

Porous metal aerostatic bearing restrictors manufactured with laser-based powder bed fusion

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Abstract

Aerostatic bearings are commonly used in precision and high-speed applications. Porous aerostatic bearings separate surfaces with a high-pressure gas film. The bearing type has no static friction and negligible dynamic friction at low speeds. Porous graphite is commonly used due to its crash resistance and the availability of the material with suitable permeability. However, the variability in material permeability leads to variation in bearing performance. Laser-based powder bed fusion of metals has been proposed as a method for manufacturing porous aerostatic bearing restrictors, with permeability adjustable by manufacturing parameters such as hatch spacing and laser power. In this study, a batch of four sets of four samples was manufactured, each set manufactured with a different hatch spacing. The permeability of the samples was measured before and after abrasive finishing, and the static load capacity, air consumption, and gap height were measured. The results were compared to a set of commercial porous graphite aerostatic bearings. The permeability and air consumption of the porous metal bearing samples were similar to those of the porous graphite bearings, with three out of the four sets showing similar results. The porous metal bearings had lower gap height than the porous graphite bearings at the same loads. The results indicate that the investigated porous aerostatic bearings, manufactured with laser-based powder bed fusion of metals, exhibit a level of repeatability similar to the tested set of commercial porous graphite aerostatic bearings.

Additive manufacturing, Gas bearing, PBF-LB/M, 3D printing

1. Introduction

Aerostatic bearings are used in precision engineering applications, including coordinate-measuring machines and high-speed spindles, where low friction and the absence of stick-slip are required. Aerostatic bearings are gas bearings that utilise an external pressure supply to form a thin, high-pressure film between the bearing and the opposing surface separating the surfaces [1]. Film thickness commonly ranges from 1-10 μm [1] to 5-20 μm [2], depending on the application. Compressed air is commonly used as it is readily available in industrial settings. The static friction of aerostatic bearings is zero, and the dynamic friction due to gas film shearing is negligible at low speeds [1].

Aerostatic bearings have a restrictor to limit the flow rate and to distribute the supplied pressurised gas to the gap between the bearing and the opposing surface. The permeability of the restrictor influences the stability, stiffness, load capacity, and operating gas consumption of the bearing. The restrictor types include porous median, slot, groove and orifice [2]. Bearings with porous restrictors generally exhibit high stiffness and load capacity while remaining stable [2].

A common material for porous median aerostatic bearing restrictors is synthetic porous graphite, such as graphite made for electrical discharge machining (EDM) electrodes. Graphite has favourable properties for use as a restrictor material due to its porous nature and crash resistance [1,3]. Although porous graphite aerostatic bearings have favourable properties, variation in graphite permeability affects the reproducibility [3]. Additional lacquer impregnation of the restrictor surface can be done to adjust the permeability [4-5]. The variation in

performance limits the use of porous graphite aerostatic bearings in precision applications [3, 6].

The manufacturing of porous median restrictors using an additive manufacturing (AM) method, laser-based powder bed fusion of metals (PBF-LB/M), has been proposed where the open porosity of the restrictor is controlled by varying the laser power [7] or hatch spacing [8-9]. A grid pattern of vertical pillar-shaped pores spanning through the restrictor can be achieved with a suitable scan pattern and large enough hatch spacing to prevent full melting of the powder bed. There has been only limited research on this method to produce porous restrictors.

Previously, the authors have presented the manufacturing of porous metal aerostatic bearing restrictors with permeability and static load capacity comparable to porous graphite aerostatic bearings [9-10]. In the present study, the number of samples manufactured with the same hatch spacing is increased to four to evaluate the repeatability of the manufacturing process. The permeability, static load capacity, air consumption, and air gap height of four sets of porous metal aerostatic bearing samples are evaluated and compared with those of a set of four commercial porous graphite aerostatic bearings.

2. Methods

2.1. Bearing samples

The porous metal restrictors were manufactured with PBF-LB/M AM method from PH1 stainless steel powder. The restrictors were 37 mm diameter disks manufactured flat on the build plate. 0.5 mm of the outer edge of the disks was manufactured solid, and the rest was manufactured with varying hatch spacing parameters to achieve open porosity throughout

the sample. The hatch spacing values were selected based on the study by Leutonen et al. [9], which used similar samples with hatch spacings ranging from 110 μm to 220 μm . In the present study, hatch spacings of 165 μm , 170 μm , 180 μm , and 190 μm were used. Four samples for each hatch spacing parameter value were manufactured.

In the AM process of the porous restrictor, a meander pattern with 90° rotation was used with a layer height of 40 μm , a scan speed of 1083 m/s, a laser power of 225 W, and a laser spot diameter of 80 μm . No upskin was used to leave the pores open. The restrictors were cut to a thickness of 4.5 mm with wire EDM as the samples were removed from the build plate. The restrictors were mounted to bearing bodies with epoxy adhesive (Figures 1 and 2) as is commonly done with graphite restrictors.



Figure 1. Anodised aluminium bearing body with air supply grooves. Epoxy adhesive applied with a robot [11].



Figure 2. Porous metal restrictor cut with wire EDM joined to the bearing body with adhesive.

Due to the internal stress from the AM process, the restrictor disks had deformed after removal from the build plate to an extent rendering them unsuitable for aerostatic bearings (Figure 3). The restrictors were finished first with 100 μm and then with 30 μm abrasive film until a flat surface was achieved (Figure 4). Light abrasive finishing was used to minimise smearing of the metal surface, which could block the pores. A finished sample is shown in Figure 5, and the porous surface is shown in Figure 6.

A set of four commercial New Way porous graphite aerostatic bearings with the same porous restrictor dimensions was selected as a reference for the performance measurements.

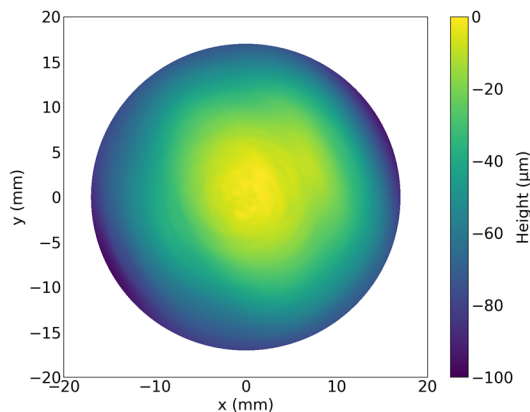


Figure 3. Exemplary restrictor surface flatness, measured with a contacting form measurement machine, after removal from the build plate with wire EDM.

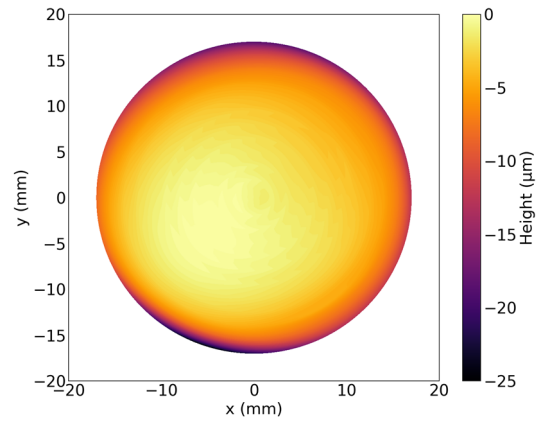


Figure 4. Exemplary restrictor surface flatness, measured with a contacting form measurement machine, of the same sample as in Figure 3 after abrasive finishing. The scale is different to Figure 3.



Figure 5. Sample finished with an abrasive.

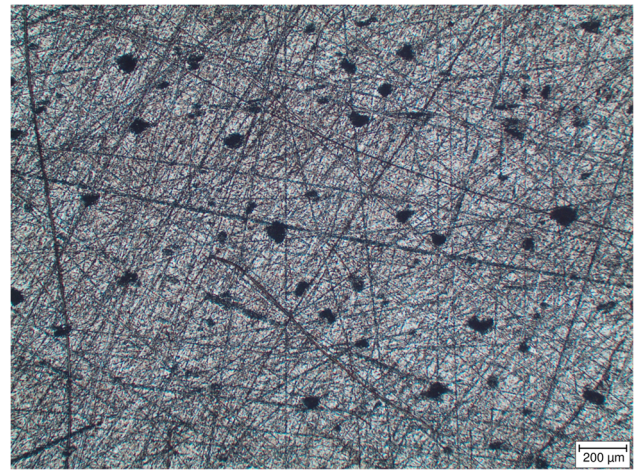


Figure 6. Restrictor surface of sample with 190 μm hatch spacing after abrasive finishing.

2.2. Measurement setup and procedure

The automated measurement setup is presented in Figure 7. The bearing sample was mounted to a four-bar linkage system with a ball joint. The four bar linkage system had flexures to enable free movement only in the vertical direction. A force was applied to the loading bar with a pneumatic cylinder. The applied load was measured with a force transducer mounted between the four-bar linkage system and the ball joint. The gap height between bearing and the opposing surface was measured with three capacitive displacement sensors. The capacitive displacement sensors were attached around the bearing in a separate holder to disconnect the measurement frame from the loading frame.

The bearings were loaded with the pneumatic cylinder with force ranging from 50 N to 600 N in 20 even steps. In each measurement, the bearing was first loaded without supply pressure to measure the reference values for the capacitive displacement sensors to counteract the effect of the loading frame deflecting. The bearing then was pressurised to 0.6 MPa, and the loading cycle was repeated. The system was let to stabilise after each load change before the measurement.

The short circuit flow rates of the bearing samples were measured without an opposing surface. 0.6 MPa pressure was supplied to the bearing, and the flow rate was allowed to stabilise before measuring the flow rate. The sample permeability κ was calculated with Darcy's equation (Equation 1) where Q_{SC} is the short circuit flow rate, μ is the dynamic viscosity of air, h is the porous restrictor height, A is the surface area of the restrictor porous section, p_s is the supply pressure and p_a is the ambient pressure [5, 12].

$$\kappa = \frac{2Q_{SC}\mu hp_a}{A(p_s^2 - p_a^2)} \quad (1)$$

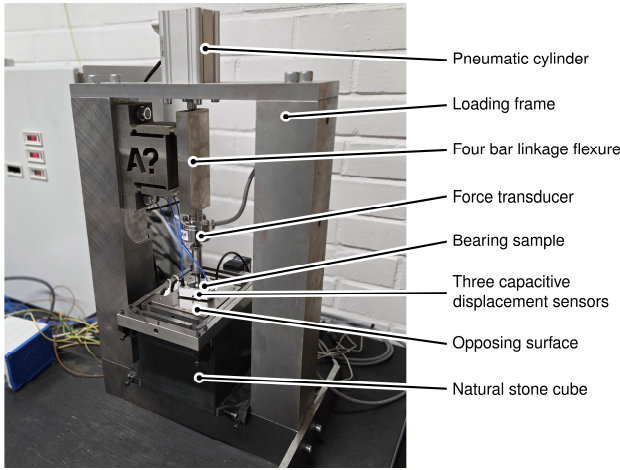


Figure 7. Measurement setup developed by Miettinen et al. [12].

3. Results and discussion

The restrictors manufactured with PBF-LB/M were deformed after the removal from the build plate (Figure 3). The restrictor surfaces were finished with an abrasive to reach a flat surface (Figures 4 and 5). The permeability results before and after abrasive finishing are presented in Figure 8. All but one sample had permeability within the optimal range before abrasive finishing, and all the samples were in the optimal range after abrasive finishing. The samples with hatch spacings of 165 μm , 170 μm , and 180 μm have permeabilities similar to the porous graphite reference samples, while the samples with 190 μm hatch spacing have higher permeability.

Although the permeability of the samples is on a similar level to the porous graphite bearings, the porous metal restrictor does not distribute the supplied pressurised gas uniformly to the surface of the restrictor. The porous graphite restrictor has pores spanning across the material allowing the flow of gas to all directions. Due to the PBF-LB/M AM process used in this study, the pores of the porous metal restrictors are only vertical through the restrictor. Therefore, the supplied gas can flow only straight through the vertical pores of the restrictor, and the gas does not flow through some of the pores. The supplied gas is not distributed to the whole surface of the restrictor when it exits the restrictor, but only on the areas where it was supplied on the opposite side of the restrictor. The permeability was calculated

based on the measured flow through the restrictor and the total surface area of the restrictor.

The feed geometry could be adjusted to evenly distribute the supplied pressurised gas across the whole surface area of the restrictor on the supply side, ensuring even distribution of gas to the gap between the bearing and the opposing surface.

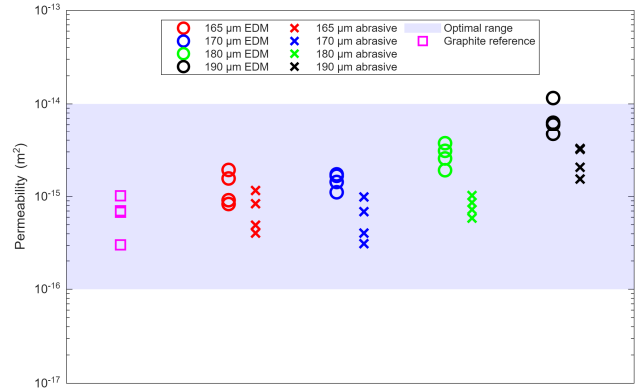


Figure 8. Bearing restrictor permeability after wire EDM cutting and after an additional abrasive finishing. Permeability calculated with Equation 1 with the measured short circuit flow rate at 0.6 MPa supply pressure. The shaded area is the permeability range for optimal static and dynamic performance of porous aerostatic bearings [3].

The load and gap height results for the four sets of samples and an additional set of four commercial New Way porous graphite aerostatic bearings are presented in Figure 9, with the average of each set of four bearings marked with a line and a shaded area that includes all four samples. The measurement results show that the load and air gap height for all samples with hatch spacing of 165 μm , 170 μm and 180 μm overlap while the samples with 190 μm hatch spacing have higher gap height. The reference porous graphite samples maintain a higher gap heights with increased load compared to the other tested samples. The width of the area including all the samples is approximately the same for all the tested sets of samples indicating a similar level of variation in the performance.

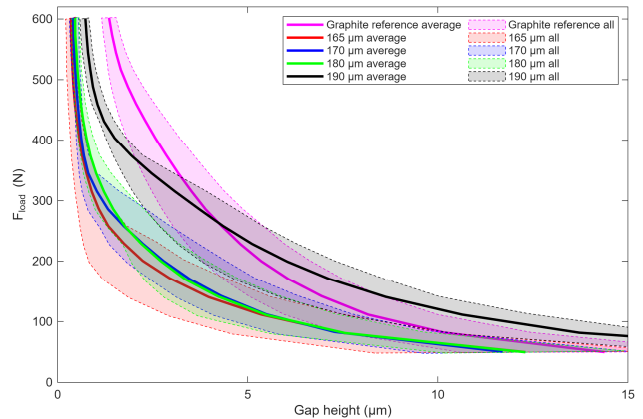


Figure 9. Bearing gap height and load capacity. The average of four samples is shown as a line, and the shaded area includes all four samples. Results include one set of commercial porous graphite aerostatic bearings as a reference and four sets of porous aerostatic bearings with metal restrictors.

In similar manner as in Figure 9, the air consumption and gap height are presented in Figure 10 with a line representing the average of the set of samples and a shaded area including all the samples. The samples with 165 μm , 170 μm , and 180 μm hatch spacing have flow characteristics similar to the porous graphite reference samples. However, at gap heights of below 5 μm , the

flow rates deviate with porous graphite flow rate gradually decreasing with decreasing gap height while the porous metal samples maintain the flow rate better with decreasing gap height. This is presumably due to the slight convex shape of the porous metal restrictor surfaces, which is not ideal for porous aerostatic bearings.

The convex shape (Figure 4) leaves a larger gap on the outer part of the restrictor compared to the centre. As the reference for air gap height is the point of contact between the restrictor and the opposing surface, the effective air gap is larger at the outer section of the restrictor surface. A larger gap height means less flow restriction for the flow out of the gap and therefore increases the measured flow rate. Improved performance could be achieved with a flatter or slightly concave restrictor surface geometry. Heat treatment could help relieve stress and reduce deformation of the restrictor after removal from the build plate. Additionally, improved surface finishing process, such as EDM, could be used to achieve a flatter surface geometry and fewer pores being closed.

The samples with 190 μm hatch spacing have significantly higher flow rate at all gap heights compared to all the other tested samples. The higher flow rate is expected based on the higher permeability than the other samples in Figure 8.

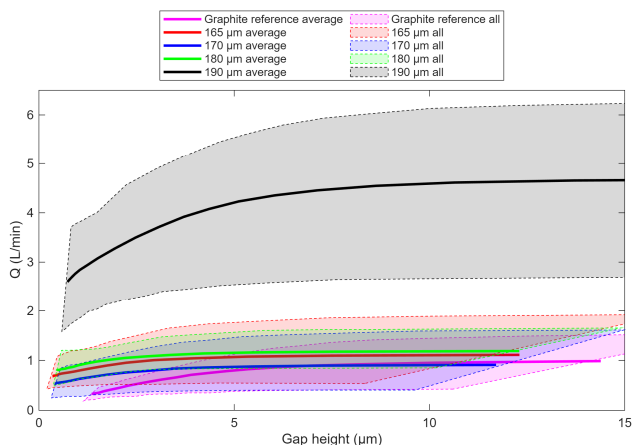


Figure 10. Bearing gap height and air consumption. The average of four samples is shown as a line, and the shaded area includes all four samples. Results include one set of commercial porous graphite aerostatic bearings as a reference and four sets of porous aerostatic bearings with metal restrictors.

4. Conclusions

A batch of porous metal restrictors were manufactured with PBF-LB/M AM method. The permeability of the restrictors was adjusted by varying the hatch spacing. The restrictors were mounted to bearing bodies and the restrictor surfaces were finished with an abrasive. Permeability, static load capacity, air consumption, and gap height were measured. A set of commercial porous graphite aerostatic bearings was also measured for reference.

The permeability of all the samples was within the optimal range found in the literature. The samples with 165 μm , 170 μm , and 180 μm hatch spacing had similar permeability as the porous graphite samples while the samples with 190 μm hatch spacing had slightly higher permeability. The abrasive finishing slightly decreased the permeability of all the samples.

The samples with 165 μm , 170 μm , and 180 μm hatch spacing had similar static load capacity while the samples with 190 μm hatch spacing had higher gap height compared to the other samples. The reference samples had similar gap height when the gap height was above 5 μm and higher gap height than the

bearings with metal restrictors when the gap height was below 5 μm . This is presumably due to the convex shape of the porous metal restrictor surfaces. The width of the graphs of the porous metal bearings and the porous graphite bearings were approximately the same, indicating similar level of variation in gap height at each load step.

The samples with 165 μm , 170 μm , and 180 μm hatch spacing had similar air consumption to the porous graphite bearings while maintaining higher flow rate at gap heights of less than 5 μm , presumably due to the convex shape of the restrictors. The variation in the flow rates was also similar to the porous graphite bearings. The samples with 190 μm hatch spacing had significantly higher air consumption.

The results of this study corroborate the feasibility of manufacturing porous metal restrictors with the PBF-LB/M process. The results indicate that AM porous aerostatic bearings exhibit a level of repeatability similar to the tested set of commercial porous graphite aerostatic bearings. However, further research is needed to determine the optimal AM process for the porous region and the optimal postprocessing and finishing methods for the bearing surface.

5. Acknowledgements

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