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The influence of worm gear material and lubricant on the efficiency and coefficient of friction

Aleksandar SKULIĆ [1,*], **Milan BUKVIĆ** [2], **Sandra GAJEVIĆ** [2], **Slavica MILADINOVIĆ** [2], **Blaža STOJANOVIĆ** [2]

[1] Kosovo and Metohija Academy of Applied Studies, Leposavić, Serbia
[2] University of Kragujevac, Faculty of Engineering, Kragujevac, Serbia
*Corresponding author: aleksandar.skulic@akademijakm.edu.rs

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Abstract

This paper presents the results of experimental tests of the efficiency of a single-stage worm gear. Two worm drives were used for testing, where the worms are made of improved steel 42CrMo4 and the worm gears are made of tin bronze CuSn12 and aluminium alloy A356. The values of the efficiency were determined at different values of revolutions and loads, where oils of different viscosities were used for lubrication. Determining the efficiency, the coefficient of friction of worm drives was calculated for experimental operating conditions, as well as the mass measurement of worm gears before and after testing. Based on the experimental results, depending on the operating mode and oil viscosity, the values of the efficiency of the worm drive made of the material 42CrMo4/CuSn12 are higher by 5 to 9 % compared to the worm drive 42CrMo4/A356. Higher values of the efficiency of the worm drive 42CrMo4/CuSn12 cause lower values of the coefficient of friction by 14 to 21 % as well as less wear of the worm gears.

1. Introduction

Worm drive transmissions, as hyperboloid gear pairs, have a very wide application in various machine structures, industrial plants and motor vehicles, but also in various devices and apparatus of wide use. The key application of worm gears is in the case of the need to transfer power from the driving to the driven shaft, whose axes usually cross at an angle of 90° [1].

Due to their advantages in terms of high transmission ratios in only one reduction stage, operation with low vibrations and low noise level and the possibility of self-braking, worm gears are an indispensable element in the technology of gear manufacturing and application. Applying the optimal choice of worm and worm gear geometry, materials for production, lubrication method and the type and properties of lubricants and choosing the appropriate operating mode, the efficiency of the worm drive transmission can be significantly influenced [2-5].

Due to the high sliding friction between the worm and the worm gear, a significant amount of heat is released, resulting in high power losses and low efficiency. Despite the lower value of the efficiency in comparison with other toothed power transmissions, worm gears are widely used. Numerous factors affect the efficiency of worm gears, such as materials from which the worm and worm gear have been made, viscosity and type of lubricant, geometry of the worm drive, peripheral speed, type of gear transmission (reducer or multiplier), working conditions, temperatures of individual elements, etc. [6-9].

The material of the worm drives is one of the most important factors that have a great influence on the efficiency, as well as on the coefficient of friction between the meshed gear teeth. The choice of material for the production of worm drives mainly depends on the operating mode of the transmission (rotational speed, load). Worms are usually made of steel for cementation and improvement, while worm gears are made of tin bronze, aluminium bronze, brass, zinc alloys, grey cast iron, plastics, etc. [10-13].

As worm gears are made of materials with less hardness compared to worms, they are more sensitive to destruction. Therefore, the main goal of this research is directed towards the selection of new materials for the production of worm gears (materials with aluminium base).

Aluminium-based alloys, such as A356 alloy, can be used to make worm gears because of many advantages over conventional materials. A356 is a hypoeutectic Al-Si alloy that has good mechanical properties, high toughness, exceptional ductility and high corrosion resistance. One of the main disadvantages of this alloy is poor wear resistance, which can be improved by adding reinforcing particles such as Al_2O_3, SiC and others [14-17]. The main part of the research presented in this paper is experimental tests of the efficiency of worm drives with worm gears made of aluminium alloy A356 and tin bronze CuSn12 and a comparison of the obtained results.

Calculation of the efficiency of the power transmission requires knowledge of either the input power and power loss or the input and output power of the transmission. The total losses of the power transmission can be expressed as the sum of the partial power losses in the meshing of the worm and worm gear, losses in bearings, losses in contact seals, losses in lubricant, etc. Losses in teething, from the tribological aspect, represent the dominant losses, that is, they take part in the largest percentage of the total power losses of the worm gear [18,19].

The importance of this paper is primarily in the presentation of the experimental results obtained during the testing of the worm drive transmission for different materials of the worm gear at different speeds and different loads, but also when using lubricants of different viscosity. Particularly significant are the comparisons of the obtained values of power losses and the efficiency of the worm gear, with detailed comments, primarily through diagrams.

2. Plan and equipment of experimental research

The experiment has been carried out using the AT 200 device, shown in Figure 1, which consists of an electric motor (1), a dynamometer with a lever for measuring the input torque (2), an electromagnetic brake (3), a dynamometer for measuring the output torque (4), a control unit (5) and a thermometer for measuring the working oil temperature (6).

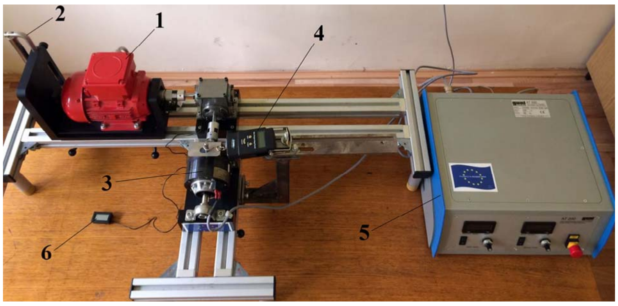

Figure 1. Testing device AT200

The electric motor with a nominal power of 0.2 kW is supported by two bearings on the upper part of the base, allowing it to rotate around its longitudinal axis. The input torque of the electric motor T1 is determined using a dynamometer connected to a 50 mm long lever placed on the front side of the stand. The load on the output shaft of the power transmission is changed via the electromagnetic brake, which can absorb a torque of 10 Nm. The output torque T2 is measured using a dynamometer connected to a 100 mm lever located on the electromagnetic brake. Changing the operating mode of the worm drive transmission is done by changing the number of revolutions of the electric motor and changing the load, by changing the current, using potentiometers on the control unit. The working temperature of the oil is measured using a digital thermometer [20-22].

Two worm drives with a transmission ratio of 18 and an axial distance of 31 mm were used for the test. Worms are made of improved steel 42CrMo4 while worm gears are made of tin bronze CuSn12 (ρ = 8880 kg/m^3, 80 HB) and aluminium alloy A356 (ρ = 2670 kg/m^3, 75 HB) (Fig. 2).

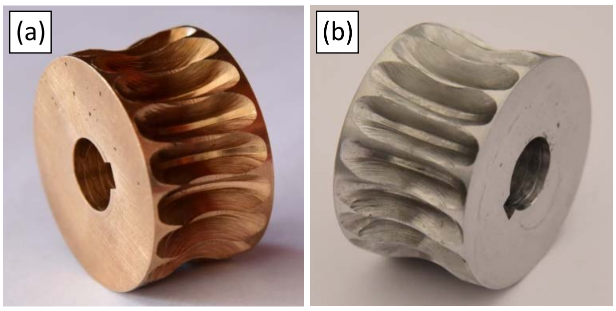

Figure 2. Worm gear made of: (a) tin bronze CuSn12 and (b) aluminium alloy A356; reprinted from Skulić [23], licensed under CC BY-ND 4.0

The other geometric and mechanical characteristics of the material of the tested worm drives are presented in the paper [24].

The tests were carried out in lubricated conditions by varying four different values of the rotational speed (1000, 1500, 2000 and 2500 rpm) and three different gear oils (Table 1). These are high-quality mineral oils with a high viscosity index that contains EP additives based on phosphorus and sulphur.

Table 1. Basic properties of the used oils

Property	Oil		
	ISO VG 220	ISO VG 460	ISO VG 680
Viscosity at 40 °C, mm^2/s	220	460	680
Viscosity at 100 °C, mm^2/s	18.43	28.91	40.8
Viscosity index	91	90.3	97

Efficiency tests are performed under different working conditions defined by the experiment plan. Namely, by changing the electric current in the interval from 0.1 to 0.2 A (with a step of 0.025 A), the braking force and thus the load, i.e. the output torque T2 is changed. The experiment plan stipulates that the test time for one oil and one value of the rotational speed is eight hours, two hours for the first load level and 1.5 hours for each subsequent level (five load levels). The duration of the experiment for the first load level is slightly longer because the lubricant needs some time to reach the working temperature. Therefore, the test time for one oil and all operating conditions is 32 hours. For the given test conditions, the torque ranges between 1.94 and 5.33 Nm for the worm drive made of 42CrMo4/A356 material and between 2.05 and 5.47 Nm for the 42CrMo4/CuSn12 worm drive.

In addition to determining the efficiency, the coefficient of friction of the tested worm pairs has been calculated. Also, the mass of worm drives is measured before and after a certain period of testing to determine their wear intensity. In this case, the attention has been focused on the wear of the worm gears, since they are made of a material with less hardness compared to the worms.

3. Results and discussion

3.1 The efficiency of worm gear

The efficiency is a very important indicator of the quality of the worm gear and is determined as the power ratio on the output shaft and the input shaft. The power on the output shaft is equal to the power on the input shaft reduced by the losses that occur during transmission operation. These power losses consist of power losses due to gear meshing friction, power losses in bearings, seals and other power losses. They can be divided into load-dependent losses and load-independent losses [25-28].

The values of the efficiency of the transmission η are determined for the defined working conditions based on the measured values of input and output torques. Diagrams of the dependence of the efficiency of the transmission and the output torque for different working conditions and oils of different viscosities are shown in Figures 3 and 4.

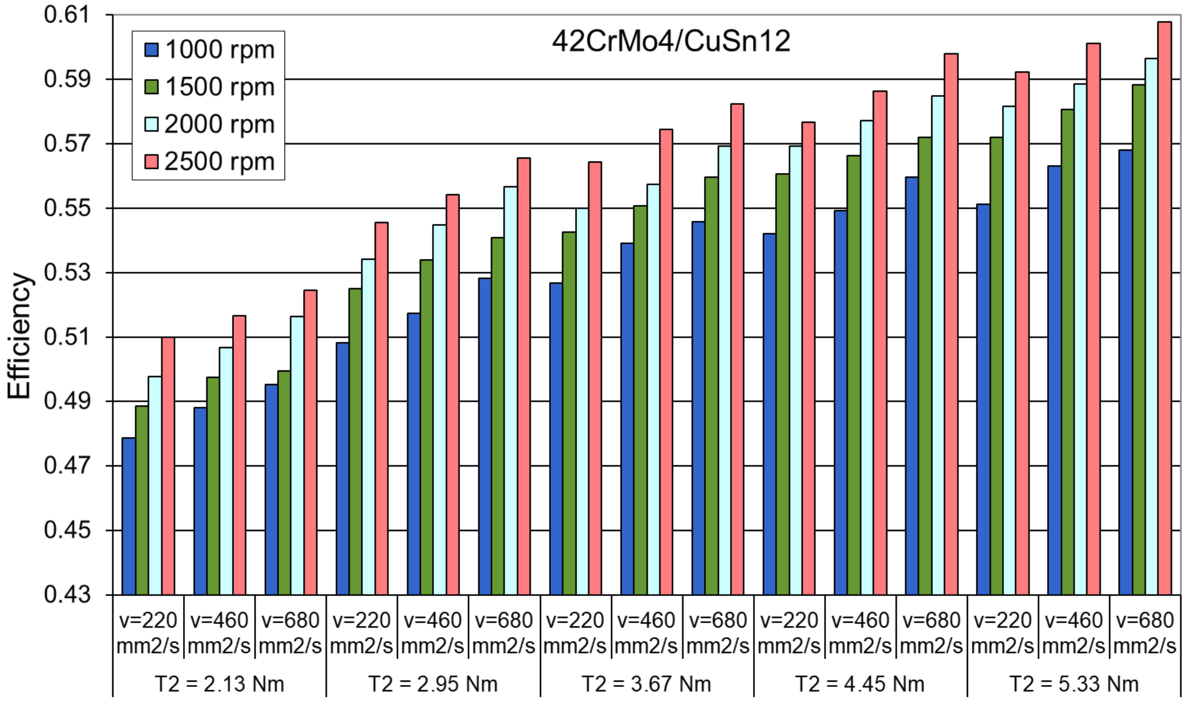

Figure 3. The efficiency of the worm gear for different modes of operation and oils of different viscosities (worm drive 42CrMo4/CuSn12)

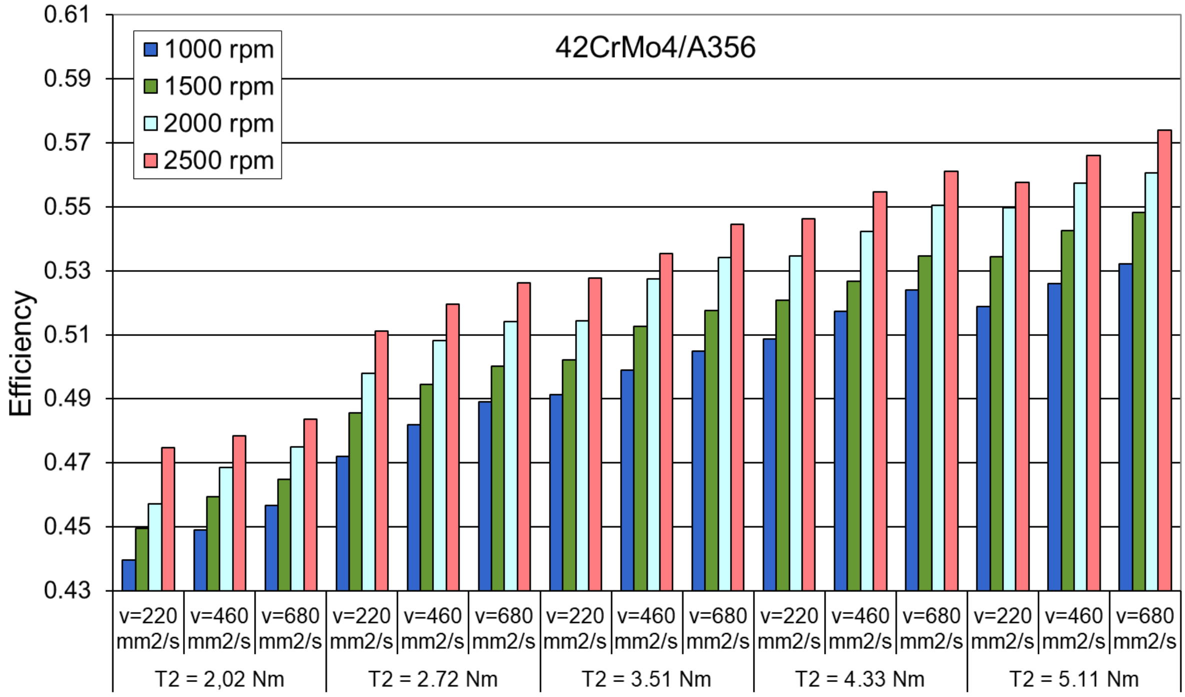

Figure 4. The efficiency of the worm gear for different modes of operation and oils of different viscosities (worm drive 42CrMo4/A356)

Based on the presented results, it can be seen that with the increase in the output torque (load), there is an increase in the efficiency of the transmission. Also, the efficiency increases at higher rotational speeds of the gears, as well as with the use of oils of higher viscosity, which was also concluded in the following papers [20,21,29].

With an increase in load, there is an increase in the output torque and, therefore, in the useful power on the output shaft of the transmission, which increases the values of the efficiency. At higher loads and relatively low peripheral velocities between the flanks of the teeth, possibly mixed lubrication is achieved. However, at higher peripheral velocities, the conditions for hydrodynamic lubrication are created or the hydrodynamic share in mixed lubrication increases, which results in higher values of efficiency. Also, by using oil with a higher viscosity, a greater thickness of the oil film between the meshed gear teeth is ensured, which transfers a part of the load through the lubricant film, which enables an increase in useful power.

Taking into account different operating modes of the transmission (rotational speed and load) and oils of different viscosities, the values of the efficiency of the transmission range from 0.47 to 0.61 for the worm drive 42CrMo4/CuSn12, i.e. from 0.44 to 0.58 for worm drive 42CrMo4/A356. Depending on the test mode and the viscosity of the oil, the values of the efficiency of the transmission with a worm drive 42CrMo4/CuSn12 are higher 5 to 9 % compared to the other worm drive.

3.2 Influence of oil viscosity on the coefficient of friction of worm drives

The values of the coefficient of friction of the worm drive depend on the working conditions that change the load, the peripheral speed and the working temperature of the oil, as well as on the type of material of the meshed gears [30]. The coefficient of friction of the worm drive μ_z is determined based on the known values of the efficiency η_z and the lead angle γ_m according to the following expression [24]

$$\mu_z = \mathrm{tg}\left[\mathrm{arctg}\left(\frac{\mathrm{tg}\gamma_m}{\eta_z}\right) - \gamma_m\right]. \quad (1)$$

The procedure for determining the value of the efficiency of the worm drive η_z is described in detail in papers [24,31,32]. These values are determined for previously defined working conditions.

Based on the calculation results, a dependence diagram of the coefficient of friction of the worm drive μ_z and the output torque has been constructed for the defined test conditions, which has been shown in Figure 5. The diagram shows the change of coefficient of friction depending on the torque T2, for a worm drive consisting of a worm made of improved steel 42CrMo4 and a worm gear made of tin bronze CuSn12.

It can be seen from the diagram that the values of the coefficient of friction of the worm drive decrease with increasing load. Also, by using oil of higher viscosity and at higher rotational speed, the coefficient of friction decreases, which leads to an increase in the efficiency of the worm drive.

Depending on the working conditions, as well as on the viscosity of the oil at working temperature, the values of the coefficient of friction of the worm drive range from 0.080 to 0.047. The lowest values of the coefficient of friction are noticed in the case of using the oil with the highest viscosity (680 mm^2/s), at the highest load (output torque) and the highest rotational speed (2500 rpm).

The results of the calculation of the coefficient of friction for the worm drive 42CrMo4/A356 are not shown in this paper because the emphasis is placed on the effect of oil viscosity on the friction coefficient. A part of these results will be presented during the investigation of the influence of the worm gear material on the coefficient of friction values.

3.3 Influence of material of the worm drives on the coefficient of friction and wear

To examine the influence of materials on the efficiency of the transmission, two worm drives made of different materials were used for the tests. Worm drives have the same geometric characteristics with a symmetrical position of the worm in relation to the bearings. Figures 6 and 7 show the results of the calculation of the coefficient of friction for oils with viscosity at 40 °C of 220, 460 and 680 mm^2/s and two different values of the input speed values (1000 and 2500 rpm). In this case, for the purpose of better visibility of the results, only the minimum and maximum input speed values were compared.

Based on the diagram, it can be seen that the values of the coefficient of friction for the worm drive made of 42CrMo4/CuSn12 material range from 0.080 to 0.047 and for 42CrMo4/A356 worm drive from 0.095 to 0.055, taking into account all conditions examinations.

According to the obtained results, it can be concluded that the values of the coefficient of friction decrease with increasing load, as well as with higher values of input rotational speeds. Also, with an increase in the lubricant viscosity, there is a drop in the coefficient of friction due to a better formation of an oil film between the meshed gear teeth. The maximum value of the coefficient of friction was achieved at the rotational speed of 1000 rpm and the lowest level of load, while the minimum value was achieved at the rotational speed of 2500 rpm and the highest level of load, observing both worm drives.

Therefore, it can be seen that the values of the coefficient of friction largely depend on the working conditions, which also influence the change of the lubrication regimes of the worm

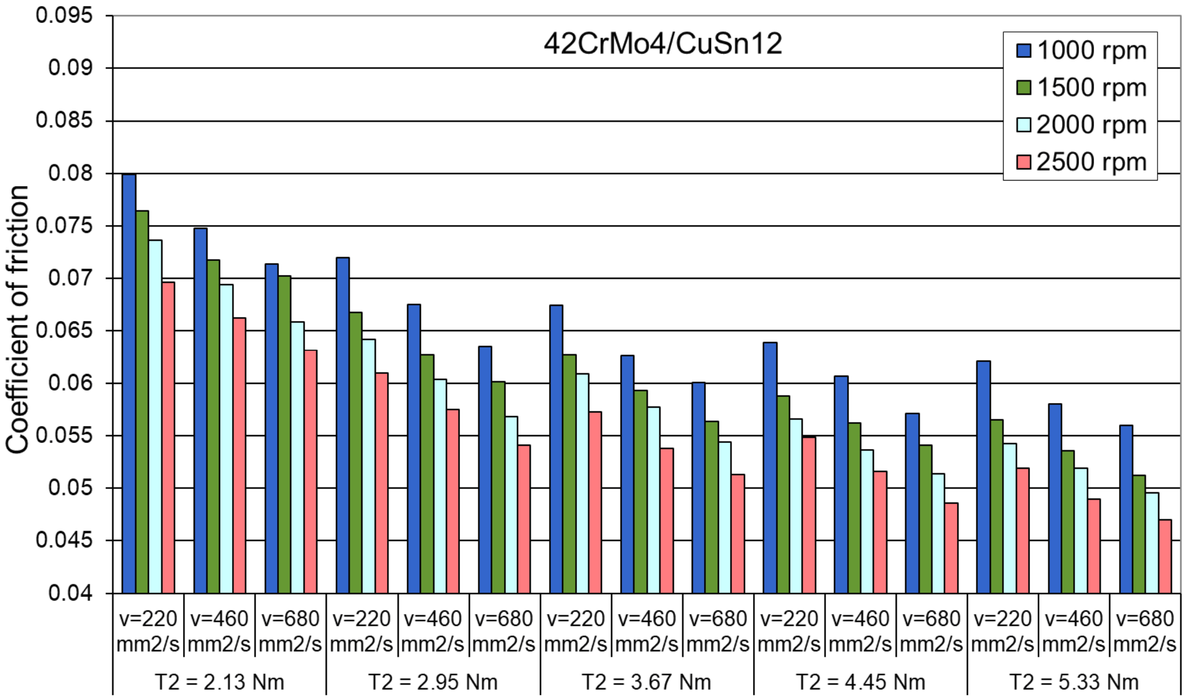

Figure 5. The effect of oil viscosity on the coefficient of friction of the worm gear 42CrMo4/CuSn12 for different operation modes of the transmission

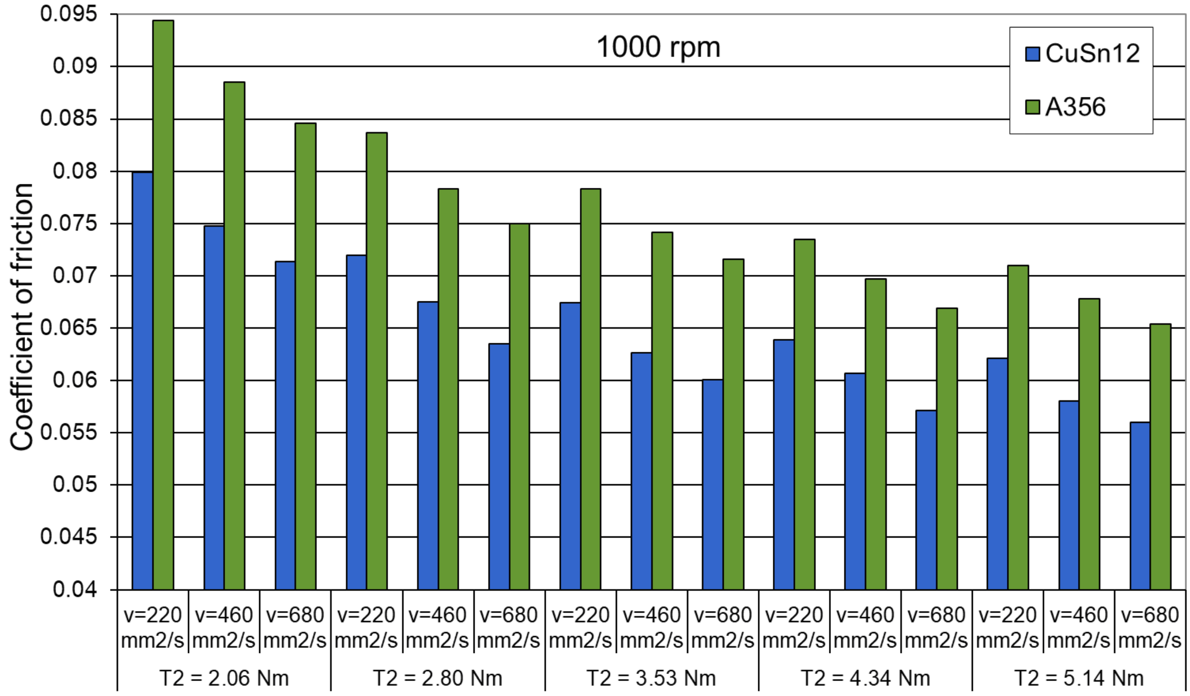

Figure 6. The influence of materials on the coefficient of friction for an input speed of 1000 rpm and oils of different viscosities

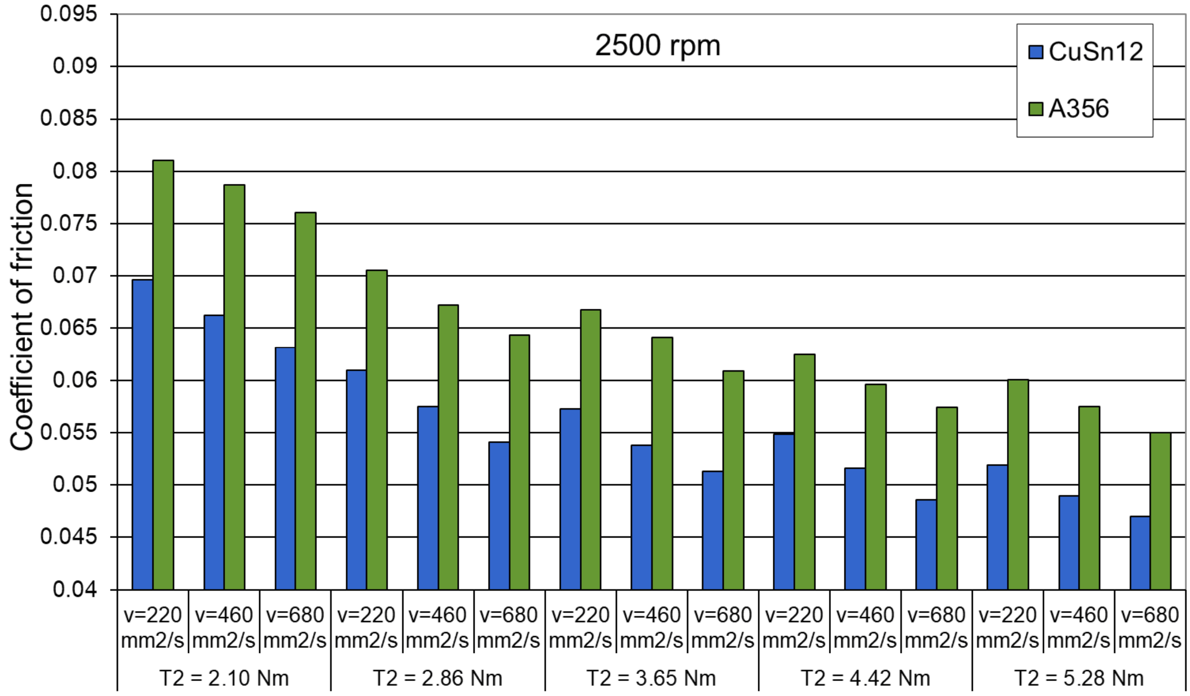

Figure 7. The influence of materials on the coefficient of friction for an input speed of 2500 rpm and oils of different viscosities

drives. The conditions for the emergence of certain lubrication regimes are illustrated by the Stribeck curve, which represents the experimentally determined function of the dependence of the coefficient of friction on the dynamic viscosity of the oil, the rotational speed and the normal load [33]. Analysing the values of the coefficient of friction, it can be concluded that both worm drives work under conditions of mixed lubrication.

By comparing the obtained results, it can be observed that the values of the coefficient of friction of the worm drive made of the 42CrMo4/CuSn12 material are lower by 14 to 21 % compared to the worm drive 42CrMo4/A356.

Lower values of the coefficient of friction between the meshed gear teeth imply less wear of the worm drives. To determine the amount of wear, the mass of worm gears was measured in different phases of the experiment. Mass measurement was performed after every 32 hours of testing for different working conditions using oil with different viscosity. Three consecutive measurements were performed, after which the average value was determined. Based on the obtained results, a diagram of the dependence of mass losses and test time for different materials of pinion gears (CuSn12 and A356) was constructed and shown in Figure 8.

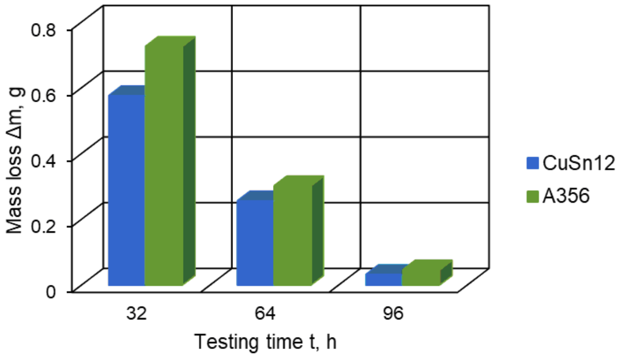

Figure 8. The amount of wear of worm gears, depending on the test time; reprinted from Skulić [23], licensed under CC BY-ND 4.0

Based on the diagram, it can be seen that the mass loss of the worm gears Δ*m* is the highest after the first 32 hours of the test, after which it gradually decreases so that in the last two phases the difference becomes insignificant. This trend of change in the mass loss of worm gears is noticeable in both worm drives.

Among other things, by comparing experimental worm drives, it can be concluded that the total mass loss of the worm gear made of tin bronze CuSn12 is about 25 % lower compared to the worm gear made of aluminium alloy A356. The percentage difference refers to the total test time of 96 hours where the average values of all three worm gear mass measurements are compared.

4. Conclusion

Taking into account the results of experimental tests, the conclusion is that with an increase in the rotational speed and load on the output shaft of the worm gear, as well as with an increase in oil viscosity, there is an increase in the efficiency of the transmission.

The obtained results indicate that in a worm drive with a worm made of improved steel and a worm gear made of tin bronze (42CrMo4/CuSn12), the values of the efficiency of the transmission range from 0.47 to 0.61, taking into account all operating conditions and oils of different viscosities.

Using the second worm drive with a worm made of improved steel and a worm gear made of aluminium alloy A356 lower values of the efficiency were achieved compared to the worm drive 42CrMo4/CuSn12. Namely, taking into account all the test conditions, the values of the efficiency of the mentioned worm drive range from 0.44 to 0.58. The given values are, depending on the operating mode of the transmission, lower by 5 to 9 % compared to the 42CrMo4/CuSn12 worm drive.

Higher values of the efficiency of the worm drive 42CrMo4/CuSn12 cause lower power losses as well as lower values of the coefficient of friction between the meshed gear teeth. With a given worm drive, the values of the coefficient of friction range from 0.080 to 0.47, which represents 14 to 21 % lower values compared to the 42CrMo4/A356 worm drive. In addition, the wear of a worm gear made of CuSn12 alloy is about 25 % less compared to a worm gear made of A356 alloy.

Further research in this field should be focused on improving the working conditions with a worm gear made of tin bronze, that is, on the application of other types of bronze, but also on to use of oils with higher viscosity.

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