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INFLUENCE OF MATERIALS ON THE EFFICIENCY OF WORM GEAR TRANSMISSION

Blaža Stojanović[1], Aleksandar Vencl[2], Aleksandar Skulić[3], Slavica Miladinović[4], Sandra Gajević[5]

Abstract: This paper presents the results of experimental research of efficiency of a worm gearbox which was designed for that purpose. The gearbox housing is of a welded construction with side openings, which enables simple assembly and disassembly of worm pairs, bearings and other elements. Two worm pairs with the same geometric characteristics were used for testing, where the worms are made of improved steel 42CrMo4 and the worm gears are made of zinc-aluminum alloy ZA12 and aluminum alloy A356. The values of the efficiency were determined at different operating modes of the gearbox (loads and rotational speeds), where mineral oil with a viscosity of 460 mm2/s was used as a lubricant. According to the previously defined working conditions, the power losses and friction coefficient of the worm gear pairs were calculated. Based on the test results, it is concluded that the values of the efficiency of the worm gear pair 42CrMo4/ZA12 are significantly higher compared to the worm gear pair 42CrMo4/A356, which is the result of lower power losses and lower values of the coefficient of friction.

Key words: degree of efficiency, worm gears, material, power losses.

1 INTRODUCTION

Worm gearboxes have a number of advantages compared to other types of transmissions, which are reflected in compact construction, high transmission ratio,

[1] PhD, Blaža Stojanović, University of Kragujevac, Faculty of Engineering, Kragujevac, Serbia; blaza@kg.ac.rs
[2] PhD, Aleksandar Vencl, University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia; avencl@mas.bg.ac.rs
[3] MSc, Aleksandar Skulić, University of Kragujevac, Faculty of Engineering, Kragujevac, Serbia; aleksandarskulic@gmail.com
[4] MSc, Slavica Miladinović, University of Kragujevac, Faculty of Engineering, Kragujevac, Serbia; slavicam@kg.ac.rs
[5] PhD, Sandra Gajević, University of Kragujevac, Faculty of Engineering, Kragujevac, Serbia; sandrav@kg.ac.rs

high load capacity, reliable and quiet operation, etc., and because of this, they are widely used for both power transmission and motion transmission [1]. The main disadvantage of the worm gearbox is a relatively low efficiency, which is a consequence of the high sliding friction between the tooth flanks of meshed gears, which leads to significant power losses and heating of the worm gearbox. In addition to sliding friction between gear teeth, friction also occurs in bearings, between lubricant and gears, in shaft seals, etc. [2].

Power losses in a worm gearbox can vary within wide limits depending on a large number of influencing factors [3, 4]. One of the most important is the type of material of meshed gears [5]. A high value of dynamic durability, high resistance to wear and pitting, good sliding conditions and a high efficiency of the worm pair are required from the material for the production of worm gear pair. A combination of materials for meshed gears that will meet the complex requirements of meshing should be selected.

A worm gear pair is a sliding joint characterized by a linear contact between the meshed elements. Since the worm has a much higher rotational speed than the worm gear, a material of higher hardness is chosen for its production in order to prevent rapid wear. The choice of material for making the worm largely depends on the operating mode of the transmission. Thus, in the case for low speeds and loads, worms of improved steel are chosen, while for transmissions of higher power, cemented or flame-hardened worms are used, which are ground and polished with a hardness ranging between 59 and 65 HRC. Tin and aluminum bronze and brass are mainly used for the production of worm gears. In the case of lower speeds and loads, pearlitic gray cast iron and nodular cast iron are used. In addition, zinc alloys, magnesium alloys and plastics are also used for production of worm gears [6-10]. The best tribological characteristics are achieved when the worm is made of hardened and ground steel and the worm gear is made of centrifugally cast tin bronze.

The main goal of this research is the application of new materials for the production of worm gears and the investigation of their influence on power losses and the efficiency of the transmission. These are materials with zinc-aluminum (alloy ZA12) and aluminum base (alloy A356). The use of these materials aims to reduce the weight of the worm gearbox and the power losses, provide better friction and wear conditions, as well as longer service life, etc.

2 GEARBOX POWER LOSS MODEL

During the meshing of gear teeth, high contact pressures, friction, flank wear, and heating occur, which limit the amount of power that can be transmitted by the worm gearbox. The power on the output shaft of the transmission is less than the input power by the amount of losses that occur during operation due to various resistances. The total power losses P_G of worm gearbox consist of power losses due to friction in the meshing of gear teeth, power losses in bearings, power losses at idle speed, power losses in shaft seals and other losses, respectively [11]:

$$P_G = P_{GZ} + P_{GL} + P_{G0} + P_{GD} + P_{GX} \tag{1}$$

Total power losses can basically be divided into load-dependent and load-independent power losses. For both cases, power losses due to friction in the gear meshing (P_{GZ} and P_{GZ0}) and power losses in the bearings (P_{GL} and PG_{L0}) have their share. Power losses in seals P_{GD} and other losses P_{GX} in gear transmission are losses that do not depend on the load (Figure 1) [12].

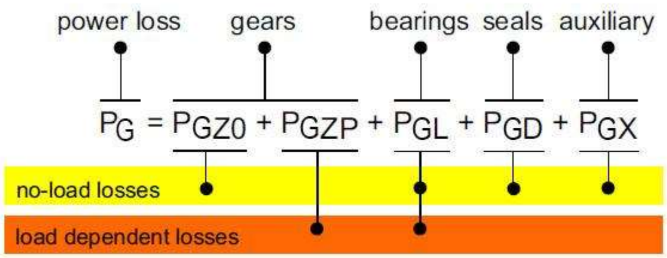


Figure 1. *Power losses in gearbox* [12]

Most gearboxes work in variable operating conditions where speed and load change frequently, so it is very difficult to develop a simple and general approach for calculating power losses. In the available literature, calculations are mostly based on existing analytical methods that are quite complex and generally require appropriate experimental data for a realistic assessment of power losses [13-16].

3. EXPERIMENTAL SETUP AND MEASUREMENTS

3.1 Gearbox test rig

Experimental tests of the efficiency of the single-stage worm gearbox were carried out on the AT200 device shown on figure 2. The device consists of an electromotor (1) with a nominal power of 0.2 kW, which is supported by two bearings on the upper part of the base so that it can rotate around its longitudinal axis. The input torque of the electromotor is determined by means of a dynamometer with a lever (2) located on the front side of the stand. Changing the load on the output shaft of the transmission is achieved by means of an electromagnetic brake (3), which can take over a torque of up to 10 Nm. The magnitude of the output torque is determined by means of a dynamometer (4) which is connected to the lever located on the brake. Changing the operating mode of the transmission (rotational speed and load) is done using the potentiometer located on the control unit (5). The working temperature of the oil is measured using a thermometer (6).

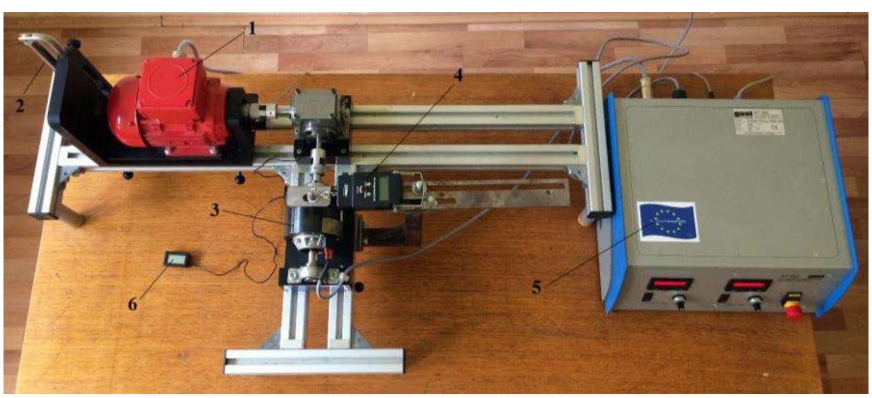
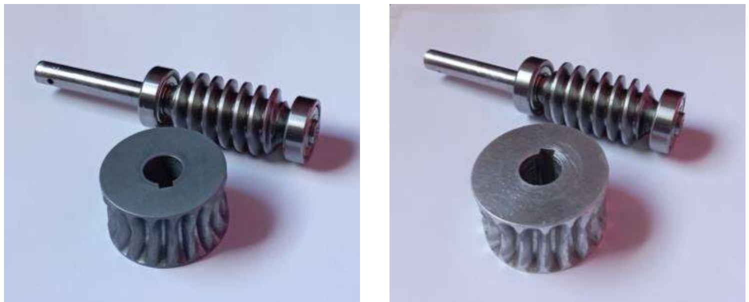


Figure 2. *AT200 device*

Two worm gear pairs with a transmission ratio of 18 and an axial distance of 31 mm were used for the test. The worm is the driving element and is made of 42CrMo4 tempered steel, while the worm gears are made of zinc-aluminum ZA12 and aluminum alloy A356 (Figure 3).



a) *b)*

Figure 3*. Tested worm gear pairs: a) 42CrMo4/ZA12; b) 42CrMo4/A356*

The worm gear shaft is supported by two single-row deep groove ball bearings with radial contact type 6000 RZ, while the worm gear shaft is supported by two single-row deep groove ball bearings type 6001Rs.

3.2 Results and discussion

3.2.1 Gearbox efficiency

The test for the efficiency is based on varying two different values of the rotational speed of 1500 min^{-1} and 2500 min^{-1}, five levels of load (output torques), while mineral oil with a viscosity of 460 mm^2/s is used as a means of lubrication. The output torque is changed by changing the current on the control unit in the interval 0.1 A to 0.2 A with a change step of 0.025 A. Considering both worm pairs, the average values of the output torque T_2 ranged between 2.11-5.32 Nm. Based on the experimentally measured values of the input and output torques, the values of the efficiency of the transmission were determined according to the following expression:

$$\eta = \frac{P_2}{P_1} = \frac{T_2}{T_1 \cdot i} \tag{2}$$

Graphical representation of of the measurement results for different test conditions is given in Figure 4. At the same time, a dependence was established between the efficiency of the transmission and the output torque.

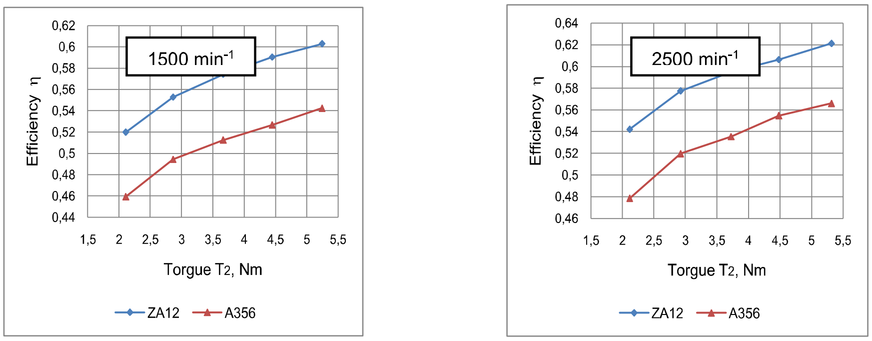


Figure 4. *Values of gear efficiency for different worm gear materials*

From the diagram, it can be observed that the values of the efficiency of the worm gearbox increase with the increase of the output torque as well as at higher rotational speed (circumferential speeds of the gears). Namely, at low circumferential speeds and relatively high specific pressures on the flanks of the teeth, borderline to mixed lubrication is achieved. However, with an increase in circumferential speed, an oil film forms more easily between the meshing gear teeth, which creates the conditions for hydrodynamic lubrication, which results in higher values of efficiency. This course of change in the efficiency is noticeable in both worm gear pairs. By comparing the measured results, it can be observed that the values of efficiency of the worm gearbox with gear pair 42CrMo4/ZA12 range between 0.51-0.62. Depending on the working conditions, these values are higher between 9% and 13% compared to the gear pair 42CrMo4/A356 where the efficiency ranges from 0.45-0.57.

3.2.2 Power losses

The calculation of power losses in the worm gear was performed according to the defined test conditions for both experimental worm gear pairs. First, power losses *in* bearings P_{GL} and shaft seals P_{GD} were determined according to the mathematical calculation of the bearing manufacturer SKF [17]. The calculation of these losses was made depending on the load of the worm gear pair, the input rotational speed and the viscosity of the oil at operating temperatures.

The power losses in the gear mesh are determined based on the experimentally obtained values of the efficiency of the worm gearbox and the power losses in the bearings and shaft seals according to the following expression:

$$P_{GZ} = P_1 \cdot (1 - \eta) - P_{GL} - P_{GD} \tag{3}$$

The results of the calculation of power losses in gear mesh for different materials of worm gear pairs and different working conditions are shown in Figure 5.

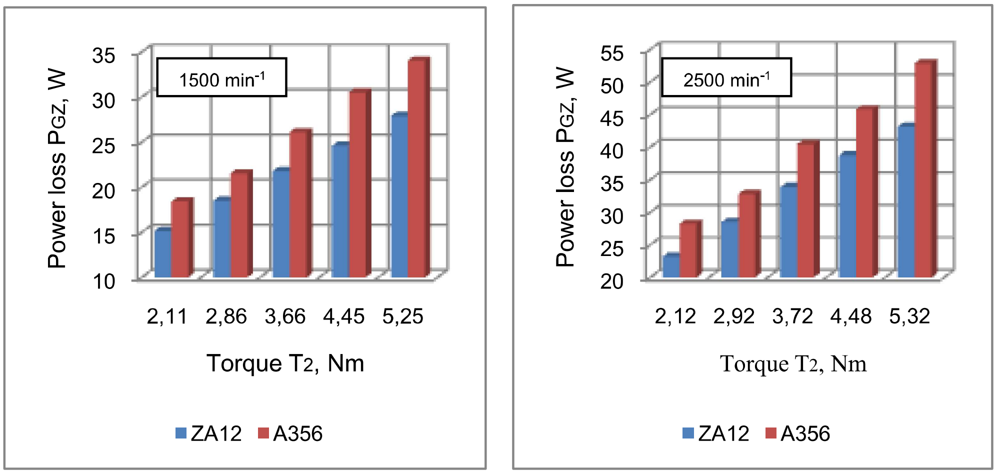


Figure 5. *Effect of materials on power losses in gear mesh for different operating conditions*

Based on the diagram, it can be concluded that the power losses in the gear mesh increase with the increase in load and rotational speed. At higher loads, the operating temperature rises, which leads to a reduction in the oil film and greater power losses. On the other hand, with the increase in circumferential speed, the total transmitted power of the worm gearbox also increases, with a reduction in the load on the worm gear pair and easier formation of an oil film. The lowest power losses occur in the 42CrMo4/ZA12 worm gear mesh and range from 15-43 W. Looking at different load levels and gear circumferential speeds, these losses are lower between 16% and 24% compared to the 42CrMo4/ZA12 worm pair. A356. A greater difference in power losses is noticeable at higher torque outputs and higher rotational speed.

Based on the calculated values of power losses, the efficiency of the worm gear pair η_z can be determined, which represents the ratio of the output P_{2Z} and the input power P_{1Z} of the worm gearbox, that is:

$$\eta_z = \frac{P_{2Z}}{P_{1Z}} \tag{4}$$

The input power of the worm gear pair P_{1Z} is obtained when the power of the electric motor P_1 is reduced by the power losses in the bearings P_{GLA} and P_{GLB} and the shaft seals P_{GDI} [18]:

$$P_{1Z} = P_1 - P_{GLA} - P_{GLB} - P_{GDI} \tag{5}$$

The output power of the worm gear pair P_{2Z} is the power transmitted to the worm gear shaft. It is obtained when the useful power on the output shaft P_2 is increased by the losses in the bearings P_{GLC} and P_{GLD} and the seals of the worm gear shaft P_{GDII} [18]:

$$P_{2Z} = P_1 - P_{GLC} + P_{GLD} + P_{GDII} \tag{6}$$

The values of the worm gear pair efficiency are determined according to expression 4 for experimental operating conditions. These values ranged from 0.55-0.65 for a worm gear pair with a worm gear made of ZA12 alloy and within 0.49-0.58 for a worm gear pair with a worm gear made of A356 alloy.

4 CONCLUSIONS

Through a comprehensive analysis of the experimental results, it can be concluded that the values of the efficiency increase with the increase of the load and the circumferential speed of the gears. The material of the meshed gears, operating temperature, power losses and the amount of friction in the contact zone of the gear teeth, as well as power losses in the bearings and shaft seals, have a significant influence on this course of change.

The type of material of the meshed gears has the greatest influence on the efficiency. Taking into account different operating conditions, the worm gearbox efficiency ranged between 0.51-0.62 for the worm gear pair 42CrMo4/ZA12 and between 0.45-0.57 for the worm gear pair 42CrMo4/A356. Depending on the load level and circumferential speeds of the gears, the values of the efficiency of the worm gearbox with the worm gear pair 42CrMo4/ZA12 are higher between 9% and 13% compared to the previous worm gear pair. As a result of the higher efficiency, power losses in the gear mesh of the 42CrMo4/ZA12 worm gear pair are lower between 16% and 24%, while the friction coefficient values are lower between 25% and 34% compared to the 42CrMo4/A356 worm gear pair.

Therefore, it is evident that a worm gear pair with a worm gear made of ZA12 alloy has better tribological characteristics and a better ability to maintain an oil film between the meshed gear teeth compared to a worm gear pair with a worm gear made of A356 alloy, which gives a recommendation for the use of this alloy for the manufacture of worm gears.

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