UDK 621.822.178:62-405.8:546.62

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APPLICATION OF CAST OPEN-CELL POROUS ALUMINUM FOR SELF-LUBRICATING BEARINGS

Applicability of cast open-cell porous Al for the use as porous 'self-lubricating bearings' was studied experimentally using tribological tests. Samples of open-cell porous Al have been produced by casting the melt of Al_7Si alloy (similar to A356 alloy) around particles of soluble salt NaCl as removed space holder. Fraction volume porosity, morphology of interconnected cells and strength properties of cast porous Al were studied and specified before tribological tests which were performed by using pin-on-disk friction machine. Samples of the cast porous Al were impregnated by motor oil and, then, tested in sliding regime against a rotating steel disk that serves as the counterbody. In this manner, tribological properties were reported as variation of friction coefficient versus time of sliding. As a main result of the tests, friction coefficient of cast porous-oil Al samples being recorded under contact pressure varied from 0.02 to 0.26 MPa and sliding velocity of 0.0942 m/s was measured and compared with that of compact Al subjected to the same operating conditions. Cast porous-oil Al samples showed promising self-lubricating properties with a friction coefficient ~ 0.08 which was less by roughly about 2 times than that for compact Al. The results of the present study testified that impregnated cast porous Al could be qualified as material used in performance of 'self-lubricating bearings'.

Keywords: *Self-lubricating bearings, Open-cell Porous Aluminium, Friction, Mechanical Properties.*

Introduction. Tools termed like 'self-lubricating bearings' covers a group of metal bearings which requires no further lubrication during the whole life time of the machine in which they are used. Most of the above metal bearings are based on either bronze or iron which have interconnected pores filled with lubricating oil. In operation, lubricating oil is stored in the interconnected pores and feeds through them the bearing surface. Since these bearings can operate for a long time period without additional supply of lubricant, they can be used in inaccessible or inconvenient parts where relubrication would be difficult. Porous metal self-lubricating bearings are widely used in industrial applications such as home appliances, medical apparatus, small motors, machine tools, aircraft and automotive accessories, business machines, instruments, and farm and construction equipment. Among them porous aluminum bearings provide for cooler operation, greater tolerance for misalignment, lower weight, and longer oil life than other porous ones, i. e. porous bronze or iron. Presently, porous ‘self-lubricating bearings’ are generally fabricated in line with powder-metallurgy technology that presupposes the sintering of metal powder [1]. These bearings are less expensive and suitable for high production rates and can be manufactured to precision tolerances. Porosity of the sintered powdered material is typically ranged from 10 to 35% of the total volume. The upper limit of porosity and, in turn, volume of oil is restricted by the strength considerations of sintered powdered material which in addition varies inversely with its porosity. This is especially true for sintered aluminium powder of reduced strength. Actually, strength properties and oil content are vital factors which influence lubrication performance of the porous oil bearings. The enhanced mechanical properties and higher oil content make it possible to widen the range of operating conditions where porous oil bearings can be used. However, it is difficult to improve mechanical properties and oil content simultaneously for the sintered powdered bearings. This problem is thought to be overcome by application of cast open-cell porous aluminium produced by casting of liquid metal over space holder particles which are removed after solidification [2]. Of importance is that the upper limit of porosity for this cast material can be extended up to 70% while its strength remains quite high [3]. In addition, cost production of cast porous aluminium is cheaper by almost order magnitude compared to analogous productions fabricated by powder metallurgy. Generally, cast open-cell porous aluminium is presently used as structural and functional material for air and drainage filters, heat exchangers, silencers, sound absorbers, etc. However, a research aimed at the study of cast open-cell porous aluminium for performance of 'self-lubricating bearings' has not been reported in the literature. The intent of the present paper is to investigate capability of cast porous aluminium to be applicable for manufacture of 'self-lubricating bearings' of improved mechanical properties and enhanced oil content.

Material and processing. Open-cell porous aluminium was produced by casting the melt of Al_7Si alloy (similar to A356 alloy) around particles of soluble salt NaCl as space holder (performed by ELMIZ Co, Kyiv, Ukraine). In this process, powder particles of NaCl was dried and preheated up to a prescribed temperature prior classification. By using corresponding sieves, heated powder particles were sieved to the sizes ranged from 0.63 to 1.60 mm and, then, placed in preheated vessel and compacted by vibration. Infiltration of liquid metal in salt powder was realized by pouring the melt into the vessel under reduced pressure. Samples used in experiments were machined from as-received cast block and just after that space-holding salt particles presented in materials were removed by leaching in water. Microphotograph of the porous aluminium sample is shown in Fig. 1.

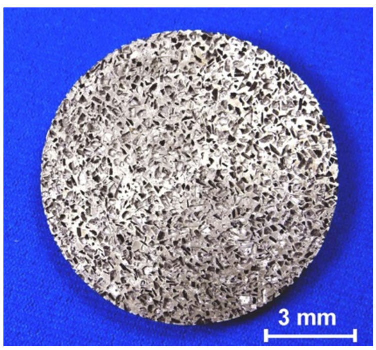


Fig. 1. Microphotograph of the porous aluminium sample

Structural characterization. Porous specimens were characterized by relative density ρ/ρ_s (where ρ and ρ_s correspond to the density of porous material and solid, respectively) to determined fraction volume of porosity from relation $\theta = (1 - \rho/\rho_s) \times 100\%$. Relative density of porous material was measured by weighting a sample of known volume. Finally fraction volume of porosity was found to be as high as roughly about 58 %.

Microstructure examination including cell morphology (size and shape) of porous aluminium was done using scanning electron microscopy (SEM) in both secondary and back-scattered modes. Electron microscope Jeol Superprobe-733 (JEOL, Japan) was used to get SEM images. Image analyzer equipped by software (SEO-SCAN Color, Sumy, Ukraine) was used to study morphology of the cells. Mean cell size was determined by the data averaging over the surface area about 250 mm^2.

Specification of mechanical properties. Mechanical properties such as structural stiffness, *m*, associated with Young modulus, *E*, and yield strength, σ_y, were determined in compression tests according to Standard ISO 13314: 2011 developed for porous and cellular metals. Quasi-static tests at the strain rates of 10^{-3} s^{-1} were performed under displacement control by using Instron machine. Cylindrical samples with dimensions about 20 mm in diameter and height of 30 mm were used to investigate quasi-static behaviour of porous aluminium. Detailed description of test method procedure was published in [4].

Tribological tests. Tribological tests were carried out at ambient temperature and atmosphere with humidity higher than 50% and performed in pin-on-disk friction machine, see Fig. 2.

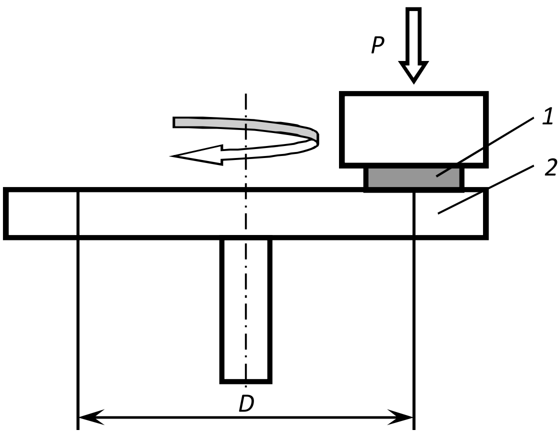


Fig. 2. Scheme of pin-on-disk friction machine: sample in form of pin (*1*), rotating steel disk (*2*)

Cylindrical specimen with 10 mm in diameter and 2.5 mm in height serves as a pin (*1*). The vertically loaded pin was sliding against a rotating steel disk (*2*), which serves as the counterbody. Removable disks with 50 mm in diameter and 10 mm in height were made from hardened H-13 steel with hardness of 60 HRC and used in tribological tests. Porous aluminium samples impregnated by motor oil were used as pins. In addition, samples of compact and porous aluminium without lubricant were used also to compare their tribological properties with those of porous oil pins. Physical properties of motor oil used for porous pins impregnation are listed in Table 1.

Table 1

Physical properties of motor oil 5W-30 used as lubricant

Parameter	Value
Viscosity at 100 ºC, cST (ASTM D445)	11.0
Viscosity at 40 ºC, cST (ASTM D445)	61.7
Viscosity Index	172
Density at 15.6 ºC, kg/l (ASTM D4052)	0.855

Tribological tests were done under different contact pressure ranged from 0.02 to 0.26 MPa and rotation speed of 60 r/min corresponded to linear sliding velocity of

0.0942 m/s. Diameter of the wear track, *D*, on the steel disk was about 30 mm. Materials and conditions used in tribological tests are listed in Table 2.

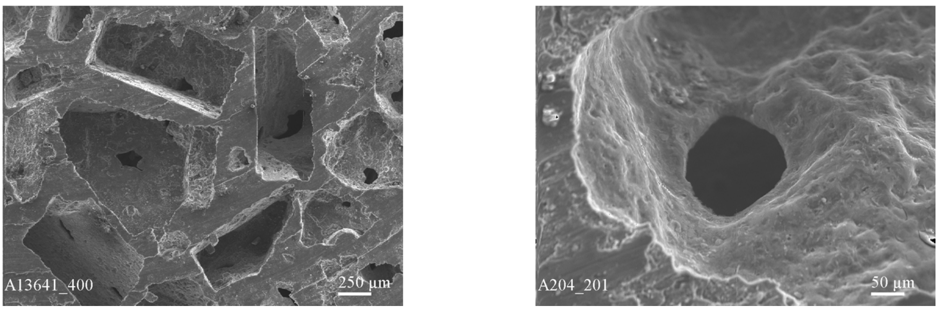
Table 2

Materials and conditions used in tribological tests

Mode	Conditions	Pin material	Steel disk
1	Dry sliding	Porous Al without impregnated oil	Dry surface
2	Dry sliding	Compact Al	Dry surface
3	Boundary lubrication	Porous Al without impregnated oil	Surface was covered by limited amount of the oil
4	Boundary lubrication	Porous Al impregnated by oil	Dry surface
5	Boundary lubrication	Compact Al immersed in oil and wiped by fabric	Dry surface

Pins of porous aluminium were weighed before and after impregnation process and then again after the tribological test to calculate the percentage of remained oil. In addition, PV (pressure-velocity) parameter was assessed and specified. Moreover, the steel disk surface was examined after tribological tests by using SEO-SCAN image analyzer.

Structure and mechanical properties of porous aluminium. Fig. 3 shows cellular structure of open-cell porous aluminium. Cells of angular shape and connected by small apertures are visible in microstructure of porous aluminium. The characteristics of open-cell porous aluminium samples are presented in Table 3.



a *b*

Fig. 3. SEM images for cellular structure of open-cell porous aluminium: (*a*) cells of angular shape; (*b*) small apertures between cells

Table 3

Characteristics for samples of open-cell porous aluminium

Parameter	Value
Material	Al_7Si alloy
Porosity, %	58
Mean density, g/cm^3	1.56
Cell size, mm	$0.6 < a < 0.90$
Aperture radius, µm	$50 < r < 100$
Oil content, wt. %	14.5
Yield strength, MPa	22
Young's modulus, GPa	12.1

Attention is paid to success combination of enhanced mechanical properties and rather high oil content contained in porous aluminium sample.

Tribological results. The results of tribological test are reported as variation of friction coefficient versus time of sliding. Before beginning the test, porous aluminium samples with any impregnated oil were run for about 100 s. in order to get smoother surfaces and expel away wear debris during the running-in process under low speed and low load conditions. As to wear-in regime of dry sliding under contact pressure of 0.06 MPa (mode 1), variation of friction coefficient for porous aluminium without impregnated oil (mode1) is very similar to that of compact aluminium (mode 2) and equal roughly about 0.45. In addition, friction coefficient for porous aluminium increases instantly after 70 s. of sliding, suggesting transition to seizure due to feasible spalling of the cell edges.

Actually, the results determine in the present study is surely expected since aluminium/aluminium alloys are prone to scuffing, welding, high coefficients of friction and high wear rates [5; 6].

Friction coefficient for porous aluminium decreases radically under boundary lubrication when limited amount of oil was bring on the surface of steel disk prior test (mode 3), as can be seen in Fig. 4*a*. However, scatter of signal associated with friction coefficient becomes greater under deteriorating an oil layer when contact pressure increases up to 0.19 MPa, as shown in Fig. 4*b*.

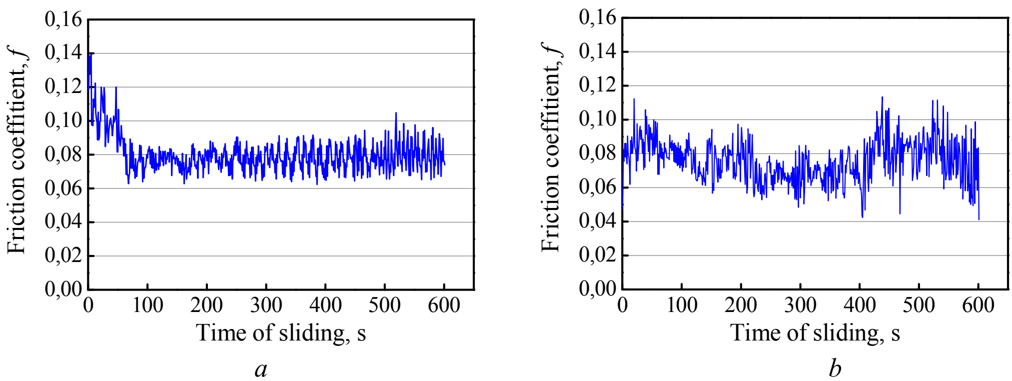


Fig. 4. Variation of friction coefficient, *f*, of porous aluminium under boundary lubricated sliding (mode 2): contact pressure is as great as (*a*) 0.06 MPa and (*b*) 0.19 MPa

Another was believed to be true for performance of porous aluminium impregnated by oil (mode 4) in comparison with compact aluminium immersed in oil when contact surface and wiped by dry fabric prior test (mode 5). Under contact pressure of 0.02 MPa and dry steel disk surface, variation of friction coefficient for porous aluminium impregnated by oil was found to be visually more stable compared to that of compact aluminium immersed in oil, as evidenced from Fig. 5*a*.

In addition, there is increased friction coefficient for compact aluminium recorded in the range from 50 to about 280 s., indicating the transition to seizure mating metal pair. The latter become especially pronounced under dry sliding of compact aluminium tested under contact pressure of 0.06 MPa (mode 4), as evidenced from Fig. 5*b*. As to the above test conditions, mean friction coefficient for compact aluminium increases significantly (up to roughly about 0.35) while that for porous aluminium impregnated by oil remains the same as that tested under contact pressure of 0.02 MPa. Of importance is the fact that any noticeable lost of oil impregnated in porous aluminium subjected to frictional tests is detected. The results of tribological tests are confirmed by observation of the steel disk surface. Pronounced friction tracks and furrows, all indicative of seizure mating metal pair, are visible in steel disk surface after aluminium compact sliding. As opposed to this, almost smooth surface of steel disk surface is resulted from sliding of porous aluminium impregnated by oil. The results of tribological tests of the samples used in the present study are compiled in Table 4.

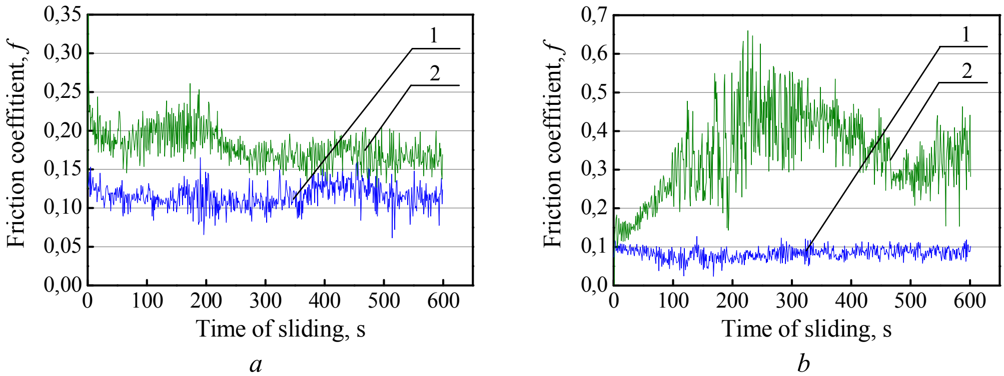


Fig. 5. Variation of friction coefficient of porous aluminium impregnated by oil (*1*) compared to that of compact aluminium (*2*) when the surface of both samples was wiped by dry fabric prior tests (mode 3): load is as great as (*a*) 0.02 MPa and (*b*) 0.06 MPa

Table 4

The results of tribological tests for the samples of open-cell porous aluminium compared to those of compact aluminium

Number	Sample material	Mode	Contact pressure (MPa)	Friction coefficient (*f*)	PV parameter (MPa·m/s)	Transition to seizure (s)
1	Porous Al	1	0.06	~ 0.45	0.006	75
2	Compact Al	2	0.06	~ 0.45	0.006	10
3	Porous Al	3	0.06	~ 0.08	0.006	-
4	Porous Al	3	0.13	~ 0.08	0.012	50
5	Porous Al	3	0.19	~ 0.08	0.018	50
6	Porous Al	3	0.25	~ 0.08	0.024	-
7	Porous Al	4	0.02	~ 0.08	0.0018	-
8	Porous Al	4	0.06	~ 0.08	0.006	-
9	Compact Al	5	0.02	~ 0.15 …. 0.23	0.0018	50
10	Compact Al	5	0.06	~ 0.16 …. 0.55	0.006	50

By comparing parameters listed in Table 4, it can be seen that the friction coefficient for porous aluminium impregnated by oil (mode 4) is the same as that for porous aluminium tested under conditions of boundary lubrication when a little amount of oil was bring on the contact surface of steel disk (mode 3). Of importance is that the friction coefficient for porous aluminium impregnated by oil is less by roughly about 2 times than that for compact aluminium. In addition, no pronounced evidence indicative of transition to seizure with steel is found during the testing process of porous aluminium impregnated by oil. Generally, the results of tribological tests show that cast open-cell porous aluminium impregnated by oil provides promising self-lubricating properties with a friction coefficient of $f \sim 0.08$ although pressure–velocity parameter used in tribological tests was too small PV < 0.01. In comparison, friction coefficients reported by Lelonis et al. [7] for solid lubricant powders such as h-BN, graphite, Teflon, and $MoSi_2$ are 0.17, 0.28, 0.60, and 0.73, respectively. Thus, by considering high porosity and, in turn, high amount of oil, combined simultaneously with quite high strength it could be thought that cast open-cell porous aluminium has potential to be applied as porous ‘self-lubricating bearings’ alternative to those fabricated by powder metallurgical technique.

Conclusions. Tribological properties of cast open-cell porous aluminium impregnated by motor oil were measured by using pin-on-disk friction machine and reported as variation of friction coefficient versus time of sliding. Friction coefficient of porous-oil aluminium under different contact pressure ranged from 0.02 to 0.26 MPa and linear sliding velocity of 0.0942 m/s was recorded and compared with that of compact aluminium subjected to the same operating conditions. Several important conclusions were derived from these tests and summarized such as follows:

- high fraction volume of porosity about 58% and, in turn, high amount of oil about 5.5 wt.% together with enhanced mechanical properties including yield strength of $\sigma_y = 22$ MPa and Young’s modulus about E=12 GPa have been found to be indicative for cast open-cell porous Al;
- cast open-cell porous aluminium impregnated by oil showed promising self-lubricating properties with a friction coefficient of $f \sim 0.08$ which was less by roughly about 2 times than that for compact aluminium;
- promising lubricating properties combined with improved mechanical properties and oil content simultaneously are qualified cast open-cell porous aluminium to be potentially applicable for its usage as porous ‘self-lubricating bearings’ alternative to those fabricated by powder metallurgical technique.

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The paper was received by the editorial office on the 26.02.2018

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ЗАСТОСУВАННЯ ЛИТОГО ПОРИСТОГО АЛЮМІНІЮ ДЛЯ САМОЗМАЩУВАЛЬНИХ ПІДШИПНИКІВ

Експериментально було досліджено застосування литого пористого алюмінію в якості самозмащувального підшипникового матеріалу. Алюмінієві зразки були отримані шляхом відливання розплавленої суміші рідкого алюмінію з частинками солі NaCl з подальшим розчиненням солі з затверділого розплаву в водному середовищі. Було встановлено, що при ковзанні без змащування практично немає різниці в трибологічній поведінці між пористими та компактними матеріалами. Перед трибологічними випробуваннями в умовах граничної змащення зразки були просочені моторним маслом. При рясному постачанні масла в зону контакту, пористі просочені матеріали показали нижчий і стабільний коефіцієнт тертя в порівнянні з компактними матеріалами. Найбільш визначна різниця була виявлена в умовах змащення з голодуванням коли поверхневий шар олії був повністю видалений з поверхонь тертя перед випробуванням; пористі просочені матеріали демонстрували значно нижчі коефіцієнти тертя, ніж компактні зразки, які також демонстрували тенденцію до схоплення при порівняно нижчому значенні навантаження.

Ключові слова: самозмащувальні підшипники, литий пористий алюміній, тертя, механічні властивості.

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