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THE USE OF ADDITIVE MANUFACTURING TECHNOLOGY TO MANUFACTURE SLIDE BEARING SLEEVES – A PRELIMINARY STUDY

ZASTOSOWANIE METODY WYTWARZANIA ADDYTYWNEGO DO WYKONANIA PANWI ŁOŻYSK ŚLIZGOWYCH – BADANIA WSTĘPNE

Key words: additive manufacturing, slide bearings, polymers.

Abstract: The paper presents the application of an unconventional method of manufacturing bearing sleeves as well as the carrying out of preliminary research in which the manufactured components were used on a real object. Additive manufacturing methods are increasingly being used, which leads to the rapid development of technologies and their applications. The MultiJet Printing technology was used in the research, which allows precise 3D printing of sleeves made of polymeric materials. The first part of the article deals with the selected manufacturing method and the preparation of a model. The study aimed at evaluating the usefulness of bearings manufactured using the 3D printing technology to support slow-speed rotors. The preliminary research described focuses on the study of operating parameters such as the moment of friction and the bearing node temperature as a function of rotational speed during operation. Experimental tests were carried out at low rotational speeds. This paper presents and determines the scope of the application of bearings manufactured using 3D printing technology.

Słowa kluczowe: wytwarzanie addytywne, łożyska ślizgowe, polimery.

Streszczenie: W pracy przedstawiono zastosowanie niekonwencjonalnej metody wytwarzania panwi łożysk wraz z przeprowadzeniem badań wstępnych z użyciem wykonanych elementów na obiekcie rzeczywistym. Metody wytwarzania addytywnego stosowane są na coraz większą skalę, co wiąże się ze znacznym rozwojem technologii i ich aplikacjami. Do badań wykorzystano technologię MultiJet Printing, pozwalającą na precyzyjny wydruk 3D panwi z materiałów polimerowych. Pierwsza część pracy poświęcona jest wybranej metodzie wytwarzania i przygotowaniu modelu. Celem pracy było określenie przydatności łożysk wykonanych technologią wydruku 3D do podparcia wolnoobrotowych wirników. Opisywane badania wstępne obejmują poznanie takich parametrów pracy jak moment tarcia oraz temperatura węzła łożyskowego w funkcji prędkości obrotowej podczas pracy. Część eksperymentalną przeprowadzono w warunkach niskich prędkości obrotowych. W niniejszej pracy przedstawiono i określono zakres zastosowań łożysk wytworzonych omawianą w artykule metodą wydruku 3D.

INTRODUCTION

Bearings are key components of any turbomachine. Their proper selection has an impact not only on the life cycle of the machine but also on its operating parameters such as dynamic properties or power losses. For their further development, it is essential to study new materials, bearing systems, lubricants, and anti-friction coatings. Depending on the operating characteristics of the machine, particular attention must be paid to the manufacturing precision of its bearings during the design and manufacture phases. This paper presents

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a preliminary study on the use of high-precision 3D printing technology as a tool to manufacture bearings that could support slow-speed rotors.

The use of additive manufacturing techniques is increasingly important for science and engineering. Since 2013, the 3D printing technology used to manufacture parts has experienced rapid development and continues to do so. Technologies based on additive manufacturing are widely used in various scientific and engineering fields, especially in medicine **[L. 1, 2]** and biotechnology **[L. 3, 4]**, to produce machine components **[L. 5, 6]**. Currently, they also make it possible to produce unique materials that are very resistant to high temperatures (for example, Inconel **[L. 7]**). With the increasing number of additive manufacturing technologies, the number of materials used in this field has also increased. Although the ability to print from metals using such technologies as SLM (Selective Laser Melting) and DMLS (Direct Metal Laser Sintering) makes it possible to obtain elements printed with high precision; however, they still require mechanical working, which also prolongs the process of manufacturing the finished part. Currently, technologies which use plastics are dominant with regard to precise 3D printing, and the majority of these technologies allow avoiding after-machining. That is why a decision was made that this paper would focus on the use of a precise 3D printing technology which uses plastics.

Currently, various types of bearings are used in machines, such as rolling bearings and slide bearings, in both, the rolling friction is reduced by means of lubricating fluids. There is also a group of non-contact bearings, such as magnetic bearings which use magnetic field properties to produce levitation **[L. 8]**; whereas, more and more often we hear about the use of gas bearings in machines **[L. 9, 10]**, whose working mediums can also be used as lubricating fluids for their bearings. Foil bearings **[L. 11, 12]** are also classified as gas bearings, and they produce an air lubricating film (at a sufficiently high rotational speed); therefore, friction usually takes place only during bearing start-up.

Studies on the use of plastics in bearing systems began in the early 1960s **[L. 13]**. Currently, polymers are the dominant materials used in plastic bearings. Polymers that are used as construction materials for bearing nodes have different properties and behave differently than metals during the friction process. Only several multi-molecular polymeric materials are currently commonly used to manufacture plastic components exposed to tribological wear. The majority of these materials are modified using fillers to improve their tribological characteristics **[L. 14]**. One of the most popular polymers used in the production of sleeves or other bearing components is polyether ether ketone (PEEK) whose efficiency is demonstrated in many scientific articles **[L. 15–17]**. Reinforced thermosetting polymers are also widely used to produce coatings for transfer or driving rollers in module machines.

Due to the rapid process of designing these types of slide bearings, a decision was made to select this type of bearing in order to carry out the study presented in this paper. Slide bearings have a very simple design compared to other bearings, and they only consist of a bearing surface and a rolling part. Their main feature is that they do not have any moving parts, but in their construction, there is a rotary element called a cylindrical sleeve. The structure of such bearings makes them suitable to be used in many different industrial sectors. Nothing can replace slide bearings when it comes to designing small constructions, transmitting loads and also in situations where a high degree of precision is required **[L. 18]**. In most cases, slide bearings are also the cheapest types of bearings. They are also both compact and lightweight and have a high load capacity.

Although, until quite recently, the manufacture of bearings using additive manufacturing technology was termed ‘non-printed parts’ **[L. 19]**, the most recent studies show that the development of this technology and therefore the advances in manufacturing precision have made it possible to successfully conduct studies concerning the manufacture of plastic bearings by 3D printing **[L. 20]**. As the studies on 3D printing of bearings that have been carried out so far have mainly focused on the use of powder technologies (Selective Laser Sintering) and technologies based on the melting of materials such as ABS (acrylonitrile butadiene styrene), for example, the technology called Fused Deposition Modelling (FDM), a decision was made to conduct an innovative study using a technology that had not yet been tested in this area. Among the additive manufacturing devices being made available to the employees of the IMP PAN (Institute of Fluid-Flow Machinery of the Polish Academy of Sciences), the MultiJet Printing (MJP) technology was selected to be used for the study described in this paper. The aim of the study was to evaluate the usefulness of plastic bearings manufactured using a high-precision 3D printer and to assess their possible operating range with the intention of their use in slow-speed machines. The high manufacturing precision and the material used (polymeric resin) made it possible to effectively carry out the study and experiments and the results are presented below.

MANUFACTURING TECHNOLOGY. RESEARCH OBJECT

The 3D printing technology called MultiJet Printing was used to manufacture a bearing sleeve. This technology uses UV-cured liquid polymeric resin as the printing material. The printhead used in MJP technology moves only in the direction of the Z-axis, with the possibility of minor adjustments in the Y-axis direction. Additionally, it is equipped with an additional set of jets used to spray an easily-removable support material which is wax. The already mentioned photopolymer is heated to an appropriate temperature (until it becomes a liquid) and then is used as a building material. The jets used for both the support and building material can be activated simultaneously or selectively. The support material is sprayed directly on the printing platform using a multi-jet piezoelectric printhead over the entire width of the printing area, thus eliminating movement in the direction of the Y-axis. The printing platform alone is able to move along the X-axis. During the movement of the platform, the jets deposit the appropriate amount of material in selected points just like in InkJet printers. The platform then moves towards the UV lamp (located at the back of the printhead), and the UV-curing process begins. The printhead is lifted to a distance equal to the thickness of one layer of the printed material, and the process is continued until the whole part is printed. The thickness of a single layer is only 16 µm, thus allowing elements to be manufactured with a high degree of precision. An additional advantage of this additive manufacturing technology is that it uses an easily meltable support material. Thanks to this technology, any desired geometry can be obtained and the external surfaces of printed elements are not damaged during the removal of the support material, thus significantly accelerating the manufacturing process. The mechanical strength of parts manufactured using this technology is similar to the mechanical strength of those manufactured using the FDM technology. The technology described above is expensive, like the SLS (Selective Laser Sintering) and SLM technologies, but it offers the best manufacturing precision among the additive manufacturing technologies mentioned. The disadvantage of elements manufactured using MJP technology is their limited operating temperature range, and the temperature should not exceed 88ºC. This technology has already been successfully used by the authors of this article to manufacture machine parts for research purposes, and the results obtained have helped to evaluate its usefulness during the design and optimisation stages **[L. 6]**.

In order to carry out the experiment, slide bearings were designed and manufactured using the above-mentioned technology. Due to the high manufacturing accuracy of the additive manufacturing technology, a decision was made to manufacture three bearing sleeves, each with a different fit on the shaft journal used in the experiment. The journal had a diameter of 25 mm. The fits between the three bearings and the journal were as follows: close fit +20 µm, nominal fit +30 µm, and clearance fit +40 µm. In the bearing sleeve design, the arrangement of measuring points was also taken into account. The bearing manufactured using MJP technology is shown in **Fig. 1**.

Before the start of the experiment, the surface roughness of the printed bearing was measured. A roughness measuring instrument (MarSurf PS1 manufactured by Mahr) was used for this purpose. The results of the measurements are presented in **Table 1**. The R_a coefficient measured for the journal surface was 0.193 µm.

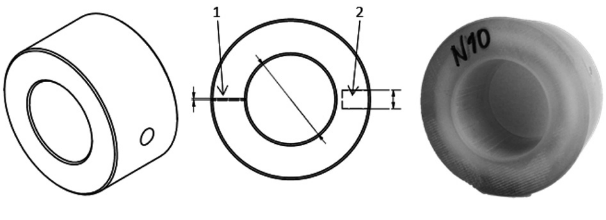

Fig. 1. Bearing design (left) and sleeve manufactured using the MJP technology (right): 1 – thermocouple, 2 – force sensor

Rys. 1. Projekt łożyska – strona lewa, łożysko wykonane technologią MJP – strona prawa: 1 – mocowanie termopary, 2 – mocowanie cięgna czujnika siły

Table 1. The surface roughness of sleeve measured after printing

Tabela 1. Wyniki chropowatości powierzchni panwi bezpośrednio po wydruku

Bearing fit	Close fit (+20 µm)	Nominal fit (+30 µm)	Clearance fit (+40 µm)
R_a [µm]	1.71	1.626	1.692

EXPERIMENTAL SETUP

The typical parameters that determine the performance of a bearing are the moment of static friction and the moment of viscous friction, which are generated during journal rotation and resulting from the contact between the journal and the friction surface of the sleeve. A test rig was built to perform experimental tests and measure parameters such as journal temperature, sleeve temperature, and torque. A force sensor (Wobitek EMS with force range 0-200 N) was used to measure the torque. It was attached by means of a metal rod, which was fixed to the bearing sleeve using a threaded hole, and the length of the rod was equal to 70 mm. The temperature of the shaft journal was measured using a pyrometer (Mirco Epsilon CT-CF22-C3 transducer) and the temperature of the bearing sleeve was measured by means of a K-type thermocouple. An LMS measurement system was used to record data from the sensors. The test rig with the measurement system used in experimental research is shown in **Fig. 2**. The drive used in the experiment can achieve a rotational speed up to 24,000 rpm.

The preliminary study carried out made it possible to determine the bearing load range. It is assumed that a bearing manufactured with the MJP technology can

Fig. 2. Test rig and measurement system: 1 – bearing manufactured using the MJP technology, 2 – drive, 3 – force sensor, 4 – sensor used to measure the temperature of the shaft, 5 – sensor used to measure the temperature of the sleeve

Rys. 2. Stanowisko badawcze wraz z układem pomiarowym: 1 – łożysko wykonane technologią MJP, 2 – napęd, 3 – czujnik siły, 4 – czujnik temperatury wału, 5 – czujnik temperatury panwi łożyska

operate under loads of up to 750 g in order not to exceed the allowable temperature of the material of which it is made. For this reason, experiments were carried out without a load and with a load of 500 g and 750 g, at selected time periods for each bearing. The weight of a bearing sleeve was 32 g. The research was conducted using run-up tests. The bearing was loaded by a weight (fixed in the bearing's axis), using a clamping ring adhering to the outer surface of the sleeve. Due to the low load, the test rig was not equipped with an active lubrication system. The bearing was lubricated in a passive manner, i.e. the sleeve was lubricated with SAE10 oil before it was mounted on the journal.

RESULTS

The experiment was conducted at two different time periods. The first tests were run-up tests that aimed at checking the operation of the bearings during a short period of time (approximately 3 minutes) up to a rotational speed of 1,000 rpm. Each run-up and each run-down lasted about 30 seconds. The first experiments were carried out without a load. Then, each bearing was loaded with a 500 g weight. The results of the experiments are shown in **Figs. 3–5**. In the graphs, the measured parameters are marked with the following colours: rotational speed – black, torque – magenta,

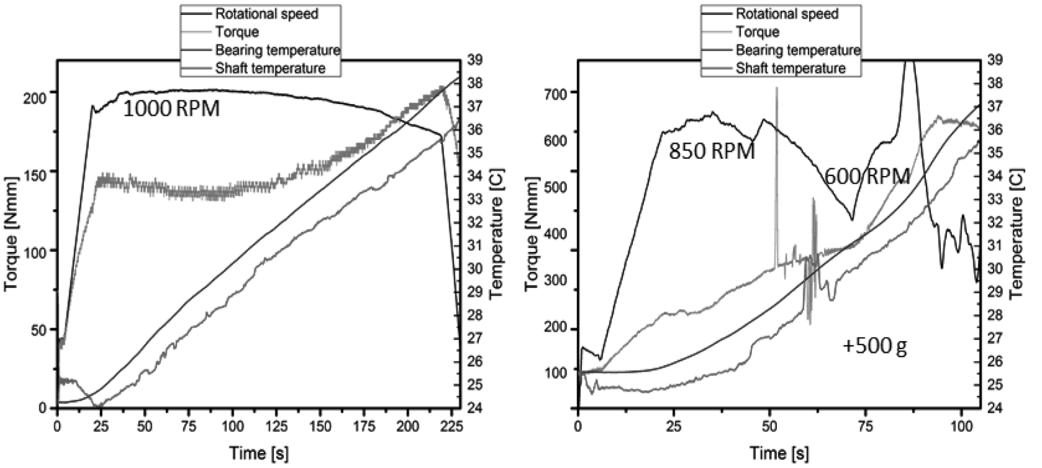

Fig. 3. Graphs showing the rotational speed, torque and the temperature of the bearing and shaft versus time, obtained during the operation of the bearing with a close fit. On the left side – bearing without a load, on the right side – bearing with an added load of 500 g

Rys. 3. Przebieg czasowy pracy łożyska o ciasnym pasowaniu w funkcji prędkości obrotowej, momentu tarcia i temperatury. Strona lewa – łożysko bez obciążenia, strona prawa – łożysko z obciążeniem o wartości 500 g bearing temperature – blue, and journal temperature – red. The left part of the curve representing the torque corresponds to static friction which then turned into viscous friction (right part).

During the test of a bearing with a close fit without a load (**Fig. 3**, left graph), the temperature of both the journal and the sleeve increased, which indicated that there was too much friction between the journal surface and the bearing. This also increased the torque and led a decrease in the rotational speed of the drive. Although the results indicated that this bearing variant would not work properly, tests under load were performed only for research purposes. The results (**Fig. 3**, right graph) clearly show fluctuations in torque and rotational speed values. The nature of such a bearing's operation indicates that there is too little clearance between the journal and the sleeve. As the temperature increased and the bearing's operating performance deteriorated, leading to a gradual decrease in the rotational speed. In order to avoid damage to the bearing, the test was stopped. The bearing with a close fit was excluded from further testing due to the results obtained.

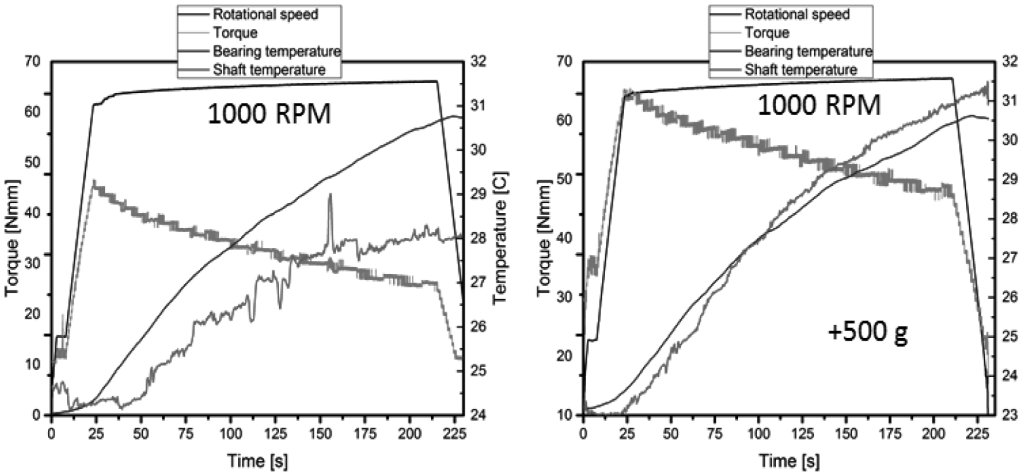

Fig. 4. Graphs showing the rotational speed, torque and the temperature of the bearing and shaft versus time, obtained during the operation of the bearing with a nominal fit. On the left side – bearing without a load, on the right side – bearing with an added load of 500 g

Rys. 4. Przebieg czasowy pracy łożyska o nominalnym pasowaniu w funkcji prędkości obrotowej, momentu tarcia i temperatury. Strona lewa – łożysko bez obciążenia, strona prawa – łożysko z obciążeniem o wartości 500 g

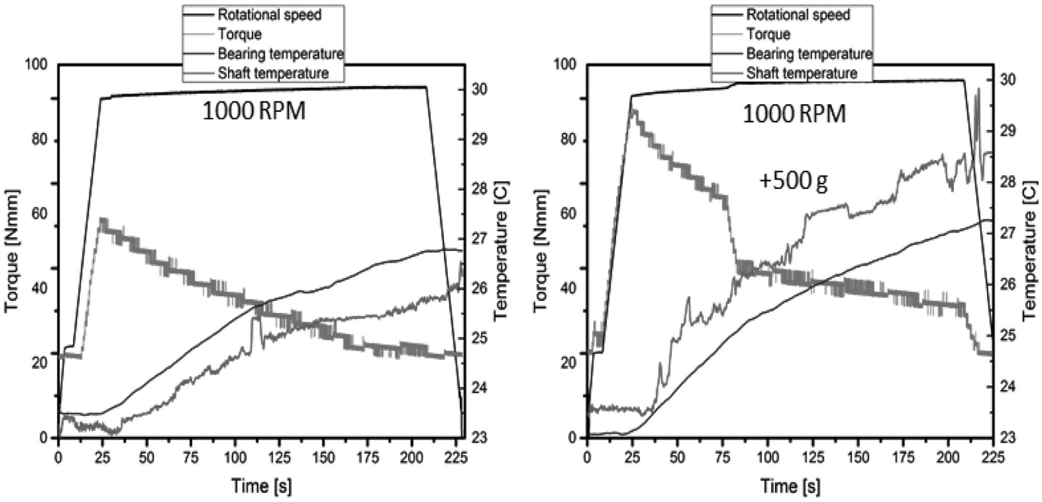

Fig. 5. Graphs showing the rotational speed, torque and the temperature of the bearing and shaft versus time, obtained during the operation of the bearing with a clearance fit. On the left side – bearing without a load, on the right side – bearing with an added load of 500 g

Rys. 5. Przebieg czasowy pracy łożyska o luźnym pasowaniu w funkcji prędkości obrotowej, momentu tarcia i temperatury. Strona lewa – łożysko bez obciążenia, strona prawa – łożysko z obciążeniem o wartości 500 g

As can be seen in **Fig. 4**, the curve representing the torque as a function of time obtained for the bearing with a nominal fit differs significantly from that obtained for the bearing with a close fit. The maximum value of the torque was more than two times lower and the curve resembles an exponential function, i.e. it increased during start-up and decreased during bearing operation (endeavouring to stabilise itself). After a load of 500 g was added to the bearing, its operating nature did not change. The temperature values increased slightly and the torque increased twofold. Compared to the bearing with a close fit, the maximum torque value was ten times lower. The clearance of the bearing with an additional load is very close to the optimal clearance.

The bearing with a clearance fit (**Fig. 5**) operated similarly to the bearing with a nominal fit. Due to the higher clearance value, we can notice that the torque value is lower and the increases in the shaft and bearing temperature are also lower. After adding a load, the operation of the bearing remained stable. There was a sharp decrease in the value of torque followed by a period where its value was almost constant. The temperatures of the two bearings were very similar and did not exceed 30°C. The load applied to properly functioning bearings was increased to 750 g and run-up tests were carried out again at the same time interval. The results of these tests are shown in **Fig. 6**. The torque of the bearing with a nominal fit increased twofold compared to the less loaded bearing and this parameter increased by approximately 50% for the bearing with a clearance fit. The temperatures in the bearing node did not exceed 30°C.

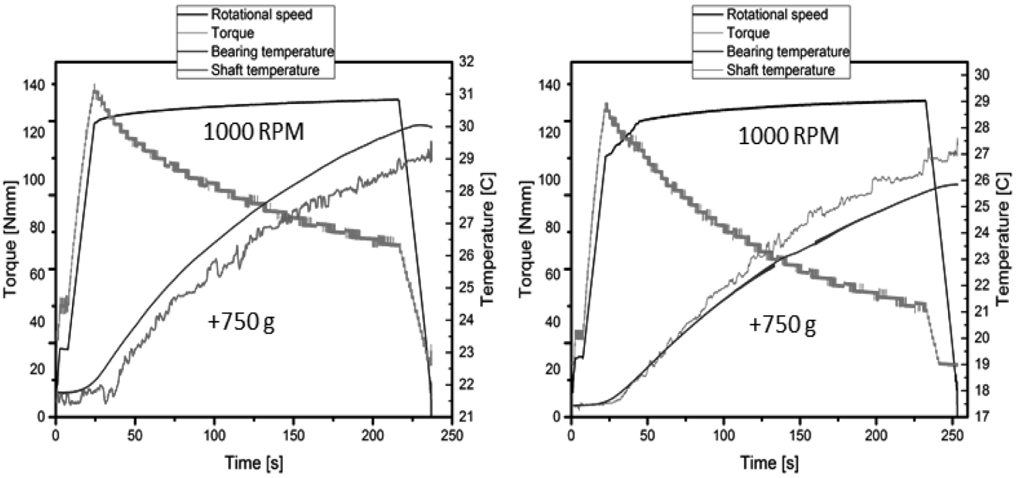

Fig. 6. Graphs showing the rotational speed, torque and the temperature of the bearing and shaft versus time, obtained during the operation of the bearing with a clearance fit. On the left side – bearing with a nominal fit, on the right side – bearing with a clearance fit. Both bearings were loaded with an additional mass of 750 g

Rys. 6. Przebieg czasowy pracy łożysk o nominalnym (lewa strona) oraz luźnym (prawa strona) pasowaniu w funkcji prędkości obrotowej, momentu tarcia i temperatury. Łożyska obciążone masą 750 g

After carrying out short run-up tests, the surface roughness of the journal and bearing sleeves was measured again. The parameter R_a of the journal still had the same value. The bearings ground in themselves during the experimental research. The obtained values of the parameter R_a are presented in **Table 2**. The surface roughness of the sleeve printed using MJP technology changed from 1.7 µm (which corresponds to a value that can be obtained by means of precise after-machining) to a value lower than 0.5 µm (which can be obtained as a result of precise grinding). Since the bearing with a close fit did not operate for as long as the other bearings, the value of the parameter R_a was higher.

The first tests of the bearings were conducted to indicate the type of fit that would be optimal. The second test consisted in carrying out a study of a loaded bearing that was to operate for a longer time. The bearings were reloaded with an additional mass of 500 g and were made to operate for one hour. Whereas, in the case of a short test, the bearing with a clearance fit had slightly better operating parameters, and the bearings with an additional load which operated for a longer period of time showed different properties. The results of these tests are presented in **Fig. 7** and **Fig. 8**.

Table 2. The surface roughness of sleeve measured after conducting research

Tabela 2. Wyniki chropowatości powierzchni panwi po przeprowadzeniu badań

Bearing fit	Close fit (+20 µm)	Nominal fit (+30 µm)	Clearance fit (+40 µm)
R_a [µm]	0.575	0.489	0.418

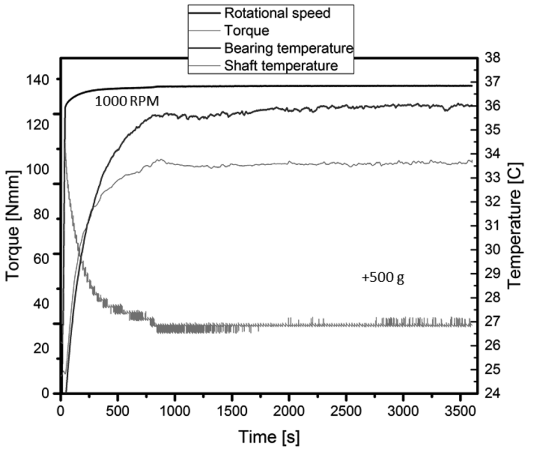

Fig. 7. Graphs showing the rotational speed, torque and the temperature of the bearing and shaft versus time, obtained during the operation of the bearing with a nominal fit. The bearing was loaded with an additional mass of 500 g and the test took an hour

Rys. 7. Przebieg czasowy pracy łożyska o nominalnym pasowaniu w funkcji prędkości obrotowej, momentu tarcia i temperatury. Łożysko obciążone masą 500 g przez czas 1 godziny

In both cases, the torque value was similar and was approximately 120 Nmm, then it stabilised itself at different levels. In the case of the bearing with a clearance fit, this parameter reached a value of 50 Nmm, whereas it had a value of 30 Nmm for the bearing with a nominal fit. The greater clearance in the bearing node did not stabilise the temperature during the 1-hour measurement. The bearing clearance was too high.

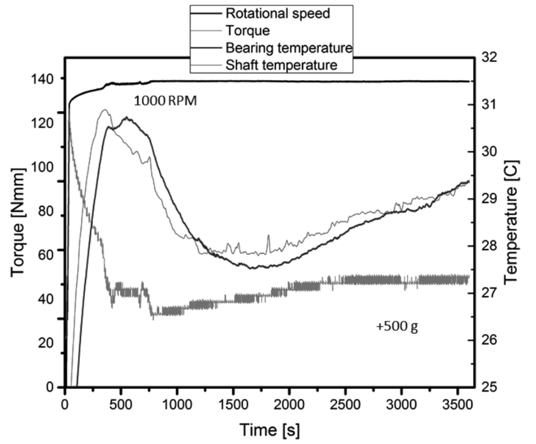

Fig. 8. Graphs showing the rotational speed, torque and the temperature of the bearing and shaft versus time, obtained during the operation of the bearing with a clearance fit. The bearing was loaded with an additional mass of 500 g and the test lasted an hour

Rys. 8. Przebieg czasowy pracy łożyska o luźnym pasowaniu w funkcji prędkości obrotowej, momentu tarcia i temperatury. Łożyska obciążone masą 500 g przez czas 1 godziny

After carrying out the above tests, the surface roughness was checked again. During the comparison of the results, no differences in the values of the coefficient R_a were observed compared to the measurements carried out previously. All the discrepancies were within the error tolerances of the measuring device.

CONCLUSIONS

The paper presents a preliminary study on the use of passively lubricated bearings manufactured using 3D printing technology, which was designed to support slow-speed rotors. For this purpose, the following works were carried out: the surface roughness of bearings was measured after they were printed and at the end of each stage of the experimental research; and, a test rig equipped with a measurement system was designed and built, which was used to determine selected operating parameters of bearings. With the help of the high-precision 3D printing technology, three variants of bearings with different clearances were manufactured.

Experimental tests were carried out on bearings that operated without a load and with a load of 500/750 g, at different operating times. The results presented in this paper demonstrate how the fit (bearing clearance) and load selection affects the performance of the bearings. After analysing the results of the first tests, it was concluded that the bearing with a close fit, manufactured using MJP technology, could not function properly under any conditions. The bearings with the other two types of fit were able to operate properly at a speed of 1,000 rpm with a load of 500 g and 750 g, both for a short and long period (approximately an hour). The measurements of the surface roughness of the bearings showed that the surface of the sleeve became more resistant to wear after carrying out the first tests. During further stages of the study, no change in the value of the parameter R_a was observed.

The bearings are intended to be used to support a slow-speed rotor operating at a constant load. Everything seems to indicate that 3D printing technology can be used to manufacture such bearings. All planned tasks have been completed successfully. After the preliminary study, bearings manufactured using the additive manufacturing technology are fully operational and ready for further tests. Future studies will focus on testing the impact of higher loads on bearings at longer operating times as well as on testing special anti-friction coatings used in order to reduce the torque during start-ups. The change in the surface roughness is a very important factor during the selection of bearing clearance and must be taken into account in future works.

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