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Three-Dimensional Printing GRCop-42

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LIST OF ACRONYMS, SYMBOLS, AND DESIGNATORS

CED	core energy density
Cr	chromium
Cu	copper
GRC	Glenn Research Center
GRCop-42	Cu-4 at.% Cr-2 at.% Nb
GRCop-84	Cu-8 at.% Cr-4 at.% Nb
HIP	hot isostatic press
MSFC	Marshall Space Flight Center
Nb	niobium
PBF	power bed fusion
UTS	ultimate tensile strength

TECHNICAL MEMORANDUM

THREE-DIMENSIONAL PRINTING GRCop-42

1. SUMMARY

GRCop-42 (Cu-4 at.% Cr-2 at.% Nb) is a copper (Cu)-chromium (Cr)-niobium (Nb) alloy that NASA developed for use in rocket propulsion components that required high thermal conductivity, excellent creep resistance, low-cycle fatigue life, and strength at elevated temperatures, such as combustion chamber liners and fuel injector face plates. Using powder bed fusion (PBF) 3D printing, NASA Marshall Space Flight Center (MSFC) and NASA Glenn Research Center (GRC) successfully printed near-fully-dense GRCop-42 components that may equal to or exceed their traditionally manufactured predecessors. This Technical Memorandum serves to summarize the process that was developed to achieve 3D printable near-fully-dense and functional GRCop-42.

2. BACKGROUND

From 2014 to 2017, a team from MSFC, GRC, and Langley Research Center completed development on 3D printing fully dense and usable GRCop-84 (Cu-8 at.% Cr-4 at.% Nb) fuel-film-cooled combustion chambers for the low-cost upper stage propulsion liquid oxygen-methane engine using the PBF additive manufacturing method, culminating in several successful hot-fire tests at MSFC in 2016 and 2017. Besides developing the process for building test hardware, another successful milestone of the program was to publish data on processing the GRCop-84, a la 'the 84', so as to establish more readily available powder suppliers, as well as 3D printing vendor shops that could build hardware with the 84. The next development effort naturally led to GRCop-42, which would give higher thermal conductivity at similar strength, and thus higher engine performance than even the 84.

Whereas 'the 42' powders were not readily available in times prior, the previously established powder vendors were now ready to move into production development for this similar alloy. The lower Cr and Nb content actually made the 42 easier for powder vendors to process to specification than the 84, in that Cr and Nb react very quickly when the Cu becomes molten, and the Cr2Nb floats to the surface of a still melt. The increased Cr2Nb in the 84 therefore exceeds solubility versus the 42. ATI produced the 42 powder used in this study to a size specification of +0/–44 µm (reads 'plus zero, minus 44').

3. PROCESS AND PARAMETER DEVELOPMENT

The GRCop-42's 3D printing process and parameters were developed on a ConceptLaser M2 (Gen 1 2012 model) PBF machine (see table 1).

Table 1. Specifications of the ConceptLaser M2 used in this study.

Build capacity	250 mm × 250 mm × 275 mm
Laser	Single 400 W Nd: YAG
Spot size	52 μm
Travel speed	50–5,000 mm/s
Inert gas	Argon

The rationale for choosing this machine is primarily that it was used in the GRCop-84 development and had proven itself 'copper friendly' with its inert glovebox and build chamber, and the 400 W laser could readily achieve the high-energy density needed to fullly melt the 42.

While the 84 development had been successful on a 0.030-mm-layer print strategy, it proved to be quite time-consuming to build larger components at that rate—essentially a 275-mm-tall part could take as long as 28 days to 3D print. The hope with the 42 development was that it could be pushed to operate at faster print speeds and scale up into larger frame machines like the 400-mm and larger PBF platforms to allow production for higher thrust engine systems. The higher conductivity of the 42 was theorized to allow for cooler parameters; i.e., lower core energy density (CED), thus achieving stable weld pools at thicker layers, so this effort started out with 50% thicker layers (0.045 mm).

Initial trials on the 42 parameters were conducted in early 2018, building a series of 25 small blocks produced in a grid at ramping powers and speeds. Previous development on the 84 yielded a CED at 95.2 J/mm^3 (see table 2, column A). The 42 test matrix was started with a similar CED to the 84, scaled up to match the 0.045-mm-layer thickness at 325 W laser power and 800 mm/s scan speed. Then, 25 cooler and faster datasets down to roughly half of the 84's CED at 225 W and 1,200 mm/s were mapped out. It was deduced that a thicker layer would require a slightly tighter hatch spacing for thorough melting, so the 84 overlap of 70% was increased to 66% for the 42 (see table 2, columns B and C).

Table 2. Bounding box parameters for GRCop-42 development.

	A	B	C	D
	GRCop-84	GRCop-42	GRCop-42	GRCop-42
Material	Default	Min CED	Max CED	Final Set
Core laser power (W)	180	225	325	270
Core scan speed (mm/s)	600	1,200	800	1,025
Hatch width (mm)	0.105	0.099	0.099	0.099
Build layer thickness (mm)	0.03	0.045	0.045	0.045
Core energy density (J/mm^3)	95.2	42.1	91.2	59.1

Immediately observed during the build was that the higher CED samples were running too hot, as they were wicking heat out into the surround powder in a halo around the parts. The parts on the lower end of the CED spectrum likewise showed a visual lack of fully melting, in that dark nuggets forming on the build layer could be seen as opposed to the shiny melt area on the hotter specimens. These 25 density blocks were sent to GRC for destructive microscopy, where they were sectioned in the yz plane, polished through 1-µm diamond, and imaged at magnification using a Nikon® Eclipse MR200 optical microscope. GRC then used *ImageJ* image analysis software to determine the average pore size and average porosity of each specimen, calculated circular equivalent diameters in Excel, and plotted the values on a color map aligned with the parameters (see fig. 1).

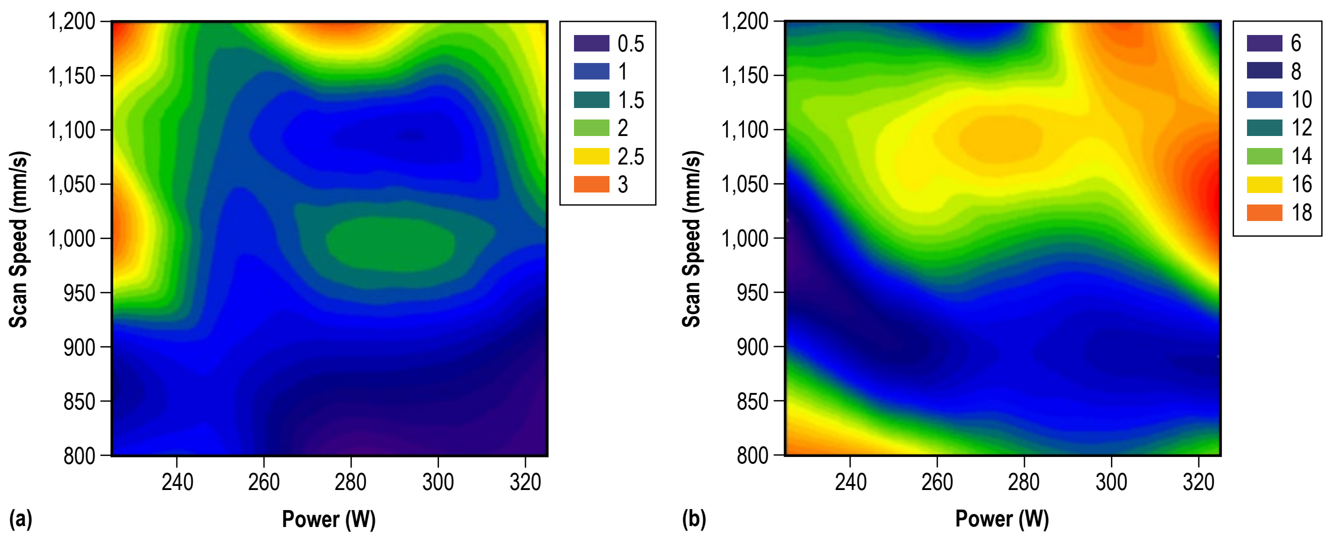

Figure 1. Porosity maps of power versus speed: (a) Overall porosity (%) and (b) average pore size (µm).

The overall porosity and the average pore size maps in figure 1 were then overlaid, which gave 25 parameter sets with >98% density with average pore sizes <15 µm. These parameters, randomized across a single build plate and 25 cylinders, 13 mm in diameter and 100 mm tall in the z direction, each with a different parameter, were 3D printed. Table 3 shows the power (W) versus scan speed (mm/s), as well as the positional callouts for each specimen on the plate. A compass-directional callout was used; in the back, left corner of the build plate is northwest (or NW) and the front, right corner is southeast (or SE), with 'O' being the center specimen.

Table 3. Parameters downselected for GRCop-42 mechanical test bars.

				Qty	**25**
7-1072-3	**230**	**250**	**270**	**290**	**310**
1,175		NW1-1			
1,125		E-1			
1,075		E-2			
1,025		N-1	NE2-2	SE1-2	
975		N-2	O	SE2-1	SW2-1
925	NW2-2	NE1-1	S-1	SE2-2	SW2-2
875	NW2-1	NE1-2	S-2	SW1-1	W1
825	NW1-2	NE2-1	SE1-1	SW1-2	W2
Chess 5 mm; H 0.1 mm (0.15 TW *0.66A1)					
ST 0.045 mm; BC 0.075 mm; IC 0.050 mm; OC 0.075 mm					

4. POST-PROCESS AND MECHANICAL TESTING

These samples were then ran through MSFC's hot isostatic press (HIP) with a standard cycle typically used for GRCop-84, then shipped to GRC for machining and room temperature tensile testing. GRC machined the samples into ASTM E8-style round tensile specimens with 9.525-mm threaded grips and a 6.35-mm-diameter gauge section, then tensile tested them in a crosshead (displacement) control at a crosshead rate of 0.635 mm/min with a 2,275-kg capacity load cell (Standard Test Methods for Tension Testing of Metallic Materials, ASTM International, West Conshohocken, PA, 2013). An extensometer with 19-mm gauge was used to record strain for the first 10% of the test, with a displacement control to ensure quick, consistent tests regardless of the build quality of each specimen.

Figure 2 shows the specimen layout in the PBF build chamber. Colored green, 20 of the specimens resulted in a very tight range of ultimate tensile strengths (UTSs), ranging only from 339 MPa to 356 MPa with elongations >20%. Of the five remaining specimens, two of them (NE1-1 and NE1-2, colored yellow) had in-family UTS but lower elongations of 12% and 15%. Two of them (E-1 and E-2, colored red) broke much lower (180 MPa and 197 MPa) with almost no elongation, while one (NW1-1, colored blue) broke much higher (459 MPa) with medium elongation (12%). The NE1-1, NE1-2, E-1, and E-2 specimens correlate directly to the highest overall porosity and highest average pore size in the initial density study. The NW1-1 sample was inadvertently excluded from the HIP cycle, which explains the very high strength with lower ductility as well.

Specimen	Power/ Speed	UTS (ksi)	Elongation (%)
7-1072-3 NW2-2	230/925	50.5	27.2
7-1072-3 NW1-2	230/825	51.1	27.1
7-1072-3 N-2	250/975	50.8	26.2
7-1072-3 NE1-2	250/925	51.5	15.3
7-1072-3 NE2-2	270/1025	50.8	21.4
7-1072-3 NW2-1	230/875	51.1	26.9
7-1072-3 NW1-1	250/1175	66.7	12.1
7-1072-3 N-1	250/1025	50.8	29.8
7-1072-3 NE1-1	250/925	49.2	12.3
7-1072-3 NE2-1	270/825	51.4	26.4
7-1072-3 W-2	310/825	50.5	27.0
7-1072-3 W-1	310/875	50.8	26.5
7-1072-3 O	270/975	51.0	25.5
7-1072-3 E-1	250/1125	26.1	0
7-1072-3 E-2	250/1075	28.6	1.0
7-1072-3 SW2-1	310/975	50.8	27.8
7-1072-3 SW1-1	290/875	50.3	27.5
7-1072-3 S-1	270/925	51.0	26.3
7-1072-3 SE1-1	270/825	51.4	26.2
7-1072-3 SE2-1	290/975	51.3	0
7-1072-3 SW2-2	310/925	49.9	27.5
7-1072-3 SW1-2	290/825	51.3	26.2
7-1072-3 S-2	270/875	51.2	25.7
7-1072-3 SE1-2	290/1025	51.6	26.8
7-1072-3 SE2-2	290/925	51.1	25.9

Figure 2. Specimen layout in the chamber for mechanical test.

5. CONCLUSION

In this study, MSFC and GRC demonstrated that GRCop-42 is a readily printable alloy that can be additively manufactured into fully dense components with consistent properties at higher throughput rates than its predecessor, GRCop-84. Performing initial parameter testing utilizing average porosity and pore sizes also showed good technique for predicting mechanical properties, particularly elongation values. The most suitable values found for 0.045-mm layers were powers of 270 W and greater, regardless of the speeds ran in this study. A 3D print time savings of about 20% is currently being seen, wherein the aforementioned 28-day nozzle now takes a little over 22 days, almost a week in time advantage.

While higher powers tend to yield higher elongation, however, the porosity begins to increase again, as well as the difficulty in removing powder from the parts due to caking. The goal, therefore, of finding the coolest, fastest parameters resulted in the values shown in table 2, column D, namely 270 W, 1,025 mm/s, or a core energy density of about 59 J/mm^3. As a reminder, this analysis was based on single data points on each density and tensile data, which leads to the next phase of this study.

6. FUTURE WORK—CHARACTERIZATION

What remains for completion is extensive testing of the established nominal parameter set in this study. The next step will be to run several large tensile builds with different lots of powder, with specimens scattered across the entire 250-mm build plate to not only verify the parameter set but also rule out any other external effects like position on the build plate or material lot/vendor. The higher powered scan speeds will also be interesting to tensile test to cement the assumption that porosity predicts elongation, so the plan is to build and test a set of 25 hot-and-fast tensile bars from 290 W at 1,125 mm/s up to 370 W at 925 mm/s if time and resources are found.

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14. ABSTRACT

GRCop-42 (Cu-4 at.% Cr-2 at.% Nb) is a copper-chromium-niobium alloy that NASA developed for use in rocket propulsion components that required high thermal conductivity, excellent creep resistance, low-cycle fatigue life, and strength at elevated temperatures, such as combustion chamber liners and fuel injector face plates. Using powder bed fusion 3D printing, NASA Marshall Space Flight Center and NASA Glenn Research Center successfully printed near-fully-dense GRCop-42 components that may equal or exceed their traditionally manufactured predecessors. This Technical Memorandum serves to summarize the process developed to achieve 3D printable near-fully-dense and functional GRCop-42.

15. SUBJECT TERMS

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