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Additive manufacturing with green lasers for space exploration

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Abstract

Additive Manufacturing (3D printing), is now an accepted form of manufacturing for a range of applications from medical, automotive, consumer products, commercial aviation and most interestingly, space exploration.
Additive processes including EBAM, WAAM and hybrid laser arc have already demonstrated the value that AM can bring to the space industry, for example, in building tanks and structures. To reach the next step in the exploration of our solar system and beyond, we need to focus on better ways of using AM to print propulsion devices for launch vehicles. Laser AM processes in particular, laser powder bed fusion (also called Laser Metal Fusion – LMF) and laser DED (Directed Energy Deposition, also called Laser Metal Deposition - LMD) are the right tools to help us achieve these lofty goals.
Green Laser technology for 3D printing is especially suitable with highly reflective materials such as aluminum, gold and copper. GR Cop 42, a copper alloy developed by NASA, provides improved thermal conductivity with printability in laser metal fusion powder bed machines. We combined LMF and LMD processes with GR Cop 42 and Green Laser technology to investigate methods that can be used to create parts and components for space.

Keywords: Space exploration; additive manufacturing; LMF; LMD; Laser Powder Bed Fusion; Laser DED; Green laser;

1. Introduction

In Laser AM (Additive Manufacturing), the two main processes for metallic materials are Laser Metal Fusion (LMF) and Laser Metal Deposition (LMD), also known as Laser Powder Bed Fusion and Laser DED (Directed Energy Deposition). Both processes are commonly employed, well understood, and use the laser as a heat source. Metal powder is introduced either on a powder bed or with blown powder through a nozzle. Then, the metal is melted and rapidly solidified to create a structure or part by moving the laser where required. The final part is created layer by layer and one can vary the speed and scan strategy accordingly per each design. Standards and certifications are being created every day for new materials and methods with these processes. Some innovative work is taking place in almost every industry sector from automotive to medical, and from consumer products to energy generation, but a particularly exciting is the use of metal AM for space exploration.

1.1. Highly Reflective Materials

Highly reflective metallic materials that are typically used in metal AM of space parts include copper and copper alloys, aluminum alloys, gold, platinum and silver. Many of these materials have advantages such as high electrical and thermal conductivity, low affinity for oxygen (in the case of noble metals), and low density (in the case of aluminum alloys). Traditionally these materials have some difficulties when using IR, or infrared lasers, for laser processes such as cutting and welding since the laser light tends to be reflected away and has difficulties coupling the beam to the metal. When considering small metal powder particles, the same is also true, IR laser light at wavelengths of 1030-1070 nm has difficulties in overcoming the reflectivity so that melting can commence. Particularly for LMF, parts that are 3D printed using reflective materials with standard IR lasers can often result in reduced print quality: porosity, spatter and poor surface finish are examples of what can go wrong. Another consideration is “wear and tear” to the internal laser optics, lenses, etc. and the requirements to clean more frequently and replace damaged parts in LMF machines, which results in increased costs and labor hours.

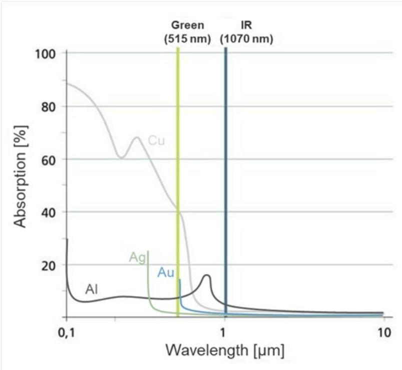


Fig. 1. Comparison of Green and IR laser wavelengths vs absorption

Copper and its alloys are particularly good candidates for laser processing with green lasers. These are lasers with the wavelength of laser light at 515 nm (in the visible spectrum). Contrasted with IR lasers, green lasers’ absorption rate with reflective materials is excellent, Fig. 1. As a result of experience in using green lasers, in particular, cutting and welding of copper sheet metal, the same theory of absorption was applied in the case of metal AM. The resulting prints were of better quality: higher density, less porosity, reduced spatter, and could be printed faster, and with a better surface finish, Fig. 2.

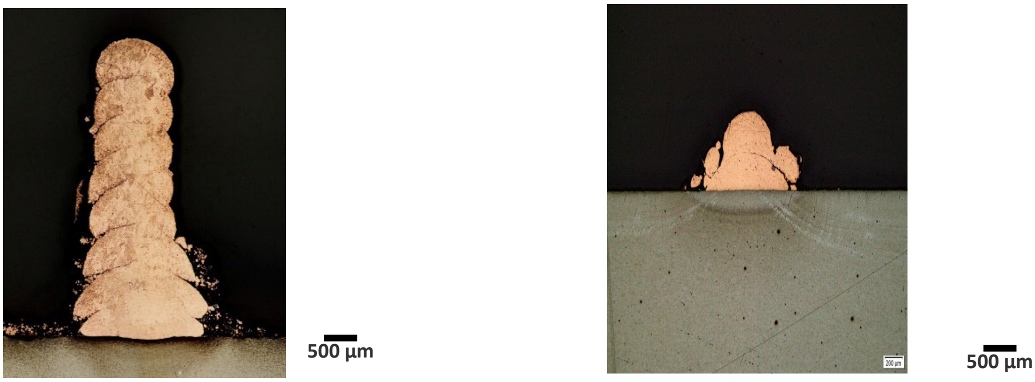
Fig. 2. A microsection through pure copper printed with > 99.9% density.

1.2. *3D Printing for Space Exploration*

With so many metallic components and structures for space exploration being designed for 3D printing, metal AM once again has a huge role to play. From rocket fuel tanks and barrel sections to turbomachinery, the focus for LMF is rocket engine components: combustion chambers, injectors and nozzles. For many of these engine components, a number of launch vehicle manufacturers are moving away from nickel-based superalloys and towards copper alloys, or even a mixture of nickel-copper bi-metallics. Despite the fact that copper alloy strength is not as high as nickel, the thermal conductivity advantages outweigh this. Copper alloy development for engines include C18150 (CuCrZr) and the GR Cop materials. GR Cop 42 in particular is a leading candidate chosen by many space OEMs in the last five years. Clearly the use of green lasers for copper alloy AM would be an advantage for all the reasons previously mentioned -- higher density, less porosity, reduced spatter, and the ability to print faster and with a better surface finish.

1.3. *Initial Deposition of Copper with Green Lasers*

Initial developments with both green and IR lasers were tested in trials with CuCrZr powder in simple deposition on a stainless steel build plate, Fig. 3. Initial trials with IR were stopped after the second layer due to unstable build-up. In contrast, by using the green laser, ten layers were able to be deposited in a stable manner with constant height on each layer.



Fillet built-up with 10 layers of constant height, 515nm

Unstable build-up, process stopped after 2nd layer, 1030nm

Fig. 3. Comparison of Green and IR deposits for “fillet” structure with CuCrZr powder.

Further trials building fillets using both methods, compared a build-up rate of green lasers by 150-200 percent improvement over IR at 1030 nm. For “cuboids”, in order to achieve similar build-up rates with IR radiation, up to 2 to 3 times more power was required (1700-2100 W) versus green at 900 W. Green lasers can print faster with lower power than IR to achieve the same result.

1.4. *LMD trials with Green Lasers*

Green laser LMD was attempted with GR Cop 42 powder. A larger powder particle size (45-106 m) was used with a TruDisk 3022 green laser with 3 kW max power available. 700 watts with a 1.2 mm spot size was used with a powder feed rate of 2 g/min and 1000 mm/min travel speed. A simple racetrack and cylinder shape were printed with excellent surface finish and very little parameter development needed.

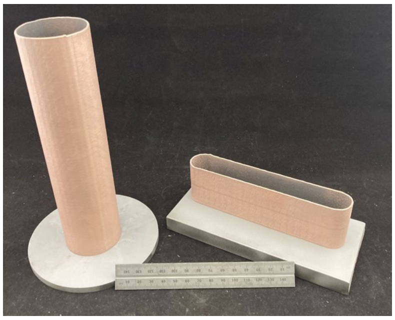


Fig. 4. LMD of GR Cop 42 with Green printed at Fraunhofer ILT (Plymouth, Michigan).

Following this success, further LMD hybrid trials were performed at TRUMPF's Laser Application Center in Plymouth, Michigan. The hybrid nature of the part, combining a green laser LMF part built with GR Cop 42 powder, and followed with LMD of blown 718 powder creates an essentially dissimilar welded component which consists of a six-factor combination in a truly hybrid way, with parameters as shown in Table 1.

Table 1. Hybrid Process Parameters for LMF/LMD part combination.

Process	Material	Wavelength	Laser Power	Powder Particle Size	Powder Feed Rate	Process Speed (Deposition Rate)	Layer Height
LMF on TruPrint 1000	GR Cop 42	515 nm	500W, 200μ spot	15-45μ	n/a	9.5 hours	30μ
LMD with TruDisk 2000 in TruLaser Cell 3000	718	1030 nm	1.4kW, 3mm spot	45-106μ	15g/min	840g/hour	500μ

The key to a successful build is a strong bond between the copper and nickel side: a dissimilar weld. The poor absorption of IR radiation by the copper needs to be overcome. By increasing the size of the fusion zone, the process speed is slowed, stabilizing the weld pool. This resulted in a double-layered fusion zone with larger mixing zone on the nickel side and a thinner zone on the copper side. Microhardness testing of the interface showed a drop with intermetallic mixing as expected when welding copper alloys and pores /defects observed were the result of ejected metal from the melt pool when meeting the higher laser power. Decreasing the speed in the interface zone to reduce spatter, or by using a graded material approach, or buttering layer, could provide a smoother transition to decrease presence of defects. Another approach might be to use green laser wavelength for both reflective and non-reflective material in the same build.

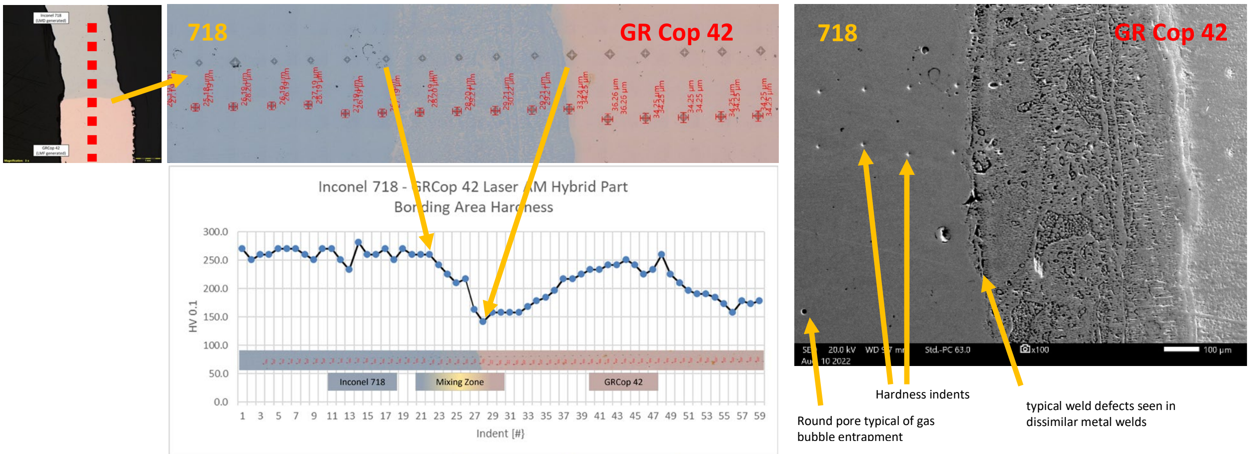


Fig. 5. Interface zone showing typical defects seen in dissimilar weld joints and hardness drops.

2. Next steps in copper nozzle development

LMD has productivity gains over LMF when it comes to printing large structures. Using a green laser optic provided by TRUMPF, RPMI (Rapid City, South Dakota) also printed copper nozzle shapes with GR Cop 42. The optic power available was 1 kW but the laser was run at 650 watts and integrated into their own RPMI 222 system. The build time for the sample structure (approx. 16 inches in height with 0.045” (1.143 mm) wall thickness), was only 52 hours, Fig. 6.

Fig. 6. Initial GR Cop 42 structure build by RPMI using a TRUMPF green laser optic.

Following this encouraging first step, RPMI also went on to create a bi-metallic LMD part, with GR Cop 42 and 625 with the same green laser optic on both materials. A green laser optic provided by TRUMPF was integrated into their larger RPMI 557 system which has multiple powder hoppers. The part shown in Fig. 7 had final dimensions of:

- GR Cop 42 wall thickness 0.045” (1.143 mm)
- 625 wall thickness 0.080” (2.032 mm)
- Minimum channel size: 0.100” x 0.100” (2.54 mm x 2.54 mm)
- Fwd OD: 4.5” (114.3 mm)
- Aft OD: 9.5” (241.3 mm)
- Height: 16” (406.4 mm)
- Build Time: 175 hours

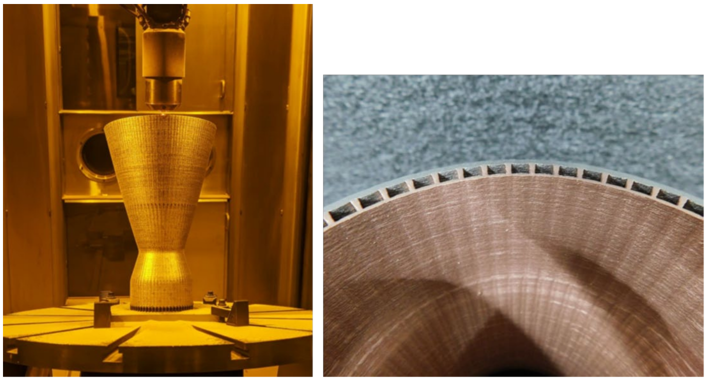


Fig. 7. Bi-metallic GR Cop 42- 625 structure build by RPMI using TRUMPF green lasers.

3. Conclusion

The initial work with green lasers on 3D printing copper alloys, particularly GR Cop 42, was developed from experience with cutting and welding copper sheet metal product. Using the best choice of process parameters for LMF, parts can be printed faster, with better density, and better surface finish. The resulting productivity gains also mean that more and new designs can be printed, faster.

Translating this effort to LMD, both hybrid processing and freeform structure building can be envisioned. For an LMF/LMD component with six-factor combination, a bi-metallic component that was hybrid in the true sense of the word was created for the first time. Several factors can be improved upon further, so that the interface between the dissimilar materials can be printed with better quality.

For space exploration, the door to 3D printing copper rocket engine components is now open. As more of these structures are printed, the process will be validated using hot fire testing, which will be seen in the next coming years. The true test will be to attach these engine components to space launch vehicles and successfully launch, achieve max Q (maximum dynamic pressure) and then reach orbit. Whether the future lies in large-scale LMD freeform structures, such as full-size copper rocket nozzles, or more bi-metallic hybrid components, metal AM with green lasers has shown a lot of potential to help the efficacy of space exploration which is an exciting development.

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