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SAFETY ASPECTS OF KINEMATIC PLANETARY PRECESSIONAL TRANSMISSIONS WITH PLASTIC WHEELS

Ion BOSTAN, Valeriu DULGHERU, Ion BODNARIUC

Technical University of Moldova, Chisinau, MOLDAVIA

dulgheru@mail.utm.md

ABSTRACT

The planetary precessional transmissions represent a new principle type of the mechanical transmissions. The specificity of the relative sphere-spatial movement of the precessional gearing elements makes the sliding friction persist. The study of the contact between two working surfaces of one gearing is very important, because the safety and the duration of the gearing running, its reliability and efficiency depend on the materials behavior, from which the prehension elements are produced.

The study of the kinematical precessional gearing is of a major importance because, in the kinematical precessional gearing, there is slipping friction, which leads to big power losses and to big heat elimination in the contact zone. This paper describes the elaboration of the kinematical planetary precessional transmissions with plastic–steel toothed wheels. To reduce the sliding friction in the gearing of the kinematic precessional transmission, the plastic - steel gearing has been utilized. This fact allowed for increasing the efficiency and a solution of the problems related to the fabrication technologies for the crown gears of the satellite block. The teeth of the central wheel have nonstandard variable convex-concave profile, described by parametric equations according to the fundamental theory of the precessional gear. Because the teeth of the satellite have a circular profile this fact allows its relative simple fabrication. The performed analysis of the state-of-the-art in the field of the technology of fabricating the wheels for the kinematical planetary precessional transmissions demonstrated the need to elaborate the constructive-technological procedures for decreasing the power loses.

This work contains a broad justification of the method for plastic materials selection, necessary for toothed wheels fabrication. As well, the plastic material selection and functioning criteria are presented. Also, a range of adequate materials for toothed wheels manufacturing is described.

Keywords: precessional transmissions, kinematics, plastic wheels

1. MATERIALS USED TO MANUFACTURE GEAR WHEELS FOR KINEMATICAL GEARINGS

The materials used to manufacture gear wheels are very different. In machine building industry, the gear wheels are made of carbon steel and alloyed steel, cast iron; for the equipment manufacturing, the gear wheels are made of bronze, titanium, aluminium alloys, metal powders, in addition to steel.

Table 1. Materials recommended for making kinematical gear wheels

	Name and conventional marking of the material	**Density, kg/m^3**	**Production mark**
1	2	3	4
1	High density polyethylene	960	PE – Schkopau, Baylon, Alkathene, Moplen, Lupolen, Vestolen, Hostalen LD, Naten
2	Low density polyethylene	920	Liten, Vestolen, Hostalen
3	High molecular polyethylene	916	Hostalen GUR, Lupolen
4	Polypropylene	905...910	Hostalen PP, Moplen, Mosten, Noblen, Novolen, Vestolen P, Napryl, Daplen
5	Polyamide 6 and its composite materials	1120... 1150	Degamid, Durethan, Ultramid B, Miramid, Akulon, Grilon, Grodnamid, Etamid, Capron
6	Polyamide 66)	1120... 1150	Ultramid A, Maranyl A, Zytel E, Leona, Sylamid, Spalamid
7	Polyamide 11	1020...1040	Rilsan B
8	Polyamide 12	1010...1020	Rilsan A, Grilamid, Vestamid
9	Polyamide 610	1070...1090	Ultramid S
10	Polyamide 6 with glass filling (PA 6 + 30% glass filling)	1350	Renyl, Zytel, Orgamide
11	Polyamide 66 with glass filling (PA 66 + 30% glass filling)	1350	Durethan, Aculon R, Catalin, Verton RF
12	Polycarbonate and its composites	1070...1230	Makrolon, Orgalan, Lexan, Merlon
13	Polyoxymethylenes and its composites	1340...1430	Delrin, Celcon, Hostaform, Duracon
14	Polyoxymethylenes with glass filling (POM + 30% glass filling	1700	Kematal, Tenac, Ultraform
15	Polybutylene terephthalate	1300	Pocan, Deroton, Ultradur, Dynalit, Crastin,
16	Polybutylene terephthalate with glass filling (PBT + 30% glass filling)	1550	Pibiter, Orgater, celanex, Snialen
17	Polyethylene terephthalate	1370	Arnite, Tenite, Vestodur, Rynite, Hostadur, Pocan, Ultradur, Lavsan
18	Polyethylene terephthalate with glass filling (PETF + 30% glass filling)	1650	Rhodester
19	Phenol ether resin	1060	Noril
20	Polysulphones	1240...1250	Bakelite P, Udel, Polisulfon
21	Polyethersulfone	1370	Poliathersulfon, Victrex
22	Polyphenilsulphide	1340	Ryton
23	Polyimide	1430	Kapton, Vespel, Kinel
24	Polyether ether ketone	1320	Victrex
25	Thermoplastic polyurethane	1250	Desmopan, Elastollen, Vulkollan, Resistifol

The plastics are most often used in small power kinematical transmissions. There are also examples of using plastics in the medium load transmissions. In the production of unique plastic wheels, they are 50% more expensive than those made of steel. The use of the plastic wheels is more rational and efficient in terms of a production in large series, replacing the non-ferrous metals and cast (pressed) ferrous metals with the plastic wheels in the heavy tonnage production [1].

When selecting the material for the gear wheels, it should be considered the following: the destination of the transmission, the duration of operation and the working conditions, the type and the character of the lubrication, the technology requirements, the existing equipment and cost of the material.

Plastics. As a result of an extensive study upon plastics, a range of types of materials suitable for making the kinematical gear wheels was established (Table 1 [1, 2, 3]).

2. MECHANICAL PROPERTIES OF PLASTICS

Plastics and polymer composites are a class of polymer based materials, which differs from the traditional building materials in terms of low density, elasticity, high strength per unit mass, high corrosion resistance in various environments, favorable and easy machinability. In addition to these basic properties, plastics are characterized by a relatively low module of elasticity, creep and relaxation, low diathermancy, high coefficient of thermal expansion, as well as strongly emphasized deformation properties and resistance to temperature [1].

As construction materials, the following items are used: the common plastics, which are produced in large quantities (hundreds of thousands of tons per year) and have low costs and the special plastics, produced in small quantities (up to several tens of thousands of tons) and with higher costs than the common ones.

Table 2. Qualitative comparison of polymer materials properties

Properties	PA	PA + filling glass	POM	PBT	PC
Rigidity	▲	●	■	■	■
Mechanical strength	■	●	■	■	■
Sliding friction wear	●	■	●	■	x
Stability of creep	■	●	●	■	■
Resistance to fatigue	■	●	●	■	▲
Temperature resistance	■	●	■	●	■
Resistance to chemicals	●	●	●	●	x
Dimensional stability	▲	■	■	■	●
Density	■	▲	▲	▲	■
Water absorption	x	x	●	●	●
Molder	■	■	■	■	▲
Properties at temperatures below 0°C	■	●	■	■	●
Stability to atmospheric influences	▲	■	▲	■	●

Note:● very good,▲ satisfactory, ■ good, x nsatisfactory; PA - polyamide, POM - polyacetal, PBT - polybutylene terephthalate, PC- polycarbonate

In order to assess the effectiveness of the polymeric materials used in a required construction, it is reasonable to consider two types of plastics – thermoplastic materials and thermosetting plastic materials, which differ not only by their behavior on repeated heating cycles of the material, but also by various indices of strength and deformation.

The specific property of the crystalline structure of thermoplastic polymers is their high rate of failure, until the appearance of completely non-crystalline sectors (amorphous). Among the thermoplastic polymers, there are amorphous or hard crystallizing polymers (polysulphones, polycarbonate, phenol ether resin, polyacrylate, fenilon – the crystallization degree being 10% to 25%), which are rigid elastic materials – polymer glass with the limiting maximum operating temperature close to the crystallizing temperature T_c. Also, there are crystalline polymers with average crystalline degree (polyamides 50-75%) and high crystalline degree (polyacetal, polyethylene – 75-96%), with the limiting maximum operating temperature which can range from T_c of the amorphous phase to the melting temperature T_{top}.

The gauze structure of the high density thermosetting plastic materials provides higher hardness indexes, modulus of elasticity, heat resistance and high fatigue resistance as compared to the thermoplastic materials; they are characterized by a low thermal expansion coefficient, allowing a high degree of filling, from 80% to 85% (wt). Phenol formaldehyde and epoxy resins are used as binders for the thermosetting plastic materials used for manufacturing gear wheels [1, 2, 3].

3. RATIONAL SELECTION OF PLASTIC MATERIALS FOR MAKING GEAR WHEELS

Certain requirements, imposed by the operating conditions, including thermal and mechanical properties of the thermoplastic materials, have to be taken into account in selecting the material for manufacturing gear wheels. The safe operating condition of the gear transmission is provided by the maximum coincidence of the operating requirements with the chosen material properties. But, in the majority of cases, practically all imposed conditions cannot be met.

Criteria for material selection

The necessary spectrum of the tasks is the most important criterion in selecting the material that determines the bearing capacity of a gear wheel. The high load capacity defines the selection of tough and rigid plastics. The tooth loading is determined by the frequency of rotation. The main criteria for selecting the material for such machine parts are the admissible temperature on long-term operation and the thermal resistance. Higher noise and vibration levels are expected at light loads and high angular speeds. For this case, it is necessary to use high damping materials. High shock elasticity materials are used in the transmissions characterized by shock load [1].

The tribological characteristics of the transmission are determined by the lubricant properties. When selecting the material, the following factors are taken into account: the influence of the environment (temperature, humidity, presence of chemicals and abrasives, etc.), the mode of operation, the load capacity of the transmission. The potential changes in the size of the gear wheels, which influence the accuracy of the transmission, are previously calculated in accordance with the specified deviations of the temperature and the humidity of the environment. In addition, the designers must take into account that there are active chemicals, under which the thermoplastic materials usually resist in unstressed state, but, under load, they are sources of micro cracks, conditioned by the existence of high remanent stresses in the material. A qualitative comparison of some properties of several polymeric materials is shown in Table 2 [1].

Operating criteria

Selecting the right material for the gear wheels supposes knowledge of defects encountered in plastic gear wheels exploitation and reasons of their occurrence. The loss of the functioning capacity of the thermoplastic polymer gears is more often the subject to the following defects: broken tooth at the base, in the dangerous section zone, cracks on the working side of the tooth surface, tooth breaking in the gearing pole zone, remanent bending of the tooth due to the material plastic flow, appearance of pitting on the lateral surfaces of teeth, wear as a result of seizure, wedging – commonly noticed for kinematical pairs.

Most failures are caused by the material properties and are subject to certain operating restrictions. In the polyamides gear wheels operation, a small remanent bending of the tooth occurs, which rapidly increases before the destruction of the gear crown. The tooth breaking at its basis is common for polyacetal gear wheels.

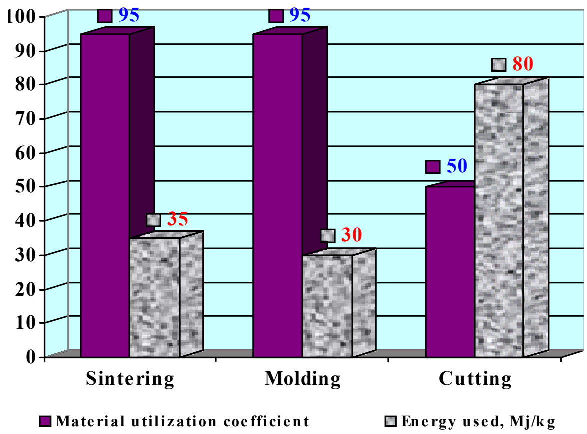

Fig. 1. Comparative diagram pointing out the cost-gear wheel manufacture.

Studying wear, subjected to mutual sliding of the side surfaces of the teeth, two types of wear can be distinguished: the wear due to the relative slip that occurs in any transmission (including transmission with an ideal geometry), wear caused by the contact of the outer edge of the metal wheel gear tooth with the root of the distorted tooth of the plastic gear wheel beyond the theoretical line of gearing - contact on the edge. In the first case (typical of metal wheels), the wear may be even or uneven, depending on the working conditions of the transmission. In the second case, a wear channel appears on the tooth root that can spread on the tooth to the gear pole. This type of wear does not destroy the tooth, but creates places with high concentration of stresses. The indicated type of wear depends considerably on the load and is most common in polyamide PA12 gears wheels and less coomon in polyamide PA6 and PA66 gear wheels. The wear channels on the teeth made of polyacetal are smaller than those made of polyamides. The wear subject to seizure is typical for the gearing operating without lubrication and the lubricated with plastic material of the polymer-metal and polymer-polymer pairs. The wear occurs as a result of the local heating on the side friction of the teeth. The wear area is the region with the highest relative velocities of sliding on head and foot of plastic wheel tooth.

Figure 1 shows the schedule of the energy consumption and the material utilization coefficient for three types of plastics processing: sintering, molding and cutting. The material utilization coefficient is about 0.95 of the initial material quantity and the energy costs are 35% of product cost when processing by sintering. The material utilization coefficient is 0.95 of the initial material and the energy costs are 30% of the product molding processing. The material utilization coefficient is 0.5 of the semi-product and the energy costs up to 80% of the product made by a material machining. As shown in the diagram, the most rational technologies in terms of costs are the sintering and casting methods.

Also, the cutting manufacture is used only in unique cases, when a few parts are needed and it is not rational to execute a mold.

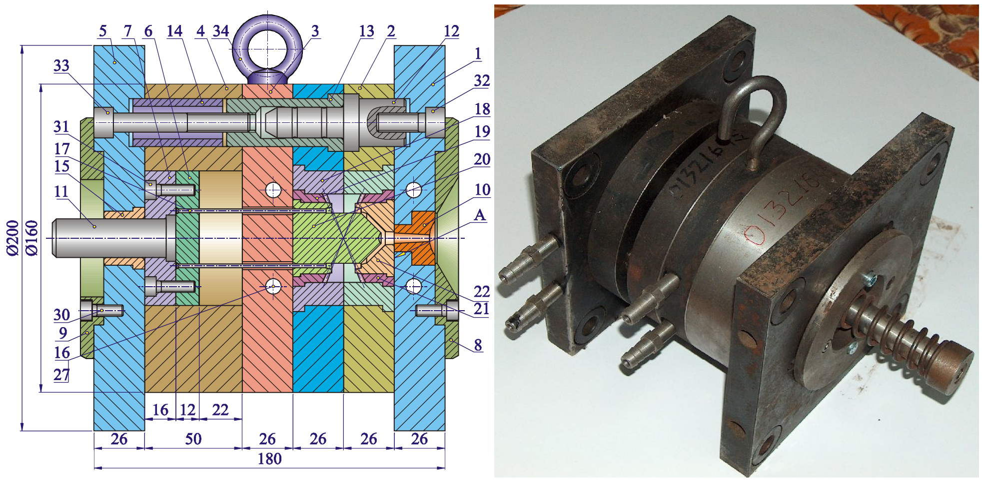

Fig. 2. Mold of plastic gear wheels in the precessional gear

Table 3. Geometrical parameters of the satellite wheels

Parameters	Symbol	Satellite wheel					
Number of teeth	Z_2	30	31	30	31	30	31
	Z_3	20	20	22	22	25	25
Conical axoid angle °	δ_1	22.5	22.5	22.5	22.5	22.5	22.5
	δ_2	0	0	22.5	22.5	22.5	22.5

Fig. 3. Set of moulds from the hollow mould

Fig. 4. Satellite gear wheels cast from different plastic materials

4. CONSTRUCTION OF PLASTIC GEAR WHEELS

The construction of the gear wheels must meet the requirements concerning its destination and the satisfy operational capacity of the wheel in given circumstances. An important requirement is the construction workability, which saves material, simplifies tools construction and molding equipment, decreases the manufacturing cost. The strength,

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the reliability and the durability of the transmission depend on the used material, the size of the gear, the execution accuracy and other factors. Obtaining a structure to meet all imposed requirements is possible only if all specific physico-mechanical and technological properties of the polymeric materials are taken into account.

Based on the analysis of the operating conditions, the wheel construction, the polymer material and the basic parameters of the wheel are established. In addition, the plastic properties must be respected, such as a high flexibility, the mechanical strength, a low diathermancy, the temperature dependence on load speed, the load relaxation.

The sections homogeneity and the wall thickness uniformity of the gear must be respected, as the difference between maximum and minimum dimensions does not exceed 25 - 30%. The correlation of the constructive parts' dimensions is indicated taking into account the possibility of the wheel molding and the use of the rational schemes for casting systems with the distribution of the splashing points. In addition, the principle of the successive filling of a mold with smelt polymer must be respected, beginning with the sections of larger sizes.

When removing out the gear wheels with small thickness from the walls of the forms, the risk of their bending arises. To remove it, the wheel disc is reinforced with stiffening ribs, which should have uniform thickness and technological inclinations. In addition, it should be taken into account that a small number of stiffening ribs makes polyhedral surfaces on the gear crown, because the radial contraction of the wheels sectors where the stiffening ribs are located, differs from areas where the stiffening ribs are missing.

5. SELECTION OF METHOD AND DESIGN FOR CASTING MANUFACTURING FORMS FOR GEAR WHEELS OF PRECESSIONAL GEARING

Based on the analysis of molding methods for the plastic gear wheels according to certain selection criteria (the simplicity and the technological design, the production volume, etc.) to manufacture the wheel, the method of casting under load was chosen, which is one of the most widespread methods for manufacturing the plastic products and the composites based on them. Its advantages are: a high productivity, the possibility of the process automation, the safe consumption of the material, comparatively higher accuracy of the obtained products, the technological simplicity and a high quality of mold products [1].

The design of the manufacturing molds for the gear wheels of the precessional gearing by casting under stress is based on a careful analysis of the construction of the casting molds and, according to the casting method, the selected construction and the technical documentation are developed. The process of the tooth mold (core of mold) manufacture is protected by a patent [4]. The casting mold for the plastic gearwheels of the kinematical precessional transmissions, as shown in Fig. 2, is composed of three parts: a fixed one, the intermediary and the mobile parts.

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