Increasing the operational parameters of worm gears

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Abstract. An analysis of factors that reduce the operational parameters of worm gearboxes has been carried out. Equations for calculating the efficiency of a worm gear, contact pressure, and the residual service life are given. It is shown that the friction angle and friction coefficient depend on the material of the worm and wheel teeth, the roughness of the working surfaces of the worm pair matings, the quality of the lubrication, and the sliding speed. Significant contact pressures and friction losses in meshing lead to heat generation, a decrease in efficiency and service life of the worm gear. To produce a worm gear with a maximum radius of a conjugate globoid-cylindrical pair with an involute profile, it is proposed to use rotational turning of the globoid worm turns with a multi-blade forcedly rotating tool, and the wheel teeth with a hob cutter. A nickel antifriction solid lubricating coating containing carbon nanotubes has increased hardness and resistance to abrasion. A method for manufacturing a ZT-type worm gear is proposed, as well as methods that reduce contact stresses and the coefficient of friction during operation of a mating worm pair to increase the service life of worm gears.

1 Introduction

Worm gearboxes are used in drives of various mechanisms [1]. One of the problems in the operation of worm gearboxes is high friction in the contact area of the worm wheel and the worm shaft, which affects the service life of the drive and reduces its efficiency. A worm gearbox with a gear ratio of 1:100 has an efficiency of 0.5, which indicates a loss of 50% of the power, which is converted into thermal energy. High temperatures of more than 100 °C lead to deformation of the worm wheel teeth and the formation of scoring on them, which leads to gearbox failure.

2 Materials and methods

Special fins are provided on the gearbox housing as cooling radiators and liquid lubricant is used. Analysis of the reasons that reduce the operating efficiency of worm gearboxes is relevant for their modernization. When worm gears operate, high sliding speeds V_S, are

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observed, which are directed tangentially to the helical line of the worm. As a relative speed, it can be determined by the equation:

$$V_S = V_1 - V_2 \tag{1}$$

where V_1, V_2 – absolute speeds of the worm and wheel, which are peripheral speeds. Sliding speed V_S is calculated by the equation:

$$V_S = \frac{V_1}{\cos\gamma} \tag{2}$$

where γ – worm helix angle.

From equation (2) it follows that the sliding speed in the worm gear VS is greater than the peripheral speed of the worm V_1. Unlike gears, in worm gears part of the surface of the wheel tooth has a zone in which sliding occurs along the contact lines and where an oil layer cannot form. In this regard, under heavy loads in this zone, seizing begins, which spreads to the entire working surface of the tooth. The unfavorable direction of the sliding velocity vector is the reason for the low efficiency of the worm gear. With a leading worm, efficiency η can be calculated using the formula:

$$\eta = \frac{tg\gamma}{tg(\gamma + \phi)} \tag{3}$$

where φ – friction angle,

$$\phi = arctgf \tag{4}$$

where f – friction coefficient depending on sliding speed.

Efficiency can be increased by increasing the number of worm passes and reducing the friction coefficient or friction angle φ. The torques on the worm shafts T_1 and T_2 of the worm wheel are determined by the equation:

$$T_2 = T_1 \cdot i \cdot \eta \tag{5}$$

where i – gear ratio.

The friction angle φ depends not only on the material of the worm and wheel teeth, the roughness of the working surfaces, the quality of the lubrication, but also on the sliding speed [2]. Large friction losses in meshing lead to a decrease in efficiency and the release of a large amount of heat, which must be removed to avoid overheating when the gear operates under load [3]. The worm and wheel must have sufficient strength, due to significant sliding speeds, and when meshed, form an anti-friction pair with high wear resistance and resistance to jamming. The wear rate of worm gears depends mainly on the contact stresses in the gear drive.

When determining the contact pressure $P_н$ in the meshing of the worm gear, the Hertz formula for the initial linear contact of two cylinders along the generatrix is taken as the initial one [4]:

$$P_{Н} = 0,418\sqrt{\frac{W_{п} \cdot E_{пр}}{\rho_{np}}} \tag{6}$$

where W_n – normal linear load; E_{np} – reduced modulus of elasticity of the materials of the worm and worm wheel; $\rho_{пр}$ – reduced radius of curvature.

The residual life L_h of the worm gear can be determined as [4]:

$$L_h = \frac{[h]}{2a \cdot G \cdot n_2 \cdot J} \tag{7}$$

where $[h]$ – permissible wear value of wheel teeth; α – half-width of the contact area according to Hertz; G – geometric parameter; n_2 – wheel speed; J – wear parameter.

$$G = \frac{g \cdot U}{z_2 \cdot \sin\alpha \cdot \cos\beta \cdot \cos\gamma} \quad (8)$$

where g – worm diameter coefficient. U is the gear ratio, z_2 is the number of gear teeth, α is the engagement angle, β is the angle between the tangent to the contact line and the sliding speed vector at the engagement pole. Sticking wear depends on the worm wheel material.

With soft material of the worm wheel (tin-bronze), this type of wear manifests itself in the gradual "smearing" of the wheel material on the worm. In this case, the transmission can operate for a long time. With hard wheel materials (aluminium-iron bronze, cast iron), wear is accompanied by scuffing followed by rapid destruction of the worm wheel teeth. Under the action of large loads, plastic destruction of the surface of the worm wheel teeth can be observed.

To prevent jamming, contact stress can be limited by using ZT type gears [5].

Providing maximum radii of reduced curvature of the active surfaces is realized in the ZT engagement, when the worm turn is made concave, and the wheel tooth profile is convex. However, such gears have not found wide practical application due to the technological difficulties of their manufacture and the difficulty of backing hobs for cutting wheels for these gears.

It is possible to produce a ZT-type worm gear with a maximum radius of mating of a globoid-cylindrical pair with an involute profile by using rotary turning of the globoid worm turns with a multi-blade tool, and the wheel teeth with an involute hob cutter.

In this case, rough and finishing cutting of worm turns is carried out by the rolling-in method with profiling using a multi-edge disk tool with an involute profile of the cutting elements during vertical movement of the multi-edge tool along its axis of rotation. A multi-blade tool is made on the basis of a conjugate cylindrical wheel, taken as a forming link, which corresponds to the second Olivier principle when forming a conjugate worm pair with a non-linear globoid worm. When cutting turns of a worm, a multi-bladed tool is installed in relation to the axis of the worm workpiece at a distance equal to the center-to-center distance of the worm gear being manufactured. The number of revolutions n_2 of a multi-edge tool is directly proportional to the number of revolutions of the worm workpiece n_1 and inversely proportional to the number of cutting elements z of the multi-edge tool.

$$n_2 = n_1 \cdot \frac{k}{z}, \quad (9)$$

where k – number of worm passes.

The vertical movement of a multi-edge tool is 0.5-1 mm/rev at a cutting speed of 18-20 m/min.

The cylindrical gear is cut using a hob cutter using the rolling method. On the basis of this wheel, taken as the basis as the initial producing one, a multi-edge tool with an involute tooth profile is manufactured.

For worm gears, it is necessary to use antifriction coatings to reduce friction in the meshing.

The use of special anti-friction solid lubricant coatings based on nickel as a binder and carbon nanotubes as a filler will make it possible to reduce sliding friction during worm gear operation.

Compared to graphite, which can be used in anti-friction coatings, graphene nanotubes have the following physical advantages (Table 1).

Table 1. Physical advantages of graphene nanotubes.

Indicator	Graphite	Graphene nanotubes
Specific strength	2.457 kN·m/kg	46.268 kN·m/kg
Tensile strength	4.3 MPa	62.0 MPa
Thermal conductivity	278.4-2435 W/m·K	4840±440-5300±480 W/m·K

It is known that graphene nanotubes are 200 times stronger than steel. The high thermal conductivity of carbon nanotubes will allow for better heat removal from the friction zone of two surfaces. Young's modulus (elastic modulus) of graphene tubes is 1.0-1.4 TPa. The specific surface openness is more than 1000 m2/g, which will contribute to better interaction with the binder compared to graphite in the manufacture of anti-friction composite coating, as well as with liquid lubricant. The electrical resistance of graphene nanotubes is low (3·10-3 Ohm cm), which will reduce electrostatic electricity during friction of two surfaces and electrochemical corrosion.

It is known that the introduction of carbon nanotubes into a metal matrix makes it possible to reduce the friction force; for example, for nickel, wear is reduced by 4 times, and the operating temperature increases to 400 °C. Graphene nanotubes prevent scuffing, which keeps the coefficient of friction low. One layer of graphene on the surface reduces friction. Several layers give greater effect [6].

It has been established that one layer of graphene can withstand 6,400 sliding cycles, and 3-4 layers can withstand 47,000 sliding cycles, which is 2-3 times higher than that of known coatings. A low coefficient of friction between two macroscopic surfaces is possible, no more than 0.004. When carbon nanotubes wear out, an antifriction composite coating can form graphene flakes, due to which the friction coefficient can be reduced to f=0.01-0.008.

The advantage of using nickel to create an anti-friction solid lubricant coating is as follows: nickel provides good adhesion to the steel base, protects the surface of the part from corrosion (atmospheric and water), and has high viscosity with a coating thickness of up to 2 mm. An important factor is that the coefficient of linear thermal expansion of nickel is close to the coefficient of linear expansion of steel ($13.3 \cdot 10^{-6}$ 1/°K and $12.5 \cdot 10_{-6}$ 1/°K). This helps ensure the strength of the antifriction solid lubricant coating when exposed to temperature deformations and force loads. Nickel coatings have a high hardness of 3.0-3.8 GPa. When the temperature rises to 400 °C, the hardness of the nickel coating increases to its maximum value, but at the same time the ductility decreases [7]. Nickel is equal in strength to steel, which makes it possible to obtain a coating of equal strength to the main substrate. A nickel solid lubricant antifriction coating containing carbon nanotubes has increased hardness and abrasion resistance. Carbon nanotubes (CNTs) are destroyed at a pressure of 100-150 GPa. Can withstand extreme deformation without stretching, returning to its original state intact at less pressure than 100 GPa. The bulk modulus of elasticity of CNTs is 462-546 GPa, which is higher than that of diamond (420 GPa). This helps to improve the performance characteristics of solid lubricant antifriction coatings under heavy loads. The high tensile strength of CNTs, 11–63 GPa [8], increases the resistance of the antifriction coating when exposed to friction forces during operation of the mating worm pair. An anti-friction solid lubricant coating, capable of stable operation under high mechanical and thermal loads, as well as under the influence of frictional forces, can be used to apply it to the screw surface of the worm and be used in conjunction with liquid lubricant during operation of the worm gear, which will increase its efficiency to 75-80 %. In this case, the worm gear gear can be made of steel, which will significantly reduce the wear of the worm pair.

3 Recommendations

The use of liquid lubricant and anti-friction solid lubricant coating will reduce the coefficient of friction and thermal loads when the worm gear operates in all modes. The production of worm pairs with a large radius ρ of mating working surfaces of the ZT type [9] will make it possible to reduce the contact pressure in the worm pair and increase the service life of worm gears according to the wear criterion.

4 Conclusion

An analysis of the reasons that reduce the efficiency of worm gearboxes is given. It has been established that high friction in the contact zone of the worm wheel and the worm shaft, high loads and contact pressure in the meshing of the worm gear reduce the efficiency and service life of worm gearboxes. To reduce the contact pressure by ensuring maximum radii of reduced curvature of the active surfaces of the worm pair, a method has been developed for manufacturing worm turns by rotary turning with a multi-blade tool, and wheel teeth with a hob cutter. In order to reduce the coefficient of friction in meshing to 0.01-0.008 when operating a worm gear, it is proposed to use a special anti-friction solid lubricant coating based on nickel as a binder and carbon nanotubes as a filler. The effectiveness of a solid lubricant antifriction coating is substantiated based on an analysis of the physical and mechanical properties of its constituent materials (nickel and CNT), as well as technological advantages. Protection of the worm turns with an antifriction solid lubricant coating and the use of liquid lubricant can increase the efficiency of the gearbox to 75-80%, its load capacity and service life.

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