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Performance Evaluation of Directional Porous Oil Storage Medium Fabricated by PTFE and Naphthalene

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1. Introduction

Self-lubricating rolling functional components can be used in the working conditions that require high cleanliness or working at heights, such as medical equipment (CT machine), semiconductor equipment (precision lithography machine), wind power generation device, and aerospace equipment (aviation optical remote sensing mechanism), etc [1, 2].

The oil media unit is widely employed in self-lubricating rolling functional parts. The lubricating oil is stored in the oil media unit which is could be divided into two types, one is a self-lubricating unit composed of an oil storage tank (oil storage) and a felt (oil control and oil delivery), the other one is a porous oil storage media self-lubricating unit [3]. The former self-lubricating unit depends on the wettability of felt, if the wettability of the self-lubricating unit is good, the oil will be abundant, otherwise, the oil will be lacking and the oil control effect will be unstable. The latter self-lubricating unit uses the pores of the porous material to store and control oil, and the self-lubricating effect is better than the former one [4].

The porous oil storage media self-lubricating unit can penetrate lubricants continuously. The surface of the porous oil storage media and its loading mechanism are covered with seeping out excess oil which are waste [8]. The waste of limited storage of lubricating oil reduces the utilization rate of lubricating oil in the porous oil storage media and shortens the service life of the porous oil storage media [9]. The excess oil is mainly due to the different directivity of the pores causes the lubricating oil to penetrate to the surrounding surfaces, and just the lubricating oil that penetrates to the surface of the friction pair participates in the lubrication condition [10].

Therefore, in response to the above lubricating question, this paper proposes to prepare a new type of porous oil storage media with directional pores by poly tetra fluoroethylene (PTFE) and naphthalene, and the performance of porous oil storage media is systematically evaluated and analysed. With the experiments and analyses, this paper aims to provide a theoretical reference for the fabrication and lubrication of porous media with directional pores for self-lubricating rolling functional components.

2. Experimental Procedure

2.1. Fabrication of porous media

PTFE (Japan's Daikin) and naphthalene are employed as base material and pore former in the fabrication experiment. The PTFE powder is dried at 120℃ for 2 h. A certain weight ratio of PTFE and naphthalene are crushed into powder with a particle size of less than 200 meshes by pulverized grinder. The mixed powder is sieved in self-preparation mold with a certain pressure, and then the molded blanks of mixed powder are natural effect more than 48 h.

The molded blank is coated with high temperature sealant, and only retains a directional open surface which is the gas escape surface as shown in Fig. 1. The coated molded blank is vacuum sintered at 385℃ for 2 h, the pore former is volatilize and escape toward the open face at this condition and then the high-temperature sealant can be removed. Therefore, the porous media with directional pores can be obtained.

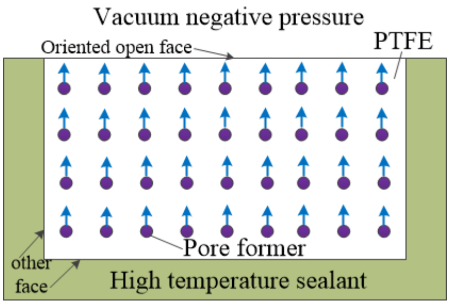

Fig. 1 Schematic diagram of porous oil storage media with directional pore

Table 1

Fabrication experiment parameters of porous media

Pressure p ,MPa	3.125	6.25	12.5	25	50
mass fraction of pore former α, %	20	35	50	65	80

Fabrication pressure p and mass fraction of pore former α are two important factors that affect the performance of porous media. In order to characterize the influence of factors within a large parameter range on the performance of porous media, the experimental factor parameters which are shown in Table 1 were measured in a proportional manner. The influence of pressure and mass fraction of pore former are tested respectively. The underlined parameters in the Table 1 represent the fixed values employed by this parameter when another parameter is a variable. For example, when pressure is analysed as a test variable, the mass fraction of pore former is employed as the fixed value of 50%.

2.2. Fabrication of porous media

The performance evaluation of porous media include dry density ρ_1, oil storage density ρ_2, Shore hardness h, porosity δ, oil storage rate ψ and oil storage retention rate ξ. The dry density ρ_1 and oil storage density ρ_2 are described as:

$$\rho_1 = \frac{m_1}{V_1} \ , \tag{1}$$

$$\rho_2 = \frac{m_2}{V_2} \ . \tag{2}$$

The m_1 and m_2 are the weight of dry sample and full oil storage sample of porous media. The porosity δ is expressed by percentage of pore volume and can be calculated as:

$$\delta = \frac{(m_2 - m_1)\rho_1}{m_1\rho_0} \times 100\% \ . \tag{3}$$

The ρ_0 is the density of lubricating oil (Mobil DTE 32). The kinematic viscosity, viscosity index, pour point, flash point and density of lubricating oil are tested according to ASTM-D445, ASTM-D2270, ASTM-D97, ASTM-D92 and ASTM-D4052 respectively. The test environment temperature of kinematic viscosity and density are respectively 40°C and 15°C. The property parameters of lubricating oil are shown in Table 2.

Table 2

Property parameters of lubricating oil

viscosity grade	kinematic viscosity,cSt	viscosity index	pour point,°C	flash point, °C	density, kg/L
32	31	102	-18	218	0.85

The porous media can completely store oil by high vacuum negative pressure oil immersion adsorption method. A low speed centrifuge is employed to carry out the oil rejection test. The oil rejection speed is 4000 r/min. The weight of porous media is weighed to calculate the variation of its oil storage rate after a certain oil rejection time interval. The oil storage rate can be calculated as:

$$\psi = \frac{(m_3 - m_1)\rho_1}{m_1\rho_0} \times 100\% , \tag{4}$$

where m_3 is the weight of the porous oil storage media after oil rejection for a certain period of time. The oil storage retention rate ξ can be described as:

$$\xi = \frac{\psi}{\delta} \times 100\% \ . \tag{5}$$

The morphology characteristics of the pores on the surface of porous media are analyzed by scanning electron microscope (FEI-Phenom prox), and the internal structure of the porous media is analyzed by industrial micro focus computed tomography (Y.CT-Precision).

3. Results

3.1. Influence of fabrication pressure on the performance of porous media

The influence of fabrication pressure on the Shore hardness h of porous media is shown in Fig. 2. It can be observed that the average hardness of open surface is 2.9% smaller than that of other surface. This is mainly because the open surface of the open face has more pores than other surface, and thus the hardness of the open surface is smaller than that of the other surface. The hardness of oriented open surface and other face of porous media are basically linear with the pressure, and can be fitted as $h_1 = 0.08148p_1 + 69.177$ and $h_2 = 0.2714p_2 + 67.9575$ respectively, the correlation coefficient values reaches 0.94 and 0.86. It can be observed that the linear fitting relationship is good.

The influence of fabrication pressure on the porosity δ of porous media with oriented open face is shown in Fig. 3. The porosity of porous media reaches peak at the fabrication pressure of 6.25 MPa. Comparing Fig. 2, it can be seen that under the same proportioning conditions, when the pressure is 6.25MPa, the hardness value is above the fitting curve, and the distance above the fitting curve is the maximum. Under the condition of constant density of naphthalene (1.145 g/cm^3) and PTFE (2.2 g/cm^3), the mixture of the two materials exhibits the best pore forming properties at this pressure, resulting in the maximum porosity of the porous medium. The porosity gradually decreases with increasing pressure after this peak, and then

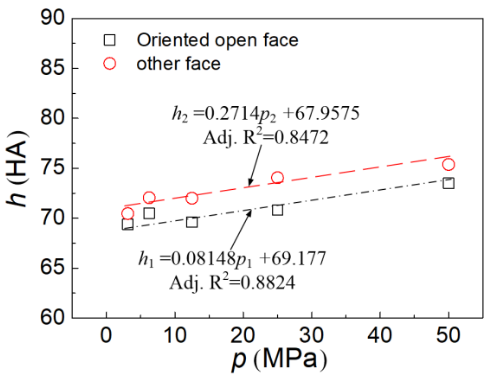

Fig. 2 Influence of fabrication pressure on the hardness of porous media

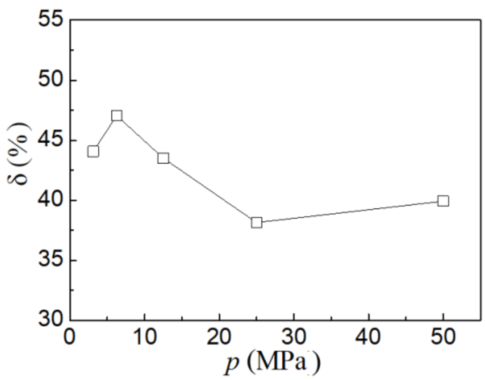

Fig. 3 Influence of fabrication pressure on porosity of porous media

the porosity reaches its lowest value at the pressure of 25 MPa, the porosity of the porous medium is the worst at this pressure. The porosity increases slightly at the high fabrication pressure of 50 MPa. With increase of fabrication pressure, the volume of molded decrease and the mass density of pore former increases. Meanwhile, the volatilization amount of the pore former in unit volume increase during the vacuum sintering, and results in the internal pore density and amount of porous media in unit volume increase. This is mainly reason why the porosity increases when the fabrication pressure is 50 MPa.

The influence of fabrication pressure on the dry density ρ_1 and oil storage density ρ_2 of porous media are shown in Fig. 4. The pressure has little effect on the density of porous media. The trend of density change is similar to that of porosity change. The dry density and oil storage density of porous media range in 0.57~0.63 g/cm^3 and 0.91~1.05 g/cm^3 respectively. The dry density variation can be fitted by ρ = 0.00066p + 0.653. With the increasing of fabrication pressure, the density of pore former and the volatilization amount volume of pore former also increase, and lead to the decreasing of the density of porous media. However, the porosity of porous media will increase when the pressure is large enough (50 MPa). That is because the oil storage capacity increases with the increasing of specific surface area of internal pores, and thus the oil storage density increases slightly.

3.2. Influence of mass fraction of pore former on the performance of porous media

The influence of fabrication pressure on the oil storage rate is shown in Fig. 5. The oil storage rate of

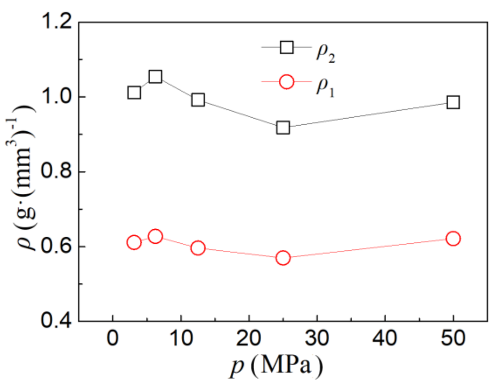

Fig. 4 Influence of fabrication pressure on the dry density and oil storage density of porous media

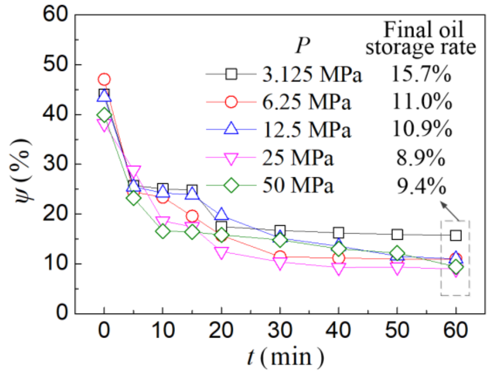

Fig. 5 Influence of fabrication pressure on the oil storage rate variation of porous media

porous media with different fabrication pressure basically shows a rapid linear reduction trend in the initial stage of oil rejection. It can be observed that the oil leakage rate of porous media with different fabrication pressure is almost the same. After 20 minutes of oil rejection, the variation of oil storage rate of the all porous media is stable, most of the lubricating oil stored in the porous media has exuded and the oil penetration rate gradually decrease. After 60 minutes of oil rejection, the porous medias also present show oil penetration state, and the final oil storage rate are 15.7% (p = 3.125 MPa), 11.0% (p = 6.25 MPa), 10.9% (p = 12.5 MPa), 8.9% (p = 25 MPa), and 9.4% (p = 50 MPa) respectively. The influence of pressure on the final oil retention rate is not significant.

The influence of mass fraction of pore former on the Shore hardness of porous media is shown in Fig. 6. The hardness of porous media decrease with the increasing of mass fraction of pore former, this is because the increasing of mass fraction of pore former lead to more volatilization inside the porous media to escape from the molded blank and increase the amount of inside pores. More amount of inside pore result in the decreasing of the hardness of porous media. It can be observed that the hardness of oriented open face is slightly smaller than that of the other surface. The hardness of the two types of surface has a linear negative effect relationship with the mass fraction of pore former, and they can be fitted as h_1 = -0.7873α_1 + 99.6583 and h_2 = -0.9934α_2 + 114.3042, the correlation coefficient values reaches 0.7835 and 0.8693.

The influence of mass fraction of pore former on the porosity δ of porous media is shown in Fig. 7. The mass fraction of porous media has a significant effect on the porosity of porous media. The amount of gas volatilization in molded blank increases with the increasing of mass fraction of pore former, and lead to the increasing of the porosity of porous media. The variation of mass fraction of pore former can be well fitted as δ = 0.7165α + 3.9927, the correlation coefficient value is 0.8878. It is a good linear positive effect relationship between the mass fraction of pore former and porosity of porous media.

The influence of mass fraction of pore former on the dry density ρ_1 and oil storage density ρ_2 of porous media is shown in Fig. 8. The variation of dry density and oil storage density present a certain linear decrease with the increasing of mass fraction of pore former, and they can be well fitted as ρ_1 = –0.014α_1 + 1.3745 and ρ_2 = –0.00791α_2 + 1.4086, and the correlation coefficient values are 0.9715 and 0.8714 respectively. There is a significant linear negative effect relationship between density and mass fraction of pore former.

The influence of mass fraction of pore former on the oil storage rate is shown in Fig. 9. The oil penetration trends of porous media with different mass fraction of pore former are different. In the initial stage of oil rejection, the larger the mass fraction of pore former is, the bigger the oil penetration rate is. The oil storage rate curves of the porous media with different mass fraction of pore former tend to be stable, and the oil penetration rate is relatively slow. The final oil storage rate are 10.6% (α = 20%), 14.9% (α = =35%), 15.7% (α = 50%), 20.3% (α = 65%), and 8.2% (α = =80%) respectively. The influence of mass fraction of pore former on the final oil retention rate is significant.

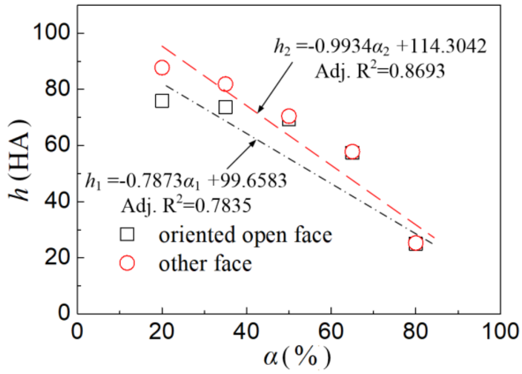

Fig. 6 Influence of mass fraction of pore former on the hardness of porous media

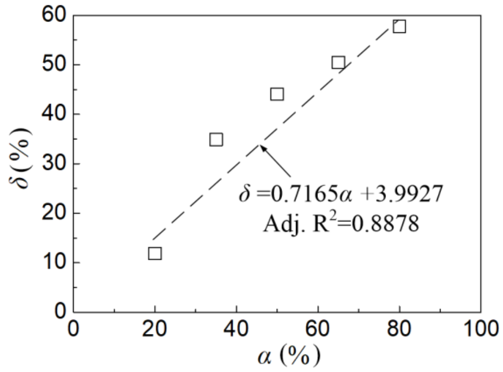

Fig. 7 Influence of mass fraction of pore former on the porosity of porous media

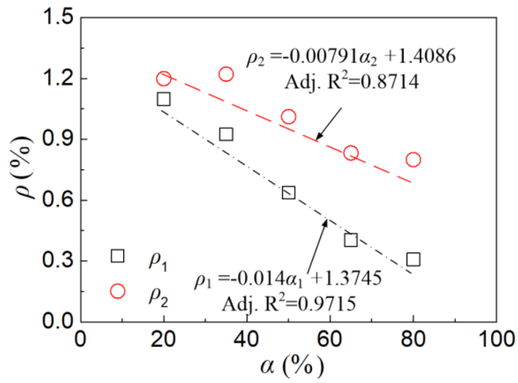

Fig. 8 Influence of mass fraction of pore former on the dry density and oil storage density of porous media

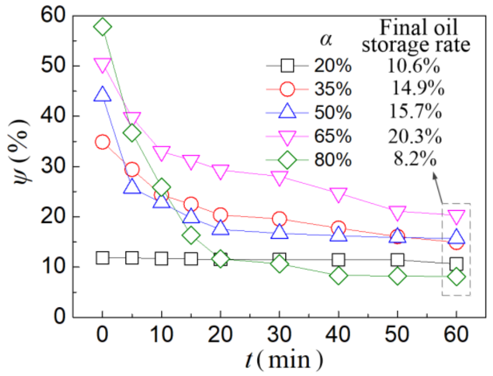

Fig. 9 Influence of mass fraction of pore former the oil storage rate variation of porous media

3.3. Microstructure of internal pore of porous media

The micro morphology of pore surface for porous media with fabricating pressure is 6.25 MPa and mass fraction is 50% is shown in Fig. 10. The pore structure in porous media is evenly distributed, and the internal pores show good connectivity as shown in Fig. 10, a. The interconnected pores can form effective pores for the storage and circulation of lubricating oil. The microscopic observation of the micro morphology is shown in Fig. 10, b. The porous media has formed many cave-type pore structures, and obvious fibrosis tissue structure appears at the pore junction. Combining Fig. 2, Fig. 3, Fig. 4 and Fig. 5, it can be concluded that the fibrous tissue and cave-type structure are one of the main reasons for the optimal pore formation of porous media under these preparation parameters. Different preparation parameters can lead to different cave structures and fibrotic tissue structures in porous media. The fibrosis is conducive to the porous media to adjust the oil penetration rate of lubricating oil in the process of oil rejection, lock the lubricating oil, avoid too fast penetration of lubricating oil, prolong the oil leakage time, and improve the oil control effect of porous media.

The tomographic analysis of the internal pore structure of the porous media measured by industrial CT is shown in Fig. 11. The plane incision surface of the porous media sample is the oriented open surface. It can be observed that although the pore size and shape are different, the distribution is relatively uniform and interconnected. The pore structure is beneficial to the storage and circulation of lubrication oil. According to Fig. 9, the larger the

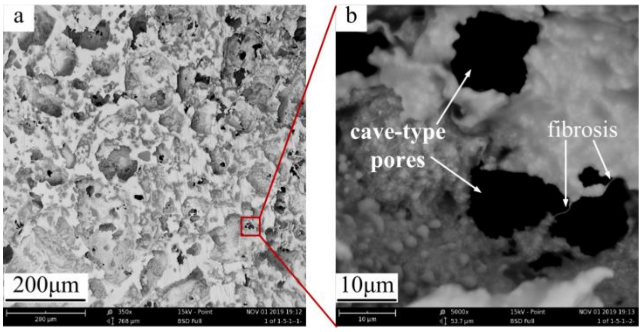

Fig. 10 Pore surface micromorphology of porous media: pore surface topography (a) and micromorphology (b)

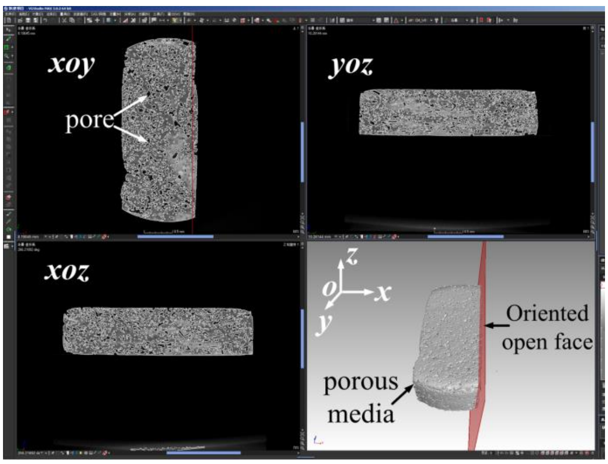

Fig. 11 CT section scan of porous media

pores, the more lubricating oil can be stored. However, excessively large pores will make it easier for lubricating oil to seep out of the pores without being affected by molecular forces. Meanwhile, it can be seen that the porous medium with the pore forming agent mass fraction of 80% has too large pores, which leads to rapid leakage of lubricating oil during the oil throwing process, resulting in the lowest final oil storage rate.

In order to analyse the orientation of the pore structure inside the porous media, the oriented open surface is employed as the initial surface of the tomography. A layered scan is performed every 0.5 mm along the centre direction of the porous media (*xo* direction), and the *yoz* section is employed as the observation surface. The pore structure characteristics of different layered sections inside the porous media are shown in Fig. 12.

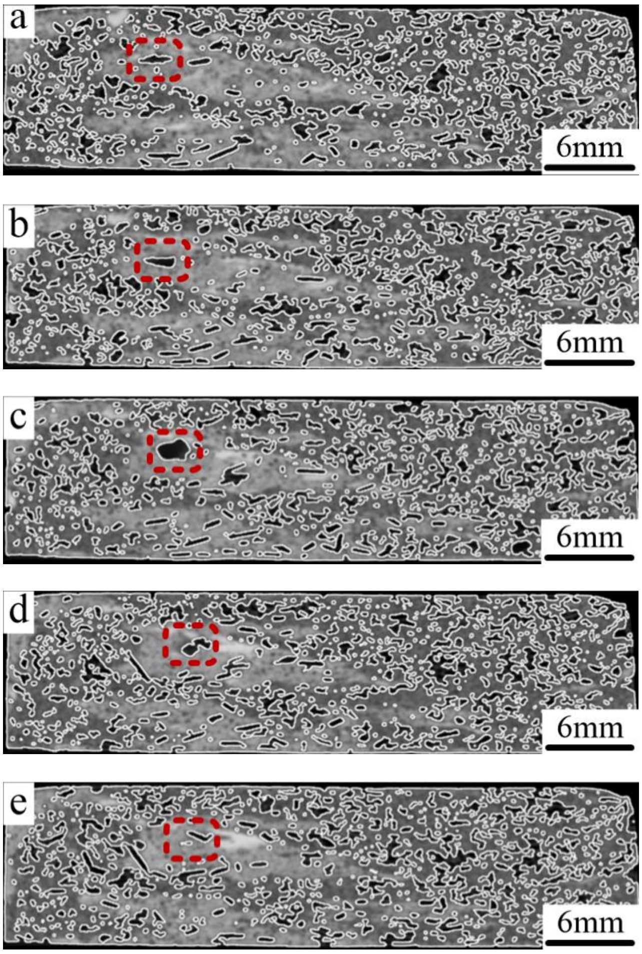

Fig. 12 Pore morphology of different cross sections (at the section of: 0 mm (a), 0.5 mm (b), 1.0 mm (c), 1.50 mm (d) and 2.0 mm (e)) in porous media

In order to track and analyse the directional characteristics of pores, typical pores in the same location of the tomography image are selected for analysis, and the pores are indicated by the box marks in the Fig. 12, a to Fig. 12, e.

The cross-sectional shape of the pores near the directional opening surface (Fig. 12, a) is relatively irregular, the pores have good connectivity with other pores, and the selected pore is elongated. The pore diameter becomes larger and becomes more round when approaching the centre of the porous media. However, the shape of the pore varies irregular, narrowing (Fig. 12, b) or bigger (Fig. 12, c) at a certain constant short distances. The typical pore forms a constriction in the middle (Fig. 12, d) and gradually divides into two parts. One part of the pore gradually disappeared and the other part gradually become slender pore (Fig. 12, e). It can be observed from the CT tomogram of the pores that although the shape and pore diameters of the pores changes irregularly, they always maintain a connected state, and the internal pores will be dispersed and collected. The pores have good orientation in the direction of the directional opening surface.

4. Conclusions

In this present work, the performance evaluation of oriented porous oil storage media fabricated by PTFE and naphthalene are investigated systematically. The main conclusions obtained are summarized as follows:

1. The fabrication pressure has a linear positive effect relationship with the hardness of the porous media, and has no significant effect on the density, porosity, oil storage rate and oil retention rate.

2. The mass fraction of pore former has a linear negative effect relationship with the hardness and density of porous media, and a linear positive effect relationship with the porosity. The greater the mass fraction of pore former, the greater the oil penetration rate in the initial stage of oil rejection, but the effect on final oil retention was not significant.

3. The internal pores of the porous media have a fibrous structure of the cave type, and the internal pores are interconnected and have good orientation.

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References

1. **Ren L.; Su Y.; Zhan S.; Meng, F.; Zhao, G.** 2019. Fully coupled fluid-solid numerical simulation of stimulated reservoir volume (SRV)-fractured horizontal well with multi-porosity media in tight oil reservoirs, Journal of Petroleum Science and Engineering 174: 757-775. https://doi.org/10.1016/j.petrol.2018.11.080.
2. **Rambarzin F.; Shervani-Tabar M.; Taeibi-Rahni M.; Tabatabaei-Nejad S.** 2016. Energy transfer in a liquid filled elemental passage of a porous medium for

permeability enhancement due to pulsations of a vapor bubble, Mechanika 22(1): 25-30.
https://doi.org/10.5755/j01.mech.22.1.14238.

3. **Wu, H. Y.; Huang H.** 2020. Influence of contact form on mechanical wear characteristics of single diamond scratching on Ta12W, Industrial Lubrication and Tribology 72(10): 1311-1316.
https://doi.org/10.1108/ILT-01-2020-0024.
4. **Yang, L.; Teng, Q.; He, X.; Feng, J.; Xiong, S.** 2019. Super-dimension-based three-dimensional nonstationary porous media reconstruction from single two-dimensional image, Journal of Petroleum Science and Engineering 174: 968-983.
https://doi.org/10.1016/j.petrol.2018.12.004.
5. **Li P.; Liu Q.** 2022. A dual porous and fractures medium CBM numerical model development and analysis, Journal of Petroleum Science and Engineering 214: 110511.
https://doi.org/10.1016/j.petrol.2022.110511.
6. **Kayhani M.; Abbasi A.; Sadi M.** 2011. Study of local thermal nonequilibrium in porous media due to temperature sudden change and heat generation, Mechanika 17(1): 57-61.
https://doi.org/10.5755/j01.mech.17.1.204.
7. **Li L., Yang J.** 2018. Surface roughness effects on point contact elastohydrodynamic lubrication in linear rolling guide with fractal surface topographies, Industrial Lubrication and Tribology 70(4): 589-598.
https://doi.org/10.1108/ILT-04-2017-0092.
8. **Menni, Y; Chamkha, A. J; Azzi, A.** 2019. Nanofluid transport in porous media: a review, Special Topics and Reviews in Porous Media: An International Journal 10(1): 49-64.
https://doi.org/10.1615/SpecialTopicsRevPorousMedia.2018027168.
9. **Eder, S. J.; Bianchi, D.; Neacsu, I. A.; Vorlaufer, G.** 2019. An experimental and signal analysis workflow for detecting cold-induced noise emissions (cold squealing) from porous journal bearings, Mechanical Systems and Signal Processing 115: 60-69.
https://doi.org/10.1016/j.ymssp.2018.05.047.
10. **Wu, H. Y.** 2021. Wear characteristics of single diamond grit scratching on sapphire with different contact forms, Ceramics International 47(7): 8840-8848.
https://doi.org/10.1016/j.ceramint.2020.12.005.

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PERFORMANCE EVALUATION OF DIRECTIONAL POROUS OIL STORAGE MEDIUM FABRICATED BY PTFE AND NAPHTHALENE

S u m m a r y

Porous oil storage media is the core of self-lubricating rolling functional components. The internal pore directivity of porous oil storage media is different and it reduces the utilization rate of lubricating oil. In this paper, a new fabrication method of porous oil storage media with directional pores is carried out, and the properties of the porous media, such as hardness, density, porosity, oil storage rate and oil retention rate are evaluated. The experimental results show that the fabrication pressure has a linear positive effect relationship with the hardness of the porous media, and has no significant effect on the density, porosity, oil storage rate and oil retention rate. The mass fraction of pore former has a linear negative effect relationship with the hardness and density of the porous media, and a linear positive effect relationship with the porosity the greater the mass fraction of pore former, the greater the initial oil seepage rate of oil rejection. The internal pores of the porous media have a fibrous structure of the cave type, and the internal pores are interconnected and have good orientation. This study aims to provide a lubricating theoretical reference for the fabrication of porous oil storage media.

Keywords: porous oil storage media, directional pore, PTFE, cave-type pore.

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