G Model
PRE-6431; No. of Pages 7
ARTICLE IN PRESS
Precision Engineering xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Precision Engineering
journal homepage: www.elsevier.com/locate/precision

Development and performance of a magnetic ionic liquid for use in vacuum-compatible non-contact seals

Takao Okabe[a,*], Daichi Moritaka[b], Masaaki Miyatake[a], Yukishige Kondo[b], Shinya Sasaki[a], Shigeka Yoshimoto[a]

[a] Department of Mechanical Engineering, Tokyo University of Science, 6-3-1 Niijuku Katsushika-ku, Tokyo 125-8585, Japan
[b] Department of Industrial Chemistry, Tokyo University of Science, 1-3 Shinjyuku-ku Kagurazaka, Tokyo 162-8601, Japan, Japan

ARTICLE INFO

Article history:
Received 18 April 2016
Received in revised form 30 June 2016
Accepted 15 July 2016
Available online xxx

Keywords:
Vacuum-compatible
Magnetic liquid
Magnetic ionic liquid
Hydrostatic bearings
Non-contact seal

ABSTRACT

For the electron-beam machining of optical media, a very low rotational speed is required to enable the precise fabrication of grooves of various depths and widths. In addition, a lubricant with a very low vapour pressure, such as an ionic liquid, and a vacuum chamber are needed to avoid contamination of workpieces. Accordingly, the development of a vacuum-compatible hydrostatic bearing using an ionic liquid is required to satisfy these rotational conditions and nanometre-order machining accuracy. To use a hydrostatic bearing in a vacuum environment, a non-contact vacuum seal is needed to avoid leakage of the ionic liquid used as the lubricant. Furthermore, making a non-contact seal using an ionic liquid requires the development of a new type of magnetic ionic liquid. Therefore, this paper describes the development of such a magnetic ionic liquid, which consists of magnetite (Fe_3O_4) particles, a newly synthesized dispersant, and a pyridinium-based ionic liquid. The outgassed products from this magnetic ionic liquid were measured when it was applied to a non-contact seal in a vacuum of about 10^{-6} Pa. In addition, its mechanical properties, such as viscosity and burst pressure as a non-contact seal, were measured. From these investigations, it was found that the developed magnetic ionic liquid would meet the requirements for non-contact seals to be used in vacuum-compatible hydrostatic bearings.

1. Introduction

A vacuum-compatible rotational electron-beam (EB) machining system for fabricating the master disk in an optical high-density data-storage system has been investigated. The rotational mechanism used in this system needed high-vacuum compatibility for accurate EB progression in addition to high rotational accuracy. To satisfy these requirements for the rotational mechanism, a vacuum-compatible aerostatic spindle has been studied by Yoshimoto et al. [1] and Khim et al. [2]. This system had a multistage vacuum seal system, which comprised a viscous seal region and an exhaust groove connected to a vacuum pump to avoid the leakage of air into the vacuum chamber. Wada et al. [3,4] and Kitahara et al. [5] also studied a rotational EB machining system using a vacuum-compatible aerostatic spindle and fabricated 35-nm-wide circular groove patterns. However, a vacuum-compatible aerostatic spindle with a multistage vacuum seal system had two disadvantages. First, the seal system needed a large space for viscous seal regions and exhaust grooves connected to vacuum pumps. Second, it needed a complex structure for the tubing. Therefore, Okabe et al. [6] proposed the use of an ionic liquid as a lubricant for a vacuum-compatible hydrodynamic spindle. It is well known that an ionic liquid has a very low vapour pressure, and accordingly, no seal system is necessary for the spindle, which would lead to a simple and compact vacuum-compatible rotational EB machining system. In addition, Okabe et al. [7] reported that a manufactured EB machining system could fabricate concentric circular grooves with a width of 40 nm and a track pitch of 180 nm at a vacuum pressure of about 10^{-5} Pa by using a modified scanning electron microscope (SEM).

Recently, holographic disk memory [8,9] has attracted considerable attention because it offers the possibility of increasing the capacity of disk memory to several terabytes. In addition to the circumferential length of the tracks, the depth of pit patterns in a holographic memory has to be variable. Accordingly, the amount of EB radiation has to be controlled for every pit pattern. This means that the rotational speed of the spindle has to be very low, less than 100 rpm. At such a low rotational speed, a small hydrodynamic spindle may not be stiff enough to support a rotor to within a

* Corresponding author.
E-mail addresses: 4514702@ed.tus.ac.jp, saisinei0324a@gmail.com (T. Okabe).

http://dx.doi.org/10.1016/j.precisioneng.2016.07.010
0141-6359/

Please cite this article in press as: Okabe T, et al. Development and performance of a magnetic ionic liquid for use in vacuum-compatible non-contact seals. Precis Eng (2016), http://dx.doi.org/10.1016/j.precisioneng.2016.07.010

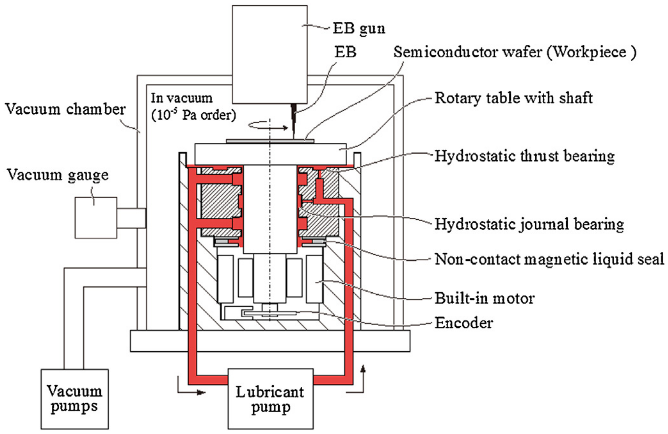


Fig. 1. A rotational EB machining system using an ionic-liquid-lubricated hydrostatic spindle.

nanometre order of accuracy, whereas it is considered that a hydrostatic spindle could offer sufficient stiffness, even at low rotational speeds. However, a hydrostatic spindle requires a pressurized lubricant, and in addition, a non-contact seal has to be installed to avoid the leakage of the lubricant into the vacuum chamber, as shown in Fig. 1. The magnetic liquid seal has advantages that it can construct a compact and non-contact seal for rotational mechanisms.

Rosensweig et al. [10] proposed a non-contact seal using magnetic fluid to prevent leakage of a lubricant or to maintain a pressure differential on either side of the seal. Rosensweig et al. [11] also described the numerical calculation method of ferrohydrodynamics which was used to design a magnetic fluid seal. Magnetic fluid used in these seals consisted of tiny magnetic particles suspended in a liquid medium such as oil or water In the case of oil, high molecular mass oils such as petroleum-derived oil and chemical synthesised oil were usually adopted. Furthermore, for a vacuum fluid seal, a hexafluoropropylene oxide polymer oil-based magnetic liquid was proposed by Kanno et al. [12], which had very low vapour pressure. However, even such an oil based magnetic fluid may cause outgassed products due to shear stress of rotational shaft under a high vacuum environment.

Therefore we developed a new type of magnetic fluid based on an ionic liquid for a vacuum-compatible hydrostatic spindle for EB machining. The objectives of the work reported in this paper were to develop a magnetic ionic liquid that consisted of magnetite (Fe_3O_4) particles, a newly synthesized dispersant, and a pyridinium-based ionic liquid, to measure the outgassed products from the developed magnetic ionic liquid when it was applied to a non-contact seal under a vacuum of about 10^{-6} Pa and to confirm the usefulness of the developed magnetic ionic liquid for a vacuum-compatible non-contact seal.

2. Development of the magnetic ionic liquid

Hayashi et al. [13,14] proposed a magnetic ionic liquid which included an Fe atom in its anion, as shown in Fig. 2(a). However, it was found by experiment that this magnetic ionic liquid was strongly corrosive toward metals and did not have enough magnetizing force to make a non-contact magnetic seal, as described in Section 3.

Fig. 2(b) shows a conceptual image of the magnetic ionic liquid that we have developed. It consists of magnetite particles, a newly synthesized dispersant, and a pyridinium-based ionic liquid. Magnetite particles do not disperse easily in an ionic liquid and will precipitate quickly to the bottom of the vessel, even if the magnetite particles are mixed with the ionic liquid. Therefore, a new dispersant was developed to enable the magnetite particles to disperse stability in a pyridinium-based ionic liquid.

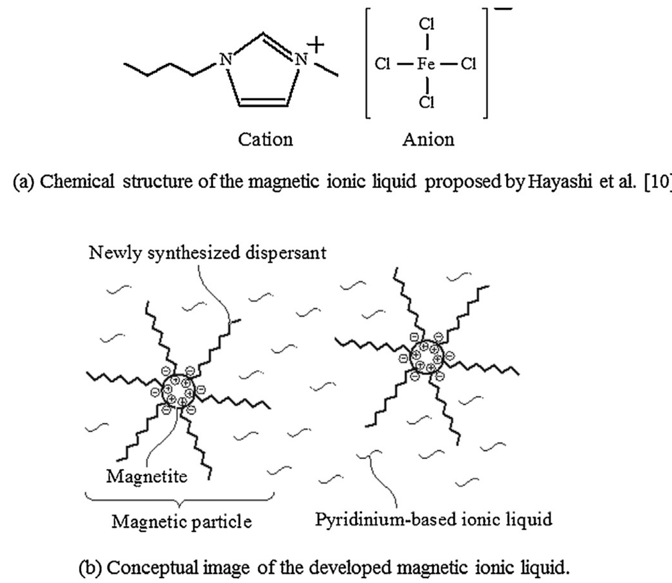


Fig. 2. Developed magnetic ionic liquid. (a) Chemical structure of the magnetic ionic liquid proposed by Hayashi et al. [10]. (b) Conceptual image of the developed magnetic ionic liquid.

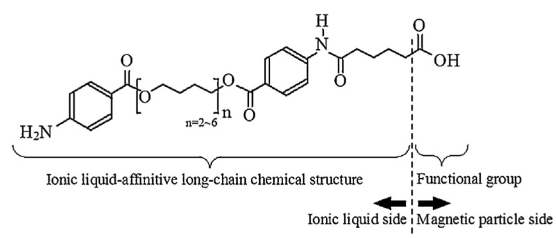


Fig. 3. Chemical formula of the newly synthesized dispersant.

Table 1
Principal features of the pyridinium-based ionic liquid.

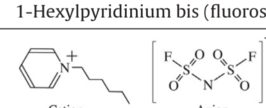
Product name	1-Hexylpyridinium bis (fluorosulfonyl) imide
Structural formula	
Formula weight	344.4
Density	1.32 g/ml (24 °C)
Kinematic viscosity	59 mPas (24 °C)
Vapor pressure	Less than 10^{-10} Pa
Characteristic	Hydrophobicity, Colorless, Transparent

Fig. 3 shows the chemical formula of the newly synthesized dispersant. It has a carboxyl functional group (COOH), shown at the right end, which can chemically connect to a magnetite particle. It is common for magnetite particles to be used in oil based magnetic liquids such as alkyl naphthalene oil- and perfluoro polyether oil-based magnetic liquids. Magnetite particles of around 100 nm to 1000 nm were used in our work, which were commercially available. Table 1 gives the physical features of, and the chemical formula for, the pyridinium-based ionic liquid used for the developed magnetic ionic liquid. The newly synthesized dispersant was coated on the surface of the magnetite particles in advance, and these particles were then mixed with the pyridinium-based ionic liquid in a ratio of 5 wt% to make the magnetic ionic liquid. The viscosity of the developed magnetic ionic liquid was 78.8 mPa s (27 °C) under no magnetic field.