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EVALUATION OF GREEN LASER SOURCE ADDITIVE MANUFACTURING TECHNOLOGY FOR ACCELERATOR APPLICATIONS WITH ULTRA-HIGH VACUUM REQUIREMENTS*

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Abstract

Additive Manufacturing (AM) offers different benefits such as efficient material usage, reduced production time and design freedom. Moreover, with continuous technological developments, AM expands in versatility and different material usage capabilities. Recently new energy sources have been developed for AM – green wavelength lasers, which provide better energy absorption for pure copper. Due to high thermal and electrical conductivity of copper, this novel AM technology is highly promising for various industries, particularly, there is a huge interest to use it for accelerator applications. In particular, these AM produced accelerator components should reach the associated Ultra High Vacuum (UHV) requirements. In this study, vacuum membranes of pure copper were produced by AM using a green laser source, in different thicknesses and built angles. Furthermore, a vacuum membrane helium leak tightness test was performed at room temperature by using a high-sensitivity mass spectrometer. Comparison of these test results was performed with previously established results. Through this study, novel knowledge and initial results are provided for green laser source AM technology usage for applications for UHV accelerator components.

INTRODUCTION

AM technologies, by which parts are built layer-by-layer from the existing 3D models, are getting more and more used in industry. AM technologies can demonstrate most of their benefits if complex and functional designs are implemented for small and medium batch sizes. The technologies have been developed constantly according to demand. Recently, new laser sources have been introduced that can more efficiently deal with highly reflective materials such as copper by using laser powder bed fusion (LPBF).

These aspects perfectly match many accelerator applications' needs. Especially, the accelerator community is interested in pure copper material usage for room temperature applications due to its high electrical and thermal conductivity. However, accelerator applications require a vacuum and even UHV compatibility as well. Therefore, in order to evaluate the performance of AM components for UHV applications, literature research has been initially performed.

The literature survey shows that AM usage within UHV applications has been investigated in several publications. In [1, 2] UHV applications were considered and LPBF manufacturing technology was used, but direct UHV characterisation like vacuum tests was not investigated.

On the other hand, in literature [3-6] not only LPBF was used, but also vacuum tightness was positively tested against UHV requirements. Even more, in [3, 6] outgassing rate was monitored. However, AlSi10Mg, Ni-5Mo-15Fe alloy and 316L materials were used instead of pure copper. Finally, in [7] pure copper UHV applications were investigated by testing vacuum and outgassing properties. However, in this research electron beam PBF was used instead of LPBF.

Literature review results show that there is interest in the AM UHV applications and the presented results reached the current requirements for UHV usage. Despite these encouraging published results, there is a lack of information regarding pure copper and green wavelength laser (515 nm), which provide better energy absorption for copper materials, AM compatibility with UHV applications. In this respect there is also the need to investigate current green wavelength laser technological limitations such as the minimal wall thickness which can satisfy the UHV requirements. Therefore, the aim of this research is the investigation of specially designed test membranes to find the wall thickness limits for pure copper components built by AM with a green laser, that are still applicable for UHV by fulfilling the leakage test.

MATERIALS, EQUIPMENT AND METHODS

To achieve this set aim, special test membranes were produced by AM with a green laser source and those membranes were leak tested.

AM Equipment Setup and Material

A TruPrint1000 Green Edition LPBF system in combination with a green TruDisk1020 laser (wavelength of 515 nm) with maximum laser power of 500 W was used at Fraunhofer IWS in Dresden. The process parameters used in the present study were based on previous

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investigations published by Gruber et al. [8] and successfully applied by Torims et al. [9]. In particular, the selected layer thickness and laser spot size are 30 μm and 200 μm, respectively.

Copper Cu-ETP (Electrolytic Tough Pitch) gas-atomized spherical shaped powder was used for the AM build process. The powder particle size distribution was between 19.5 and 34.9 μm.

Test Samples Manufacturing and Preparation

Previously mentioned equipment, setup and materials were used to manufacture the test membranes which can be seen in Fig. 1. The thickness – Z of the samples was varied as follows: 2.5, 2, 1.5, 1, 0.75, 0.5 mm.

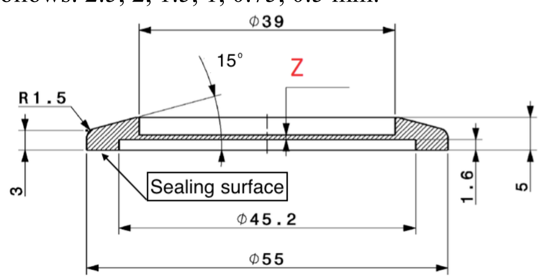

Figure 1: DN40 KF CERN standard leak test design.

In order to investigate the effect of AM build angle, three build angles were tested 90°, 67° and 45° (Fig. 2.). Orientations between 90° and 45° are considered as the most suitable for AM build jobs. The same built angles were used for Radio Frequency Quadrupole prototype [9, 10].

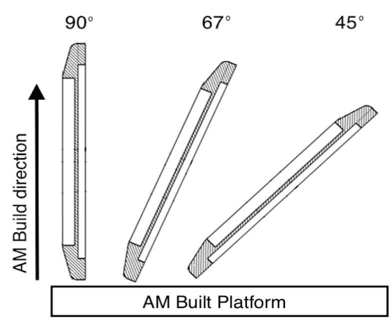

Figure 2: Scheme of membrane manufacturing angles.

Membranes after the manufacturing process were removed from the powder bed, and regular AM procedures were applied to remove samples from the built plate e.g. removal of support structures and for cleaning. The Ra of AM parts can range from 10 to 15 μm, as shown in [9]. Machining was done for the sealing surface (Fig. 1 and Fig. 4) by using a lathe, to reduce roughness and assure a circular surface pattern to provide better sealing characteristics.

UHV Test, Equipment and Requirements

For UHV systems the helium test method is used to detect leaks for the following reasons:

- Leaks below $1{\cdot}10^{-6}$ mbar·l·s^{-1} and down to 10^{-10} mbar·l·s^{-1} can be detected;
- there is a low concentration of helium in the atmospherc air, approximately only 5ppm, so the background level is very low;
- Helium is an inert gas and will not react with most other substances, plus it is non-flammable and harmless;
- Helium is non-condensable throughout technical applications, and lighter than air, meaning if leaks accidentally occur from the test system, the gas moves upwards;
- The gas is widely available at affordable prices.

In the particular test that was carried out at CERN, Leybold Phoenix 300i equipment was used. The leak tests are carried out at room temperature. Vacuum is provided into the system at 10^{-3} mbar. When the background value is below the detection limit (10^{-10} mbar·l·s^{-1}), helium is sprayed for 10 to 30 seconds in an enclosure on top of the upper surface of the pure Cu disk to reach He concentration close to 100%. The He signal is recorded to detect any leak. The test set-up can be seen in the Fig. 3.

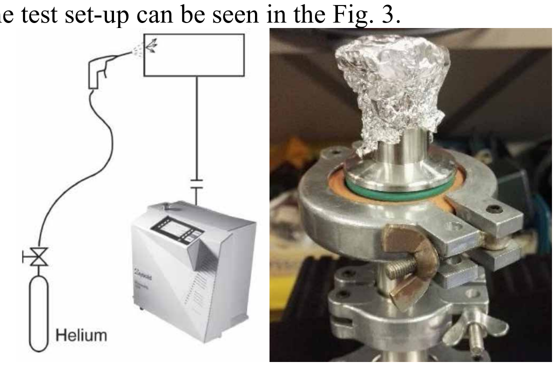

Figure 3: He leakage test set-up [11].

To classify components as suitable for UHV applications in terms of leak-tightness, no helium signal shall be seen with a sensitivity of at least 10^{-10} mbar·l·s^{-1}.

RESULTS

Pure copper membranes (18 pieces) were successfully built by AM (Fig. 4).

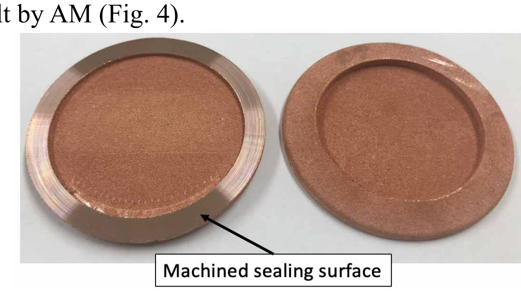

Figure 4: UHV Test membranes.

The leak detector threshold value is set as $1{\cdot}10^{-10}$mbar·l·s^{-1} according to CERN Criteria for vacuum acceptance tests [12] and if the value is reached or even exceeded, then the helium leakage test is considered as passed (in Table 1 – "PASS"). If the test is not passed, then the exact reading of the experiment is given.

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After the test for the samples with wall thickness 0.5 mm that did not pass the helium leakage test membrane surface deformation was noticed.

Table 1: Helium Tightness Results

Thickness Z (mm)	**Angle/Result (mbar/l/s^{-1})**		
	45°	**67°**	**90°**
2.5	PASS	PASS	PASS
2	PASS	PASS	PASS
1.5	PASS	PASS	PASS
1	PASS	PASS	PASS
0.75	PASS	PASS	**$1{\cdot}10^{-6}$**
0.5	PASS	**$2.5{\cdot}10^{-3}$**	**$5{\cdot}10^{-2}$**

DISCUSSION

As summarized in Table 1, in the helium leakage test for AM built pure copper test membranes, only three samples out of 18 did not pass UHV leak requirements. However, those samples in the test reached $5{\cdot}10^{-2}$, $2.5{\cdot}10^{-3}$ and $1{\cdot}10^{-6}$ mbar·l·s^{-1}, where those leaks can be classified as water, vapour and virus tight respectively.

The real wall thickness can influence the test results. The AM-manufactured wall depends on the powder size distribution, laser scanning paths, the laser spot size and in the case of copper also the porous, rough surface layer in range of 150 µm [8]. Those small defects from both sides could reduce the monolith wall thickness by up to 200 to 300 µm.

It was observed that results depend on the membrane build angle. The explanation comes from the fact that by varying the AM build angle from 90° to 45°, the wall "cross-section" (the area which is scanned by the laser during one layer) is getting larger. As a result, it makes internal defects less impactful at 45° build angle.

According to the results, the membrane deformations did not occur for 0.5 mm samples built at 45° angle, which can lead to conclude that wall mechanical integrity is higher for those samples than samples built at 67° and 90°. However, Gruber et el. [8] after the tensile tests concluded that 45° built angle showed lower mechanical properties compared to 90° as well as Cu grains in AM process typically grove parallel to the build direction. So, clear conclusions cannot be made without detailed research.

The next step to ensure and test UHV requirements is for an outgassing test to be performed. As well to ensure more evidence regarding AM build direction influence on the leak tightness and other UHV requirements, consequent tests with different built angles and supports structures should be done.

CONCLUSION

The helium leakage test was successfully run for pure copper membranes built by AM with a green laser source (wavelength of 515 nm), with varied wall thicknesses and build angles.

According to the test results and discussions, the following can be concluded:

- Membranes in all wall thicknesses down to 0.5 mm were successfully built with the green laser source;
- The green laser source is applicable for thin wall UHV applications;
- 1 mm wall thicknesses can provide UHV leak tightness in all applied build angles (90°; 67° and 45°);
- 0.5 mm wall thickness samples deserve more accurate investigation before drawing concluding results.

Achieved results are better than expected which can be applied to accelerators and vacuum systems that are operating at room temperatures, such as linear accelerators, beam transfer lines and injectors with larger designing flexibility. Furthermore, this research in comparison with others that are described previously gives more applicable information by showing the AM technology opportunities.

REFERENCES

[1] F. Grazzi *et al.*, "A multi-technique tomography-based approach for non-invasive characterization of additive manufacturing components in view of vacuum/UHV applications: preliminary results", *Rendiconti Lincei. Scienze Fisiche e Naturali*, vol. 32, p. 463–477, 2021. doi: 10.1007/s12210-021-00994-2

[2] R. McCann, C. Hughes, D. Brabazon, "Laser Powder Bed Fusion of Aluminium Alloy 6061 for Ultra-High Vacuum Applications", *Key Engineering Materials*, vol. 926, p. 242–249, 2022. doi:10.4028/p-zg7019

[3] N. Cooper *et al.*, "Additively manufactured ultra-high vacuum chamber for portable quantum technologies". *Additive Manufacturing*, vol. 40, 2021. doi:10.1016/j.addma.2021.101898

[4] J. Vovrosh *et al.*, "Additive manufacturing of magnetic shielding and ultra-high vacuum flange for cold atom sensors". *Scientific Reports,* vol. 8, 2018. doi:10.1038/s41598-018-20352-x

[5] S. Jenzer *et al.*, "Study of the suitability of 3D printing for Ultra-High Vacuum applications". *Journal of Physics: Conference Series*, 874, 2017. doi:10.1088/1742-6596/874/1/012097

[6] S. Jenzer *et al.*, "Is it possible to use additive manufacturing for accelerator UHV beam pipes?". *Journal of Physics: Conference Series*, vol. 1350, no. 1, p. 012199, 2019. doi:10.1088/1742-6596/1350/1/012199

[7] G. Lanza *et al.*, "Outgassing of Electron Beam Printed Copper," *2021 22nd International Vacuum Electronics Conference (IVEC)*, Rotterdam, Netherlands, 2021. doi:10.1109/IVEC51707.2021.9722518

[8] S. Gruber *et al.*, "Physical and Geometrical Properties of Additively Manufactured Pure Copper Samples Using a Green Laser Source". *Materials*, vol. 14, p. 3642, 2021. doi:10.3390/ma14133642

[9] T. Torims *et al.*, "First Proof-of-Concept Prototype of an Additive Manufactured Radio Frequency Quadrupole". *Instruments*, vol. 5, no. 4, p. 35, 2021. doi:10.3390/instruments5040035

[10] T. Torims *et al.*, "Evaluation of geometrical precision and surface roughness quality for the additively manufactured radio frequency quadrupole prototype". *Journal of Physics: Conference Series 2420*, p. 787-791, 2023. doi:10.1088/1742-6596/2420/1/012089

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPM031

[11] *Fundamentals of leak detection*. Cologne, Germany December 2016. https://www.leyboldproducts.com/media/pdf/90/c7/87/Fundamentals_of_Leak_Detection_EN.pdf

[12] P. Chiggiato, "J. A. F. Somoza Criteria for vacuum acceptance tests". CERN Technology Department EDMS, No.1752123. Geneva, November 2018.