Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Is it possible to use additive manufacturing for accelerator UHV beam pipes?

To cite this article: S. Jenzer *et al* 2019 *J. Phys.: Conf. Ser.* **1350** 012199

Is it possible to use additive manufacturing for accelerator UHV beam pipes?

S. Jenzer[1], M. Alves[1], S. Bilgen[1], J. Bonis[1], F. Brisset[2], S. Djelali[1], A. Gonnin[1], M. Guerrier[1], D. Grasset[1], F. Letellier-Cohen[1], B. Mercier[1], E. Mistretta[1] and G. Sattonnay[1*]

[1] LAL, Univ. Paris Sud, CNRS/IN2P3, Orsay, France
[2] ICMMO, Univ. Paris Sud, CNRS, Orsay, France

E-mail: *sattonnay@lal.in2p3.fr

Abstract. Additive Manufacturing (AM) enables 3D metallic objects to be built by adding layer-upon-layer of material. This technology can be applied to produce Ultra High Vacuum components for particle accelerators. We investigated in this work the reproducibility of AM 316L stainless steel properties for different specimens supplied by several manufacturers with the same process. Microstructure and mechanical properties of AM samples depends on manufacturers: indeed, they are largely influenced by processing parameters, which produces heterogeneous and anisotropic microstructures that differ from traditional wrought counterparts. The outgassing rates of vacuum AM 316L tubes were determined and the secondary electron yield was also measured. Results are very promising to consider the use of AM to construct accelerator beam pipe components.

1. Introduction

Recently, additive manufacturing (AM) has revolutionized mechanical engineering by allowing the quick production of mechanical components with complex shapes. AM by selective laser melting (SLM) is an advanced manufacturing process which uses lasers to melt metal powders one layer at a time to produce final 3D components. This technology could be also used to make Ultra High Vacuum (UHV) components. Nevertheless, the microstructures and therefore the mechanical properties of AM components are largely influenced by processing parameters, including laser power, scanning speed and powder granulometry. AM components are subjected to a complex thermal history as the material first undergoes a rapid solidification, and then is heated and cooled with each additional layer. These complex thermal cycles can create heterogeneous and anisotropic microstructures that differ from traditional wrought counterparts. To be used in accelerator beam pipes, UHV compatibility of AM components must be tested. Moreover, due to dynamic pressure effects occurring when a particle beam circulates in an accelerator, fundamental factors involved in the electron cloud phenomenon, such as the secondary electron yield (SEY) of the material surface, must be measured.

Therefore, we investigated in this work the reproducibility of AM 316L stainless steel properties for different specimens supplied by several manufacturers with the same SLM process. Outgassing rates of unbaked and baked vacuum tubes were measured and the SEY was determined for unbaked samples but with a different surface roughness. In all cases, results were compared to those obtained with a conventional 316L stainless steel.

2. Microstructural and mechanical characterisation

The SLM 3D additive manufacturing method is likely to introduce strong microstructure anisotropies inducing anisotropy of mechanical properties. It is therefore essential to characterize samples from different manufacturers in order to highlight these anisotropies according to the provenance of the manufactured specimens. For this, several complementary analysis techniques -Scanning electron microscopy coupled with Electron BackScatter Diffraction (SEM / EBSD), X-ray Diffraction (XRD), confocal microscopy- have been implemented in order to show the relationship between the micro-structure and the mechanical properties. The sides of the samples, that have been characterized, are surfaces parallel to the build plate of the AM machine or perpendicular to the plate. These samples were made on the same build plates as the tensile test pieces (Fig. 1).

Figure 1. Example of additive manufacturing build plate.

An important result is that the microstructure (grain size, texture) of the samples depends on the manufacturer (Fig. 2).

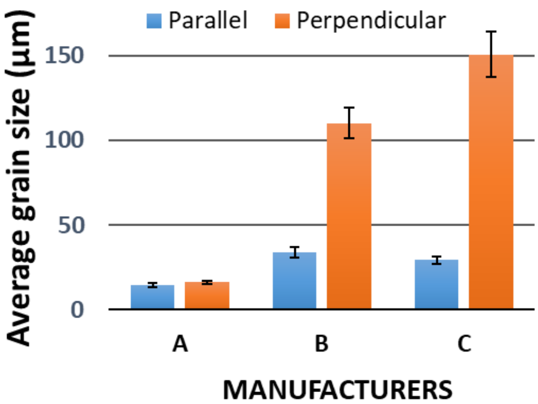

Figure 2. Average grain size for samples produced by different manufacturers and for two different orientations: parallel or perpendicular to the build plate.

On average, the grain size of samples from manufacturer C has a larger grain size (150 µm) than those of the manufacturer B (110 µm) and the manufacturer A (16 µm), a difference that is particularly visible on the perpendicular faces. By comparing the grain sizes deter-mined for parallel sides with those obtained for sides perpendicular to the plate, we notice an anisotropy of the grain size for a given sample (the grain size is larger for the perpendicular side than for the parallel one). In most cases, long columnar grains oriented perpendicular to the build plate (direction of growth) are observed. This microstructure is associated with the presence of thermal gradients between the build plate and the sample surface during the processing of layer-by-layer deposition).

Moreover, EBSD/SEM images in Fig. 3 show very clearly a difference of preferential orientation (crystal-line texture) between the samples of A, B and C.

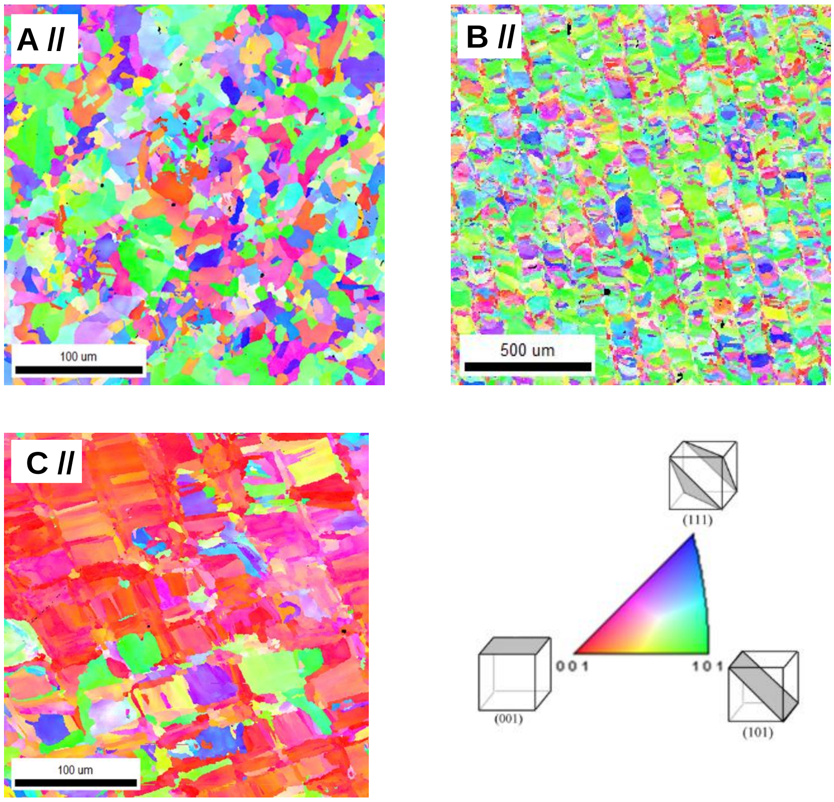

Figure 3. EBSD images for AM 316L samples, side parallel to the build plate, from different manufacturers (A, B and C) and standard stereographic triangle.

The sample of the manufacturer A has no marked texture (no color is predominant), whereas the samples of the manufacturer B have a majority of green and blue (thus a texture in the directions <101> and <111>) whereas the sample of the manufacturer C shows a strong preferential orientation along the <001> direction (red color is predominant).

In summary, although the samples were obtained with the same additive manufacturing technique (SLM), important differences in morphology and grain size between the samples are observed, with a strong orientation anisotropy, which is also different from one manufacturer to another. This feature can impact the mechanical properties of AM components.

Tensile specimens from the three manufacturers were characterized, with three different directions of growth (see Fig. 1): horizontal, vertical or inclined at 45° to the plate. Figure 4 summarizes results for the yield strength. Each value is an average determined for each type of sample from five tensile tests. The microstructural anisotropy that has been observed also causes anisotropy of the mechanical properties since the yield strength depends on the growth direction of the specimen. In particular, it appears that the 45° samples have the highest yield strength. The differences in microstructure found for the samples developed by the different manufacturers also affect the mechanical properties. Thus, the mechanical characteristics are better for the manufacturer C than for the B and the A. Moreover, it is worth noting that the yield strength of AM specimens is higher than those of as-cast counterparts indicating finally that AM can be beneficial for the mechanical properties.

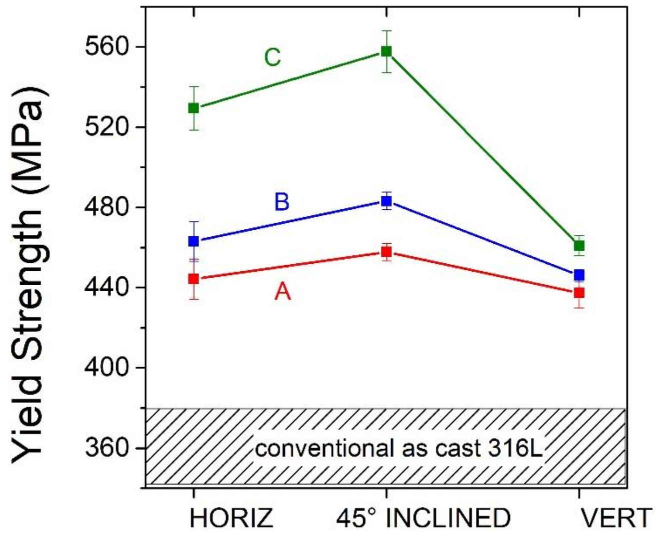

Figure 4. Yield strength determined on AM 316L tensile test specimens from different manufacturers (A, B, C), for horizontal, vertical and 45° inclined growths with respect to the build plate and comparison with the one of as cast counterparts [1].

Further investigation should be performed to study the structural stability of AM material properties after heat treatments reproducing baking at high temperature.

3. Outgassing test

To test the suitability of 3D printing to UHV applications, we have acquired 130mm long DN40CF tubes in 316L stainless steel produced by AM (Fig. 5).

Figure 5. DN40CF tubes in 316L stainless steel by AM.

As expected the surface quality of 3D printed tubes is very different of that obtained from conventional techniques. A previous work showed that the flanges must be lathed to avoid leaks [2]. We investigated both the case where only the flanges are lathed and the case where both the flanges and the tube inside are lathed. The surface roughness of the raw tubes was measured to be Ra = 8.5 µm to 10 µm.

Outgassing rates were determined by the gas accumulation method (also known as the rate of rise method). Unbaked and baked AM tubes were tested and compared to conventional tubes. Figure 6 shows the pressure rises measured during the outgassing tests for all tubes.

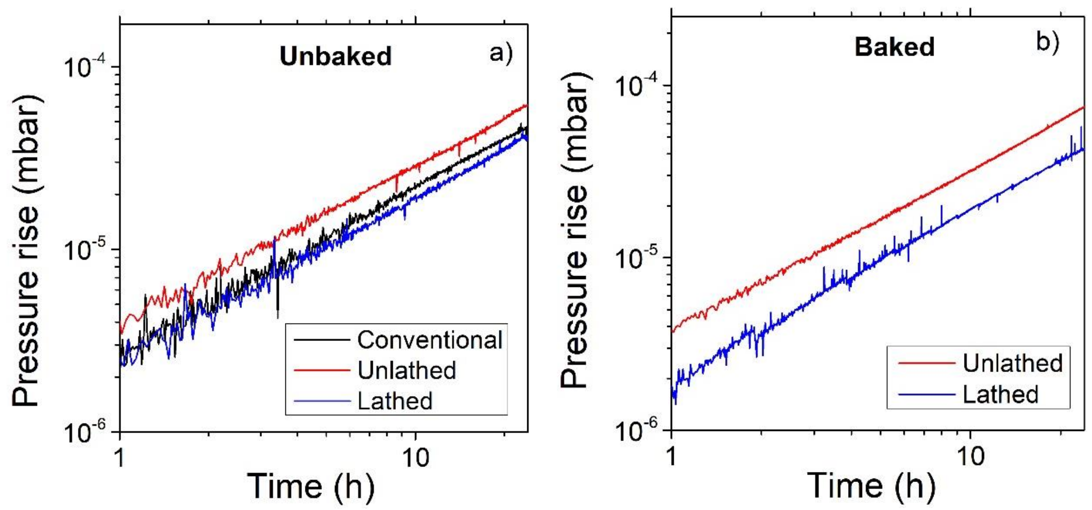

Figure 6. Pressure rise (N_2 equivalent) as function of time for conventional, unlathed AM and lathed AM tubes: unbaked (a) and baked under vacuum at 200°C (b) respectively.

Outgassing rates for 100h of pumping are reported in Table 1 for unbaked tubes and after baking under vacuum at 200°C during 72h.

Table 1. Outgassing Rates at 100h (T=20°C)

Treatment	Tube	Outgassing rate (mbar.l/s.cm^2)
Unbaked	Conventional	$6.0\text{x}10^{-12}$
	Unlathed AM	$5.6\text{x}10^{-12}$
	Lathed AM	$7\text{x}10^{-12}$
Baked at 200 °C	Unlathed AM	$3.6\text{x}10^{-13}$
	Lathed AM	$3.4\text{x}10^{-13}$

Values of AM tubes and conventional ones are equivalent, in agreement with literature data [3]. Moreover, the surface roughness has no impact on the results. Outgassing rate is one order of magnitude lower for baked tubes than for unbaked ones.

4. SEY measurement

SEY measurements versus electron energy were performed on as-received and polished AM samples in order to study the influence of surface roughness (9±1µm and 0.35±0.05 µm for the as-received and the polished samples, respectively). Measurements were also performed on a conventional 316L sample with a surface roughness of 1µm. No baking was performed on samples. The SEY (δ), i.e. the ratio of the number of electrons leaving the sample surface (I_s) to the number of incident electrons (I_p) per unit area, is determined experimentally by measuring I_p and the total sample current $I_T=I_p–I_S$ so that $\delta = 1\text{-}I_T/I_P$. To measure I_p and I_T, a negative bias voltage (-20 V) and a positive bias (+50V) respectively, was applied to the sample. Short pulses (30 ms) of low intensity (some nA) are used to reduce the electron dose received by the sample. Samples were irradiated at a primary electron energy E_p=500 eV up to a total dose of Q=1.5x10^{-2} C/mm^2 to perform a conditioning of the surface. Figure 7 shows that the SEY curves measured on the as-received and polished samples exhibit a same δ_{max} value of 2.8 whereas for the conventional sample δ_{max} is lower (2.3).

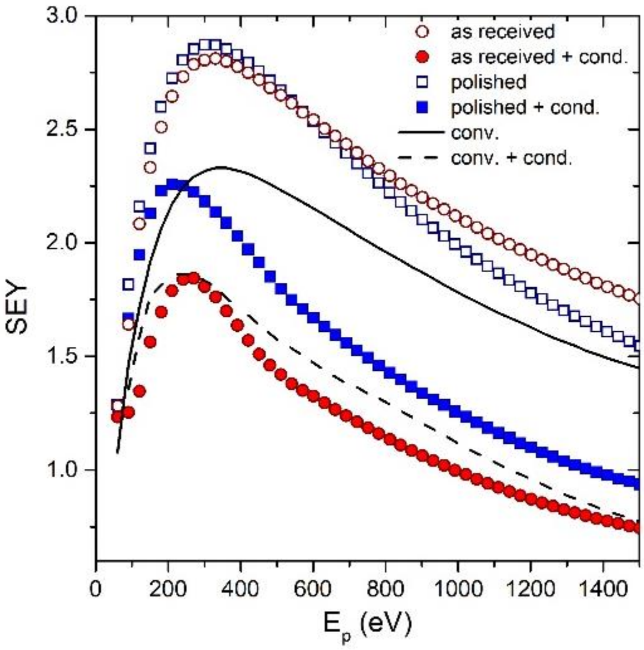

Figure 7. SEY curves measured on the as received AM 316L (circles), on the polished AM 316L (squares) and on the conventional 316L (lines) before and after conditioning with 500 eV electrons.

After electron conditioning, a decreasing of SEY is observed: the SEY curve presents a δ_{max} value of 1.84, 2.25 and 1.87 on the as-received AM, the polished AM and the conventional 316L samples, respectively. This result shows that the roughness of AM samples is beneficial and accentuates the efficiency of surface scrubbing. The higher decrease in δ_{max} is obtained for the as-received AM specimen (0.96 compared with about 0.5 for the other samples). Further investigation is needed to explain this phenomenon.

5. Conclusion

316 L stainless steel samples were fabricated using AM via SLM in order to investigate first the anisotropy induced by the manufacturing processing of both microstructure and tensile mechanical properties. AM samples exhibit a higher yield strength than conventional 316L steels. Secondly, the outgassing rates measured on AM tubes are found to be UHV compatible. We have also shown than the SEY of AM samples can be decreased by electron scrubbing even for samples with a high roughness.

This work demonstrates the potential of AM to create UHV components with high performance for accelerator beam pipes.

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