimedes' Method using water as liquid

Electrical Conductivity

- 4-point probe procedure
- Conductivity calculated per International Annealed Copper Standard as:

$$\sigma_{IACS} = \frac{\left[\left(\frac{I}{V}\right)\left(\frac{L}{Cross\text{-}sectional\ area}\right)\right]}{5.800\ x\ 10^7\ S/m\ [1]}\ x\ 100$$

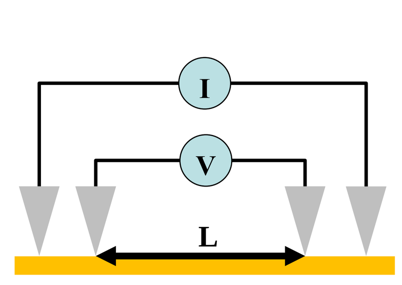


Figure 1: Schematic of 4-point probe conductivity testing where I is applied current, V is measured voltage, and L is the length between voltage probes.

[1] ASTM E1004-17, Standard Test Method for Determining Electrical Conductivity Using the Electromagnetic (Eddy Current) Method , ASTM International, West Conshohocken, PA, 2017.

Heat Treatment of C18150: Results and Discussion

Mechanical Properties

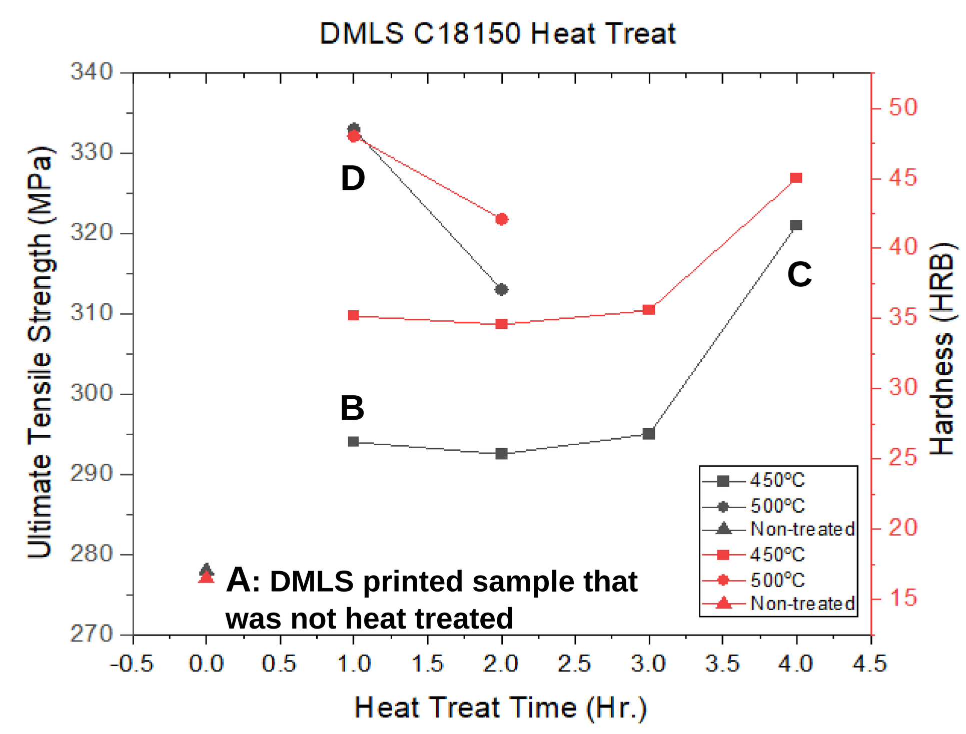


Figure 2: Comparison of tensile strength and hardness of heat treated DMLS printed C18150 samples. Heat treating to 500°C for 1hr causes the greatest increase the tensile strength and hardness of the samples. All heat treatments improved the samples' tensile strength and hardness compared to the non-heat treated samples. None of the samples were as strong as cast equivalents with UTS of 370 MPa and hardness of 80 RHB.

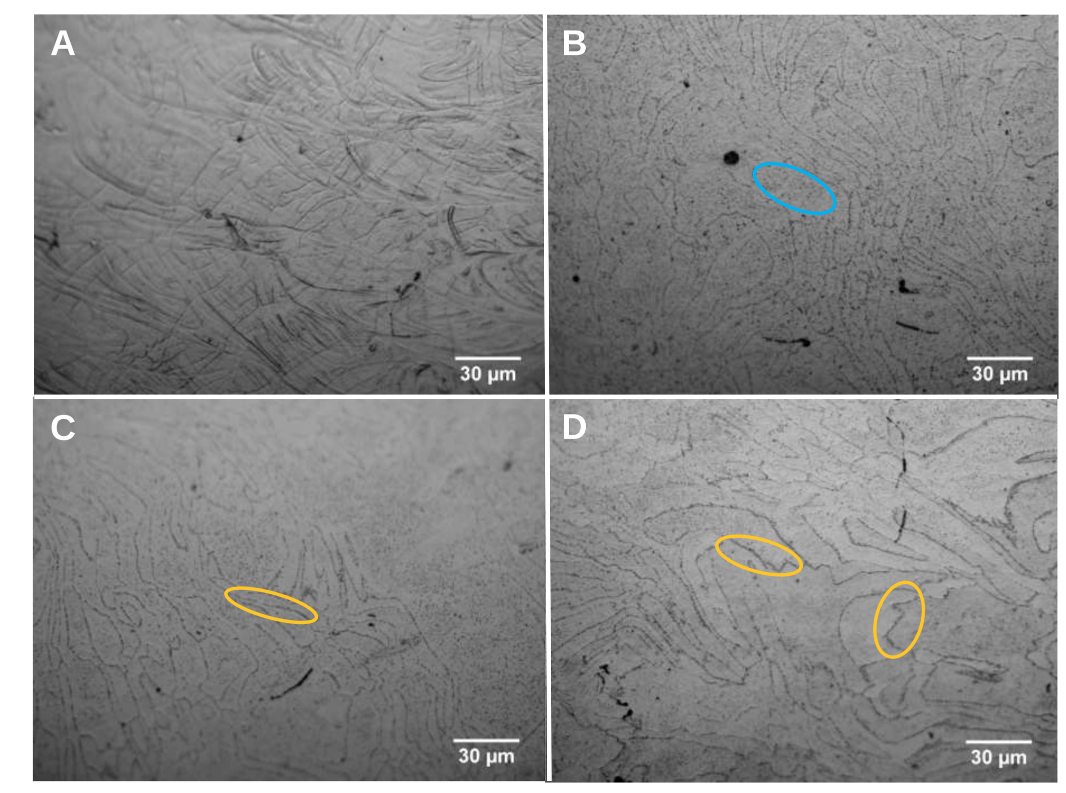


Figure 3: Heat treating printed C18150 drew out chromium precipitates (indicated by blue and yellow circles) that are not seen in an nontreated sample (A). These precipitates increase strength and hardness due to their incoherent interface with the copper matrix. The strongest samples were treated at 450°C for 4 hours (C) and 500°C for 1 hour (D) due to precipitate migration to the grain boundaries.

Electrical Conductivity

- One printed, non-heat-treated bar was tested (Table 2)
- Cross sectional area: 0.027 cm^2 ; Current: 50 mA
- Conductivity of DMLS is much lower than wrought reference (80% IACS), due to much smaller grain size in DMLS samples
- Heat treated samples not tested due to constraints of number of samples

Table 2: Conductivity Testing Results

Voltage (μV)	Length (cm)	Resistivity (nΩ•m)	Resistivity (%IACS)
71	6.30	55.6	31.0
46	4.62	53.0	32.5

Sintering of C102: Results and Discussion

Density

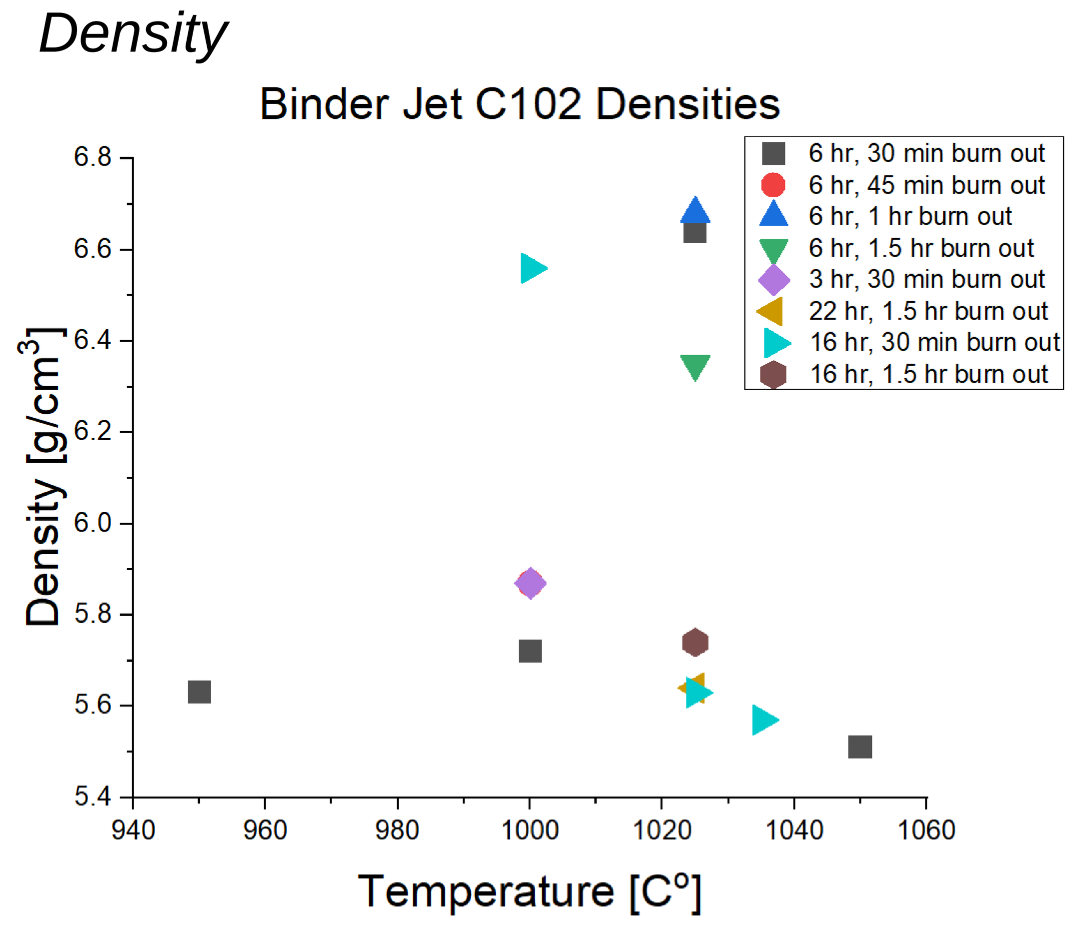


Figure 4: Plot of density of binder jet printed C102 samples after sintering at various temperatures. The highest densities were achieved at 1025°C after 6 hours of sintering and were 74.2% dense compared to pure copper.

Factors that Varied in Sintering Studies

- Temperature
- Sintering time
- Burnout time
- Rate of gas flow

Summary of Sintering Studies Results

- Highest density from sintering was achieved at 1025°C held for 6 hours. Gas was flowing for the burnout and cooldown periods but was shut off during sintering. Post-sintered oxygen contamination was minimal (0-5%). Samples still contained significant porosity between printed rows after sintering.

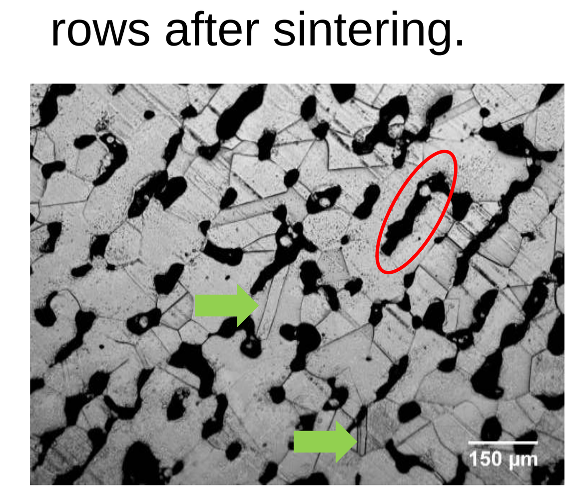


Figure 5: The microstructure of the sample sintered for 6 hours at 1025°C displays relatively large grains (3316 ± 4 μm² area) with twinning visible (indicated with green arrow). Voids appear to cluster along build planes (circled in red).

Conclusions and Recommendations

- Heat treating DMLS C18150 improves mechanical properties but not to the level of wrought parts
- DMLS C18150 has much lower conductivity compared to wrought samples due to smaller grain size. Conductivity tests should be completed on heat-treated DMLS printed C18150 samples to compare
- More work in sintering is necessary; we recommend more work to improve the green body packing density.

Acknowledgements

The team would like to thank Wieland for the project and support, Bill Shelley for his guidance, Chris Schade and the team at Hoeganaes GKN for supplying samples for testing and guidance in many aspects of the project, Mohammed Naziru Issahaq for his aid in electrical conductivity measurements, and Philip Steckler for his work on the project in the first semester.