The use of polymer composite materials in cylindrical gears

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Abstract. The paper describes the use of PCM-polymer composite materials in the construction of cylindrical gears. Various types of composite materials and their characteristics for gear links of cylindrical gears, in particular with an asymmetric profile, as well as shell forming matrices for their manufacture from PCM are considered. The main issues of ensuring the accuracy of PCM gears for assessing their quality level are presented.

Keywords: polymer composite materials (PCM), gears, shell forming matrices, precision gears made of PCM.

1. Introduction
Currently, there is a steady trend of using structural polymer materials (PCM) for the manufacture of gears in the instrument mechanisms of mechatronic devices for various purposes. The advantages and disadvantages of composite and plastic gears are well known [1-4]. The advantage of polymer composite products is to reduce friction, and as a result, reduce wear, as well as reduce weight, increase durability and reliability, which directly affects the cost of the product. This is reflected in detail in [5-9].

The advantage of toothed links made of composite materials over metal ones is the fact that they have less friction losses. Gears made of structural polymer materials are lower noise, retain their inherent lubricity, are smaller in weight and are corrosion-resistant.

It can be noted that in many structures of mechanisms, gears made of such materials are used with reverse, and the so-called dead stroke occurs due to the presence of gaps in the joints and elastic deformations [10]. Thus, there is an objective need to significantly reduce the dead stroke of the transmission.

In some cases, there is a need to increase the load capacity of gears from PCM.

2. Polymer composite materials. Properties, applications, databases
Composite materials (composites) – multicomponent materials consisting, as a rule, of a plastic base (matrix) reinforced with fillers that have high strength, rigidity, etc. The combination of dissimilar substances leads to the creation of a new material whose properties differ quantitatively and qualitatively from the properties of each of its components. By varying the composition of the matrix and filler, their ratio, and the orientation of the filler, a wide range of materials with the required set of properties is obtained. Composites, in which the matrix is a polymer material, are one of the most numerous and diverse types of materials. If you combine the matrix and filler, calculate different proportions, you can easily get materials much better than "traditional", while they are generally much easier than ordinary reinforcement. The properties of polymer composite materials (PCM) are becoming more accessible and are already being used not only in the field of space technologies, but also as a more accessible basis for household appliances.

Composite components can be plastics, almost all metals, polymer fibers, etc. There are even more complex composites – polymatric ones, if they use several different polymers for the matrix, as well as hybrid variants, in which reinforcing fibers are combined.

The density of PCM varies widely from 400 to 2800 kg/m$^3$ and averages 1400 kg/m$^3$. Metals are much heavier, for example, the density of steel – 7800 kg/m$^3$, copper – 8900 kg/m$^3$, aluminum – 2700 kg/m$^3$. Thus,
the density of the polymer composite is 5-6 times lower than that of ferrous and non-ferrous metals and alloys, and 2 times lower than that of aluminum.

PCM based on glass fiber and basalt fiber are excellent dielectrics. The electrical resistivity of fiberglass is 1.0×10^10 Ohm·m. The specific resistance of steel at normal temperatures from 13 to 30×10^8 Ohm·m, which is 18 orders of magnitude less. At the same time, carbon plastics conduct an electric current, which can also be used in engineering.

Polymer composite materials with a glass or basalt filler as dielectrics do not break down in electrolytically conducting media, i.e. they do not corrode in the ground, water, under the influence of atmospheric precipitation, etc.

With its low density, PCM has high physical and mechanical characteristics.

So, the tensile strength of carbon steels is 240 MPa, aluminum alloys – from 50 to 440 MPa, polymer composites from 70 MPa (fiberglass with a minimum content of glass fiber) to 1800 MPa (high-strength carbon fiber). The coefficient of thermal expansion of polymer composites is significantly lower than that of metals and simple polymers, which allows the use of PCM products in a wide temperature range.

PCM refers to materials with low thermal conductivity. So, the thermal conductivity of steel is 64 W/m°C, aluminum – 105-200 W/m°C, and fiberglass – 0.75 W/m°C.

The variety of PCM in composition and properties has led to the creation of many local databases in practice, and the complexity of forming materials and developing technologies for their manufacture (in the context of designing specific products) has led to the creation of numerous modeling programs based on mathematical models. There are also regulatory documents to help you work. For example: "GOST R 56806-2015 Polymer Composites. Identification of polymer composites in electronic databases".

Today there are extensive databases of polymer composites:
1) Total Materia of the Swiss company Key to Metals AG [11];
2) Material Data Center of the German developed by M-Base Engineering + Software GmbH [12];
3) Plastinfo.ru localized for processors in Russia and CIS countries material Data Center database of the Russian Plastinfo LLC.ru [13].

International database of polymer materials Material Data Center. It combines the full range of characteristics of polymer materials offered worldwide. The data in the database includes characteristics such as fairly detailed curves of properties depending on temperature and / or time. It is also possible to superimpose such curves for different materials on a single diagram, which provides a visual comparison of the manufacturability of materials or their thermal and mechanical properties [14].

3. Use of polymer materials in gears
It is advisable to consider the characteristics of such materials, on the basis of which it is possible to form composites for use in gears.

The most commonly used materials for the manufacture of gears are ABS and PLA plastics. With the help of additive technologies, you can get products with the specified parameters, but the accuracy of printing leaves much to be desired.

The main disadvantage of this technology is a small resolution, both horizontally and vertically, which leads to a more or less noticeable layering of the surface of the manufactured model. It is also worth noting that traditional software solutions do not fully meet the quality requirements, since various defects can be formed during the printing process, which negatively affect the subsequent operation of finished products.

Casting in forming matrices allows you to get products of almost any complexity and avoids the occurrence of porosity and the formation of surface defects. In this way, you can make complex shaped cast parts, including cone-shaped gears. Finished products can have various physical and mechanical properties-rigid, imitating the properties of ABS, semi-rigid, elastic, heat-resistant, transparent, as well as combined.

The condition for reliable operation of a gear train made of composite polymer materials is the maximum compliance of operational requirements with the properties of the selected material. The high load determines the choice of hard rigid plastics, in particular reinforced thermoplastics.

Research shows that polymer materials are very actively used in various fields of technology [15].

Currently, various technological, physical-mechanical, tribological and chemical properties of polymer materials are used for the manufacture of gears, such as polyamide and its variety – polyamide 6, better known as caprolon, and fluoroplast, both pure and with various fillers.

Polyamides have high strength, hardness, elasticity, wear resistance, heat resistance. Caprolon is in addition to all the above has a high tensile strength. This material has a low coefficient of friction in a pair with any metals, it is well and quickly worked out, 6-7 times lighter than bronze and steel, instead of which it can be used. It is highly technologically advanced.
Composite materials based on them are also known: glass-filled, mineral-filled.

Polypropylene belongs to the class of polyolefins. Melting point 160-176 °C; thermal degradation begins at 300 °C; density 0.90-0.92 g/cm3; shrinkage 1.3-2.4%. Distinctive properties of polypropylene: resistant to water (up to 130°C), to acids and alkalis, increased impact resistance, resistance to bending loads; good wear resistance, the maximum operating temperature of polypropylene products is 120-140 C. [16]

The second most common polymer - fluoropolymer

Fluoroplast has an extremely low surface energy and can therefore be used as an anti-adhesive material.

It is resistant to aging under normal conditions and has high anti-friction properties, an exceptionally low coefficient of friction (in certain conditions and pairs, the coefficient of friction is up to 0.02). [17]

Compositions based on fluoroplastics are also widely used when fillers are introduced into the fluoropolymer that increase the wear resistance, strength, hardness or elasticity of products made of fluoroplastics.

As fillers for fluoroplast compositions, materials that can withstand the sintering temperature of the fluoroplast are used. The most common fillers can be divided into the following groups:

a) powdery;

b) fibrous (reinforcing fillers);

c) reinforcing fillers of the frame type.

When using glass fiber, silica, asbestos fabric, and metal wool as fillers, the composite stiffness increases, and the relative deformation decreases at low friction coefficients [18].

Gears can be made from polymer materials with improved properties. Whether they are used as part of combined wheels with metal or combined bushings, polymer materials after high-precision processing allow you to get a long service life without lubrication in the packaging, food, medical and semiconductor industries.

The advantage of gears made of composite polymers over metal ones is not only reduced noise level, but also greater efficiency (efficiency) due to lower friction losses.

The design of the polymer gear largely determines the performance of the gear. The chosen ratio of the crown dimensions, the reliability of the interfaces, and the location of the reinforcing elements depend on the manufacturing accuracy and strength of the transmission. Polymer gears are divided into all-polymer and reinforced according to their design [19].

4. PCM in non-standard gears

To increase the load capacity of the gear transmission, as well as to increase its service life, the following addition to their design can be proposed - to make the profile of the teeth of the rims asymmetric. This option should be used only if the torques are different when changing the direction of rotation [20]. This is illustrated in figure 1, which shows asymmetric involute teeth formed from two main circles dba and dbb.

The studies have shown that to ensure a high-quality working surface of the proposed gears, it is advisable to make them from composite thermostoics by casting them into shell-forming matrices [21, 22], and to fill the matrix with reactoplastics, for example, from phenol-formaldehyde and epoxy polymers. Thermosets have a fairly great stability of physical and mechanical properties when changing influences from the environment. Due to their strength and electrical insulation properties, as well as the ability to operate at high temperatures and in any climatic conditions, phenopolasts are successfully used for the manufacture of structural, friction and anti-friction products, housings [23]. In this case, the internal surfaces that form the cavity should be made of metal in the form of a shell.

This can be done if the toothed crown of metal connection with the material of the forming matrix. An made from a thin ribbon by bending it along the continuous increase in roughness leads to an increase in the of the master model. In this capacity, it is recommended with a cohesive strength.

to use cold-rolled tape made of low-carbon steel, whichCurrently, it is advisable to make a master model for is often used when bending parts. It is worth noting that the shell on a 3D printer. This design of the on the inner (adjacent to the workpiece) side of the forming matrix is shown in figure 2. It should be noted metal tape, it is necessary to create a microlief within in order to increase the bending strength of the the specified functional parameters, on the other hand, in some variants, reinforcing disks with a metal surface - with sufficient roughness for a strong
toothed rim of gear should be used. This option is shown in figure 3.

Figure 2. Fragment of the forming matrix.

Figure 3. Cross-section of a toothed reinforced rim of gear with an asymmetric external profile (the internal reinforcing rim of gear is symmetrical).

In the above figure 3, the teeth of the rim of gear are made of composite material and are asymmetric in the profile, and the reinforcing metal rim of gear is made symmetrical.

5. Evaluation of the accuracy of non-standard gears from PCM

Given the fact that PCM products have the property of shrinkage and warping (uneven shrinkage), accuracy should be highlighted among the quality indicators for evaluating gears. For gears, accuracy is the main indicator due to the limited materials used for manufacturing the transmission and the thermochemical treatment of gears.

In the Russian Federation, according to the GOST 1643-81 standard, there are 12 degrees of accuracy, 6 types of coupling are set for gears with a tooth modulus $m \geq 1$ mm: A, B, C, D, E, H and 8 types of $T_{in}$ tolerance for the backlash: x, y, z, a, b, c, d, h. The accuracy of manufacturing the gear and transmission is set using the degree of accuracy, and the requirements for the backlash are set by the type of coupling according to the standards of the backlash.

For cylindrical gears that are mainly involute, taking into account mounting errors, the values of the minimum and maximum kinematic error are determined by the expressions:

- for degrees of accuracy 3–6: $F'_{1\text{max}} = 0.62 K_s \left( F_{11} + F_{12} \right)$,

- for degrees of accuracy 7–8: $F'_{1\text{max}} = 0.71 K_s \left( F_{11} + F_{12} \right)$.

For all degrees of accuracy (the same applies to other gears)

$$F'_{1\text{max}} = K \left[ \sqrt{(F_{11}')^2 + E_{\Sigma M1}^2} + \sqrt{(F_{12}')^2 + E_{\Sigma M2}^2} \right],$$

where $K, K_s$ – phase compensation coefficients, i.e. coefficients that take into account the degree of change in the tangential composite deviation from the initial position of the links; $F_{11}', F_{12}'$ – tangential composite deviations of the driving and driven gears, respectively; $E_{\Sigma M1}, E_{\Sigma M2}$ – the total reduced installation error (in GOST 21098-82 is determined by Appendix 2).
Tolerance for the tangential composite deviation of the gear:  \( F'_t = F_p + f_j \), where \( F_p \) is the tolerance for the accumulated error of the gear pitch, \( f_j \) is the tolerance for the error of the tooth profile.

The value of the minimum kinematic backlash of the gear transmission:

\[
j_{\text{min}} = \frac{j_{\text{min}}}{\cos \alpha \cos \beta},
\]

where \( j_{\text{min}} \) is the allowance backlash (normal); \( \alpha \) is the pressure angle of the standard basic rack tooth profile; \( \beta \) is the helix angle.

The value of the maximum kinematic backlash for a cylindrical gear transmission:

\[
j_{\text{max}} = 0.7\left(E_{Hs} + E_{Hs/2}\right) + \sqrt{0.5\left(T^2_{Hs} + T^2_{Hs/2} + 2f_a^2_G + G_r^2 + G_r^2\right)},
\]

where \( j_{\text{max}} \) – the maximum circular backlash in the gear transmission, \( E_{Hs} \) is the smallest additional bias source circuit; \( T_{Hs} \) – tolerance on the basic racks tooth profile modification; \( f_a \) is the center distance limit error, \( G_r \) is the radial clearance in the bearings of rotation, is equal to the radial runout (in GOST 21098-82 is defined in Annex 2).

You can also use the probabilistic method for calculating the accuracy - the Monte Carlo method, in which the components of the tangential composite deviation and backlash will be random values in certain intervals [25-26].

6. Conclusion

Thus, the considered options and features of the manufacture of non-standard cylindrical gears from polymer structural materials, for example, such as those with asymmetric reinforced wheel teeth, make it possible to improve their quality in practice. The given characteristics of various materials for the considered structures of cylindrical gears provide an opportunity to rationally design them and form technologies for their manufacture, in particular, by using shell shaping matrices. The above questions of the accuracy of PCM gears make it possible to assess their quality level.

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