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Permeability and dynamic elastic moduli of controlled porosity ultra-precision aerostatic structures

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Abstract

Porous ceramic aerostatic bearings enable precise and smooth motion and improved stiffness compared with widely used orifice restrictor bearings. However, the processing techniques so far used are too complex or rely in lowering the sintering temperature to increase fluid flow.

Preferred combinations of fine-grade alumina powders and starch granules were used to produce quality porous structures using fixed processing parameters. Component shrinkage, permeability, pore size and elastic properties were comprehensively characterised as a function of porosity.

The new porous ceramic structures exhibited controllable and reproducible permeability and modulus, within the range required for ultra-precision porous aerostatic applications.

Keywords: B. Porosity; C. Mechanical properties; D. Al_2O_3; E. Porous bearings; Permeability

1. Introduction

Porous ceramics are typically used in a variety of applications such as filters, high temperature insulators and sensors. [1,2]. They have also been developed for high-precision porous thrust aerostatic-bearings applications [3,4]. These bearings enable precise and smooth non-contact relative motion of machine components. Clean compressed air is supplied to the bearing clearance through the extremely large number of integrated restrictors in the porous wall. As a result, the bearing fluid-film pressure distribution is improved. This in turn results in an enhanced load carrying capacity and stiffness, higher than that of widely used discrete orifice-restrictor bearings. Porous aerostatic bearings can potentially be used in the manufacture of highly value added components such as precision optics, coordinate measuring machines (CMMs), MEMS, replication drums, etc.

Further advantages of ceramics as bearing material are their low coefficient of expansion, long term dimensional stability and stiffness over a wide range of temperatures. In addition, ceramics can be machined without pore smearing [5]. In addition to more traditional porous bearing materials such as bronze, porous graphite and ceramics, high strength porous cementitious composites have been recently explored [6].

Precision porous guideway thrust bearings may have the shape of a simple disc or pad. These bearings enable precise and smooth linear motion. The accuracy-demanding applications in which they are used require well defined and controlled permeability coupled with good mechanical properties. Based on analytical models, Kwan [5] calculated the permeability and Young's modulus requirements for ceramic aerostatic porous pads. His study showed the permeability required for high stiffness ranged from 3.13×10^{-15} to 8.44×10^{-14} m^2. A desirable value of Young's modulus for the porous material was estimated at 102 GPa to prevent excessive deflection under pressure. These values were used as targets at the start of the research.

Manufacture methods that have been previously used were either too complex [4] to be widely employed, or relied in lowering the sintering temperature to increase fluid flow [3]. The latter is widely known to result in reduced mechanical

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properties. Kwan [4,5] first developed an alumina porous ceramic material suitable for high precision aerostatic bearings. A multi-layer approach was used combining several ceramic processing routes. The first layer was a 23 µm alumina powder substrate that provided the bulk of the mechanical properties. This was fabricated by capsule free Hot Isostatic Pressing (HIPing). The second layer was a fine pressure restricting layer made form 0.45 µm alumina powder fabricated by slip-casting. A tape-cast strip made with 0.45 µm alumina placed in-between the 2 layers was used for bonding by hot pressing. Roach [3] investigated several ceramics manufacturing routes in order to simplify the manufacturing method proposed by Kwan [5]. He focused his work on the ceramic injection moulding and slip casting techniques, primarily using sub-micron alumina powders.

The authors have recently published a paper [7] that dealt with porous ceramic hydrostatic journal bearings for rotational motion, manufactured by the starch consolidation technique (SC). These bearings had hollow cylinder geometry and used oil or water as fluid. Their permeability, porosity and pore size were all expressed as a function of the alumina size and volume per cent of starch. In difference to those, aerostatic guideway pad bearings, provide virtually frictionless linear motion using air as fluid film. The compressibility of air often means that the bearing gap is usually smaller (typically ≤ 10 µm) to avoid instability. As a result, the permeability requirement for optimum performance differs slightly from that of porous hydrostatic bearings.

In the present work, the effect of porosity on the permeability, microstructure and pore size on a range of disc-shaped aerostatic-pad starch consolidation (SC) specimens has been examined. Young's and shear moduli have been characterised for the first time for SC porous bearings.

2. Theoretical

2.1. Dimensional shrinkage and process densification

The sintering process is generally accompanied by some degree of shrinkage. From a bearing pad processing point of view, it is important to account for this to produce usable porous bearing castings with controlled dimensions. Shrinkage S is defined as the change in compact length from the green dimension Δ_{L} divided by its initial dimension L_0 [8].

$$S = \frac{\Delta_L}{L_0} \tag{1}$$

The density of typical sintered compacts can be calculated from initial values of the green density and the amount of shrinkage by [8]

$$\rho_s = \frac{\rho_g}{\left(\frac{1-\Delta L}{L_0}\right)^3} \tag{2}$$

where ρ_s is the sintered density and ρ_g is the green density.

2.2. Permeability

The permeability of the porous wall profoundly influences the overall bearing performance [9]. Other design parameters such as the bearing gap, the bearing dimensions and the fluid supply pressure also play a significant part [10].

Bearing permeability is generally expressed using Darcy's law [9]. This describes the flow of fluids through porous materials at relatively low velocity, where only viscous factors are prevalent. The equation used to derive the viscous permeability coefficient ψ can be written [11]:

$$\frac{\Delta_p}{e} = \frac{Q\,\eta}{A\,\psi} \tag{3}$$

At higher flow rates, inertial effects become significant and Forchheimer's equation is used for the determination of the viscous ψ and inertial permeability ψ_i coefficients [11]:

$$\frac{\Delta_p}{e} = \frac{Q\,\eta}{A\,\psi} + \frac{Q^2\,\rho}{A^2\,\psi_i} \tag{4}$$

where A is the area of the porous material normal to the direction of the fluid flow in m^2, Δp is the pressure drop in $\mathrm{N/m}^2$, e is the thickness of the test piece in m, Q is the volume flow rate in m^3/s, η is the absolute dynamic viscosity in $\mathrm{Ns/m}^2$, ρ is the density of the test fluid is $\mathrm{kg/m}^3$, ψ is the viscous permeability coefficient in m^2 and ψ_i is the inertial permeability coefficient in m^2. Eqs. (3) and (4) describe the relationship between pressure drop Δp and volume flow rate Q.

Permeability has been traditionally expressed as a function of porosity and particle size [12] and also the porosity and mean pore size [13]. Permeability of SC porous structures was first characterised by Vasconcelos et al. [14], as a function of their mean pore size, using a power law form equation:

$$\Psi = kd^a \tag{5}$$

where k and a are the empirical constants and d is the mean pore size.

For SC porous hydrostatic journal bearings, permeability has been expressed as an exponential function of the volume per cent of starch for each alumina size used [7]:

$$\Psi = ke^{as} \tag{6}$$

where s is the starch volumetric constant.

2.3. Young's modulus requirement

Estimation of Young's modulus requirement of a porous ceramic pad bearing has been previously [5] calculated using [15]:

$$\delta_c = -0.07\frac{\Delta p r_p^4}{X {z_p}^3} 12(1-\nu^2) \tag{7}$$

where δ_c is the deflection at the centre of a simply supported porous pad. Δp is the pressure drop across the bearing. X is the modulus of elasticity, r_p is the radius of the pad, z_p is the thickness and υ is Poisson's ratio. Kwan's [5] ultra-precision