Argument on Plastic Gears for Power Transmission*

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First, I introduced various kinds of plastics, showed relationships between the relative prices of the principal ones and their heat resistant temperatures, and described various characteristics of plastics, taking the examples of polyamide (nylon) and polyacetal, which are commonly used plastic gear materials. Subsequently, I studied the dynamic behavior of plastic teeth, which is not observed in metal teeth and is related to the viscoelastic properties of plastics, and described various phenomena such as the temperature distribution on the tooth profile, the change in the tooth profile, the recess (groove) occurring near the pitch point, and breakage of the tooth, which are problems of plastic gears.

Key Words : Machine Element, Tribology, Wear, Gear, Plastic Gear

1. Introduction

Although there exist a great variety of plastics depending on the kind of monomers that constitute the polymer chain and their different bonding states, plastics sold in large quantities number about forty. Among them, the plastics having heat-resistant temperatures of at least 100°C, tensile strength of at least 49 MPa, and Young's modulus of at least 2.4 GPa, which are mainly used in industrial applications such as for structural and mechanical members, are called "general-purpose engineering plastics" (hereinafter referred to as "E. P."). Furthermore, the plastics suitable for use at high temperatures of at least 150°C are called "super-engineering plastics" (hereinafter referred to as "S. P."). Also, according to a classification method⁽¹⁾, engineering plastics with characteristics intermediate between those of E. P. and S. P. may be called "quasi-super-engineering plastics" (hereinafter referred to as "Q. S. P.").

E. P. are of two types: thermosetting resin and thermoplastic resin. Both are generally used as com-

paratively low-priced gear materials having a particular strength and heat resistance, as shown in Fig. 1⁽²⁾. For general gear materials, for example, demand for phenol resin (PF), a thermosetting resin, is increasing, as is demand for thermoplastic resins such as polyamide (PA) (also called "nylon (N)"), polyacetal (POM) and polycarbonate (PC). In particular, PA and POM account for 85% or more of gear materials used.

Recently, there has been a tendency to aim at enhancing the performance of a machine by using plastics to achieve improvements in areas other than weight and cost reduction. For this reason, composite plastics in which the E. P. are filled with solid lubricants, such as carbon fibers, as well as Q. S. P. and S. P. have been widely used as gear materials.

I have evaluated almost all of the plastics described above in terms of suitability as gear material, and reported⁽³⁾ the results quantitatively. In this paper, first I describe various characteristics of the PA and POM gears which are in wide use, and then describe two or three problems related to these characteristics.

2. Basic Characteristics of Plastic Gears

Because of its low frictional properties, the plastic gear can be used without lubrication, and has a

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PI : Polyimide
 PAI : Polyamidimide
 PEEK: Polyetheretherketone
 PPS : Polyphenylenesulfide
 PES : Polyethersulfone
 PAR : Polyarylate
 PSU : Polysulfone
 PBT : Polybutyleneterephthalate
 PC : Polycarbonate
 PA : Polyamide
 PPE : Polyphenylenether
 POM : Polyacetal
 ABS : Acrylonitrile butadiene styrene copolymer
 PP : Polypropylene
 PVC : Polyvinyl chloride
 PS : Polystyrene copolymer
 PE : Polyethylene

Fig. 1 Comparison of plastic prices (price of each plastic (Yen/kg)/price of polyacetal (Yen/kg)) and heat-resistant temperature

weight 1/6 to 1/7 that of a steel gear. Plastic gears have many other advantages, such as being able to reduce vibrations and noise, which are problems in terms of environmental pollution.

However, plastic gears also have many demerits. Compared with steel, for example, the mechanical properties of plastics are notably inferior, having a tensile strength of about 1/7, Young's modulus of about 1/75, thermal conductivity of about 1/80 and coefficient of linear expansion about 11 times those of steel. Plastics also have the disadvantages of high hygroscopicity and variation of their mechanical properties with temperature.

Thus the differences in behaviors of plastic and steel gears can be accounted for by differences in properties.

2.1 Deflection of tooth

When a load P acts on the plastic gear shown in Fig. 2, the gear tooth instantly deflects by more than 30 μm , and with continued application of the same load, the deflection increases with time to nearly 40 μm . That is, creep occurs in the tooth. When the load is removed after a predetermined time, the deflection decreases and reaches 0 only after a certain time.

The shape of this deflection curve is similar to that of the three-element dynamic model. However,

Fig. 2 Static deflection of tooth

Fig. 3 Hysteresis loop of plastic

when a plastic gear is operated under a large load for a long time, permanent deformation (plastic deformation) occurs, and the deflection does not reach 0 after the load is removed, even over time. In this case, the shape of the deflection curve is similar to that of the four-element model. The formula for calculating tooth deflection for such plastic gears and its analysis have been presented⁽⁴⁾ previously.

The deflection of the tooth varies with the kind of plastic, as shown in Fig. 2. In this case, since POM is somewhat inferior in rigidity to PA, the POM gear tooth undergoes a greater deflection than the PA gear tooth at the instant the load is applied. However, since POM has a lower viscosity than PA, after a certain elapsed time, the POM gear tooth exhibits a smaller deflection than the PA gear tooth, and reaches 0 within a shorter time after removal of the load.

Plastics exhibit such deflection behavior as shown in Fig. 2, because they are viscoelastic. In viscoelastic materials, a stress-strain relationship different from that for steel is observed. A stress-strain diagram for plastics is presented in Fig. 3. When stress is applied at A, strain increases following the path B to C with increasing stress. When the stress is removed at C, the strain recovers following the path D and returns to A. Thus, a hysteresis loop of ABCDA is drawn. The area bounded by this loop represents energy lost in the form of heat which raises the gear temperature.

These characteristics of plastics, which are not observed in steel, account for various phenomena in gear behavior. The shape of the hysteresis loop varies with the viscosity of the plastics. For example, PA, which has higher viscosity than POM, has a larger loop. Accordingly, a particular phenomenon unique to plastic gears as mentioned later in Chapter 3 is more pronounced in the PA gear than in the POM gear.

2.2 Tooth temperature

Temperature distribution of the plastic gear in the tooth profile direction (tooth depth direction) is as shown in Fig. 4(a), although it varies slightly with the kind of plastic used and the operating conditions⁽⁵⁾. This accounts for the manner in which a PA gear coated with thermopaint discolors. The temperature is higher near the pitch point, where rolling contact occurs, than at the tip and root of the tooth, where fast sliding occurs. This is because in a plastic gear of a material with a viscosity as high as that of PA, a considerable amount of heat is generated due to the hysteresis loss, as described above, and the radiation of heat occurs more easily at the tip and root of the tooth than near the pitch point. Figure 5 shows the heating value of a plastic gear tooth per rotation as calculated by Takanashi⁽⁶⁾, versus distance from pitch point. The shape of the heating value distribution in the tooth profile direction based on this calculation is very similar to the shape of the temperature distribution obtained from the experiment, as shown in Fig. 4(a).

Fig. 4 Temperature distribution in tooth profile direction and within tooth of nylon gear

In a plastic gear, temperature varies with the position of a point on the tooth even in the face width direction⁽⁵⁾, as shown in Fig. 4(b). This is because the end surfaces of a tooth are cooled by the rotation of the gear.

2.3 Coefficient of linear expansion

The coefficient of linear expansion of plastics is generally $(8 \text{ to } 13) \times 10^{-5} \text{ 1/K}$. That of some composite plastics filled with, e.g., carbon fibers, is about $1.5 \times 10^{-5} \text{ 1/K}$, while that of the new high-molecular-weight liquid crystal polymers is $1.13 \times 10^{-5} \text{ 1/K}$, which is almost equal to that of aluminum.

2.4 Hygroscopicity and moisture absorption rate

Plastics absorb moisture even from the atmosphere, to say nothing of absorbing it in water. The amount of moisture absorbed varies with the kind of plastic; polyethylene and fluoroplastic, for example, are only slightly hygroscopic whereas vinyl chloride and PA, among others, are highly hygroscopic. Since POM is not as hygroscopic as PA, a POM gear is generally more suitable for use underwater, where operation results in less wear than in the case of operation without lubrication in the atmosphere, since the water takes on the role of lubricant. Figure 6

Driving gear: Steel (S45C) gear,
 21 teeth
 Driven gear: Nylon (MC nylon) gear,
 26 teeth
 Module: 5
 Pressure angle: 20°
 Normal load per unit tooth width: 20N/mm
 Rotating speed of nylon gear: 570rpm

Fig. 5 Example of calculation for heating value of plastic tooth

shows relationships between the moisture absorption rate of PA, POM and PC and the dimension change rate. PA has a small dimension change rate although it is highly hygroscopic⁽⁷⁾.

3. Problems of Plastic Gears

Due to some of the properties of plastics mentioned above, various problems arise when a plastic gear is used to transmit power. Major problems inherent in operation without lubrication will be described here.

3.1 Abnormal wear of root of tooth and change in tooth profile

The following three cases are considered: plastic gears are used as the driving gear as well as the driven gear; a plastic gear is used as the driving gear and a metal gear as the driven gear; and a plastic gear is used as the driven gear and a metal gear as the driving gear. Any of these combinations has both merits and demerits⁽⁸⁾. Figure 7 shows a case where a plastic gear is used as a driving gear and a steel (metal) gear as a driven gear; the gears are rotating in the directions indicated by arrows. The worst loading point is denoted by w , and the distance between points i and w represent the range of meshing of a pair of teeth. Since the specific load share β is 1 in this region, a plastic tooth ② undergoes maximum deflection δ at point w . Therefore, this deflection delays the driven steel gear by δ in rotation from the normal position in

Fig. 6 Water absorption rate and dimension change rate of plastic gears

Fig. 7 Meshing of plastic gear in region of meshing of two pairs of teeth

the line of action, allowing the tip edge (edge of addendum) of the succeeding steel tooth ③ to scoop into the root of the plastic tooth ①⁽⁹⁾. Here, almost all of the loads are shared, and the region between points w and t is subjected to only an extremely small load. That is, the meshing of the plastic gear looks like the meshing of a pair of teeth throughout the meshing region.

As mentioned above, the root of the plastic tooth ① is subjected to a strong load near point f due to meshing with the steel gear such that the tip of the steel tooth scoops into the root of the plastic tooth, resulting in extensive wear of the plastic tooth. Figure 8 shows a record of the above-mentioned wear obtained by measuring with a tooth profile measuring machine. While extensive wear occurs from f to near the pitch point p , only slight wear occurs in the vicinity of the tip of tooth t . This pattern of wear is typical when a plastic (especially PA) gear is used as a driving gear, and the marked wear at the root has been called "abnormal wear at the root of tooth". Figure 9 is a conceptual drawing showing the change in tooth profile of the worn gear shown in Fig. 8.

Wear of a plastic gear basically depends on the PV value which is the product of contact stress and sliding speed of the tooth. When, however, comparatively little wear (wear on the addendum side) dependent on the PV value occurs, as in the case of the PA gear, and abnormal wear at the root of the tooth

Fig. 8 Tooth profile change of MC nylon gear

Fig. 9 Wear distribution and tooth profile change of plastic gear

accounts for the major part of the total amount of wear, it is necessary to introduce a tooth deflection factor which accounts for the abnormal wear when establishing an equation of wear⁽⁹⁾.

Figure 10 shows slip factor σ of a tooth of a plastic gear, and specific load share β and $\beta\sigma$ value of the tooth when power is transmitted. By comparing this figure with the tooth profile of the worn PA gear shown in Fig. 8, it can be seen that the tooth profile change at $N_T=10^7$, for example, is not V-shaped as shown by the slip factor plot in Fig. 10(a), but more closely follows the $\beta\sigma$ value plot in Fig. 10(c). In other words, it can be seen that the change in tooth profile of the PA gear depends more on tooth deflection than on tooth slip.

The tooth profile of the POM gear, as shown in Fig. 11, changed in a manner unlike that of the PA gear⁽¹⁰⁾. The root of the tooth of the POM gear is notably scooped out (portion of the profile which shows a large dip) by the tip edge of the paired steel

Fig. 10 $\beta\sigma$ value

Fig. 11 Tooth profile change of polyacetal gear

gear tooth basically in the same manner as in the PA gear, but the wear of the entire tooth depends on the PV value and the entire tooth is greatly worn (great Tn). Therefore this portion does not account for the majority of the total amount of wear of the tooth. This form of tooth profile change also occurs in the PC gear though it is different quantitatively⁽¹¹⁾.

PA, POM and PC have different coefficients of friction and are also different from one another in amount of wear, which depends on the PV value. When the changes in the tooth profile of these gears are compared, it is necessary to take into consideration also the different viscosity of each of the plastics.

When a preceding tooth of the plastic gear is deflected, as shown in Fig. 7, almost all of the load is applied at the root of the succeeding tooth. However, in the POM gear having low viscosity, when the load is shared by this succeeding tooth, a sufficient load is removed from the preceding tooth to reduce the deflection, and the tooth approaches the original shape and the load is shared more evenly. Accordingly, there exists a region for meshing of two pairs of teeth. This phenomenon is true also of the PA gear, but since the PA gear has higher viscosity than the POM gear, the preceding tooth slowly approaches the original shape, and therefore the region for meshing of two pairs of teeth becomes smaller than for the POM gear.

Figure 12 shows results of the experiment in which the above was verified⁽⁹⁾. Intermeshing time for two pairs of teeth is denoted by t , and it can be seen

Fig. 12 Difference in intermeshing time between nylon gear and polyacetal gear

that this value is smaller for the PA gear than for the POM gear.

3.2 Change in tooth profile in face width direction

When the face width of a plastic gear is increased in order to transmit greater power, the tooth profile (tooth trace) in the face width direction changes into the shape of a cask, as shown in Fig. 13. This is because the temperature at the central portion of the face width becomes higher than that at the end surface portions, as shown in Fig. 4(b), and the central portion becomes greatly thermally expanded. When the tooth profile changes in this manner, gear contact becomes greater at the central portion, thus possibly causing cracks there, as shown in Fig. 14, or spalling, as shown in Fig. 15.

If a plastic gear is designed with the same weight as a steel gear, it is possible to increase the face width by about six times that of the steel gear. In this case, however, the amount of thermal expansion is calculated over the entire face width, and crowning opposite that for the steel gear is provided such that the face width becomes gradually more concave toward the central portion⁽¹²⁾, as shown in Fig. 16.

When a plastic gear is used as a driving gear, a recess, as shown in Fig. 17, may occur near the pitch point depending upon the kind of plastic. This is partly because high temperatures are reached in the vicinity of the pitch point, as shown in Fig. 4(a),

resulting in softening of the teeth there, and partly because the direction of slide of the teeth is changed to the addendum side and the dedendum side with the pitch point as the boundary⁽¹²⁾.

The phenomena shown in Figs. 13 and 17 are much more pronounced in PA gears than in POM gears. This is because, although signs of thermal expansion or of a recess occurring near the pitch point appear in the POM gear as in the PA gear, they disappear as the wear of the POM gear increases and becomes severe.

3.3 Breakage position of tooth

In the plastic gear, the tooth is not always broken near the root where the maximum bending stress occurs. In materials such as plastics in which the strength greatly depends on the temperature, the breakage of the tooth is affected by the temperature distribution on the tooth profile, and occurs where the

Fig. 15 Spalling occurring in nylon gear

Fig. 13 Conceptual drawing for change of tooth profile of plastic gear in face width direction

Fig. 16 Amount C of "anticrowning" provided for nylon gear

Fig. 14 Cracks in Central portion of face width of nylon gear

Fig. 17 "Recess" appearing near pitch point of nylon gear

Fig. 18 Breakage near pitch point of nylon gear

maximum stress/strength value is reached. In the PA gear having high viscosity, since the temperature distribution of the tooth is as shown in Fig. 4, the stress/strength value becomes maximum near the pitch point, and breakage usually occurs at the position⁽⁵⁾ shown in Fig. 18.

From the foregoing, I have proposed a formula, in which a factor related to the “operating time of stress-strain load” has been introduced, as the strength design formula for plastic gears, which expresses the fatigue life (operating life) of the POM and PC gears in relation to the stress/strength value⁽¹³⁾.

4. Conclusions

The roles of plastic gears have been shifted and developed from substitution for metal gears to uses aiming at higher and increased value-added functions, and along with this development, the performance requirements for plastic gears have also become severe. However, since plastic gears have a shorter history of use than metal gears and many issues remain unclarified, plastic gears are currently regarded as unreliable. Under these circumstances, it is necessary to investigate the factors affecting the physical properties of each plastic as well as the safety of plastic gears, and to study how consideration of these factors should be included in the design process.

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