Studies and Research on Adhesive Wear of Gears with Pairs of Gears Made of Plastics and Steel

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Abstract: *Steel and plastic twin gear gears are increasingly used in various industrial sectors. They often work in areas where gear lubrication is not possible or very difficult. So, between the sides of the two gears there is a dry friction and intense adhesive wear. The present paper carries out theoretical research on the phenomena from the contact between the sides of the gears and aims to determine, by calculation, the speeds of adhesive wear that occur at each of the two gears that form the gear.*

Keywords: *adhesive wear, gear, plastic-steel.*

1 INTRODUCTION

Technical plastics are macromolecular materials that are increasingly replacing steel parts in certain industrial fields. This is possible due to their advantageous technical characteristics: low density, high corrosion resistance, resistance to chemical agents, good thermal and electrical insulation, low energy costs, fatigue resistance, shock resistance and the possibility of easy processing of complex parts.

The category of complex parts also includes gears. In recent years, gears have been made more and more frequently in which one of the gears is made of steel and the other gear is made of plastic. Technical plastics have good mechanical properties, and, although not always, can successfully replace steel.

The main types of plastics recommended in the manufacture of gears are: polyamides (PA), polyacetals (POM), polyethylene terephthalates (PETF), polycarbonates (PC) etc.

The choice of the materials of the gears that make up the gear is made according to the operating conditions. In the case of the steel-plastic coupling, the heat resulting from friction is easily dissipated, a very important aspect for the plastic gear and that is why it is the most advantageous situation. The metal gear will have a high hardness offered by heat treatment which leads to reduced wear for both wheels. It should also be mentioned that it is not necessary to grind the flanks on the metal toothed wheel.

2 TRIBOLOGICAL ASPECTS OF STEEL-PLASTIC GEARS

At the contact between the flanks of the teeth of the two toothed wheels, a sliding friction and a rolling friction appear, which will produce phenomena of wear of the flanks but also thermal phenomena by increasing the temperature.

At slip friction, the friction force F_f during the relative movement of the two flanks consists of F_{fa} the strength of resistance of the adhesion bonds and F_{fd} the strength of resistance of the deformations.

$$F_f = F_{fa} + F_{fd} \qquad (1)$$

The size of the adhesion force F_{fa} between the two molecular bodies in contact depends primarily on their molecular structure. This molecular structure, for plastics, is very varied from one material to another. Therefore, the adhesion tendency of different plastics is very different, which has direct effects on the friction and wear properties. At the contact between two identical plastics or with similar molecular structure, the adhesion has very high levels and, as a result, the friction coefficients have high values that can reach supra-unit values (μ=1.2) or in some even higher operating conditions.

Due to this fact, for friction couples it is preferable to choose a pair of different materials consisting of a metal part and a plastic part. Thus, they have different molecular structure and adhesion strength will have lower values and thus friction and wear.

Large adhesion forces can sometimes occur at the contact between metal and plastic if a layer of plastic appears and deposits on the metal surface. It is favorable in terms of wear but produces a higher coefficient of friction due to the appearance of a plastic-plastic contact instead of the desired metal-plastic contact. The adhesion force is proportional to the effective contact surface.

The second component of the friction force - F_{fd} deformation force - depends primarily on the cross-sectional area of the ripples on the contact surfaces.

At low load stresses of the friction torque, the adhesion force is predominant. As the load increases, the deformation force becomes the main one. At very high loads the deformations can become permanent and can affect the shape of the bodies and the functionality of the parts.

Friction and friction force can be limited by decreasing the effective contact surface, micro-neregularities, by increasing the hardness of the friction coupling surfaces and by lubricating the contact. The introduction of lubricants at the metal-plastic contact creates superficial layers with low shear strengths that lead to minimal friction. Unfortunately, however, the use of lubricant on gears with metal-plastic contact is not possible in all areas of their use because they can affect the proper functioning of the product of which they are part.

In the case of the engagement of two involute teeth, both types of friction meet: sliding friction and rolling friction. From the point of view of the effects it produces (the size of the wear, the increase of temperature, etc.), the sliding friction is the one that predominates in relation to the rolling friction.

3 ADHESIVE WEAR AT GEARS WITH A PLASTIC TOOTH WHEEL

Wear that inevitably occurs as a result of the friction process is a complex physico-chemical process that cannot be described by general laws. Therefore, in practice, wear is described by simple processes that can be modeled mathematically. Thus, we distinguish:

- adhesive wear;
- abrasive wear;
- wear of fatigue;
- oxidation wear - corrosion;
- fretting wear;
- erosion wear;
- cavitation wear etc.

The adhesive wear is caused by the adhesive connections that appear at the contact surface between the bodies: the atomic and molecular bonds at the contact surface break, there is also a transfer of material in the form of microparticles that detach from those bodies.

Materials with similar crystalline structure (two identical pure metals in contact) tend to form strong adhesive connections, which can lead to rapid wear and premature destruction of the contact surface. Therefore, such situations should be avoided, recommending the choice of pairs of materials with different structures such as: cast iron steel, bronze steel, plastic steel, etc. The adhesion tendency of the metal can be significantly reduced by alloying or by heat treatments applied to the metal toothed wheel.

According to Archard's theory, the adhesive wear W_v can be calculated with the relation below, if the wear coefficient k is known

$$W_v = k \cdot A_t \cdot L_s = k \cdot \frac{F_N}{HB} \cdot L_s \ [mm^3] \qquad (2)$$

where:

A_t is the real contact surface;

L_s - the length of the friction space;

F_N - normal (perpendicular) load;

HB - hardness of the material subject to wear.

The wear coefficient k depends on the pair of materials, the type of lubrication, the operating parameters and the interaction of the environment.

In practice, the oxide layer, the absorbed gas and the hardened layer at the contact surface lead to the decrease of the adhesion tendency. Adhesion can also be prevented or attenuated by lubrication, when this is possible in the operation of the gear.

Lubricants that contain polar molecules are absorbed on the metal surface and lead to a decrease in friction and wear.

In the case of heavy loads, excessive wear can be avoided by creating artificial layers (sulfites, phosphites, chlorites). These artificially created layers are usually more effective than oxide layers. But they can not completely prevent the wear process but greatly reduce the adhesion component of wear.

The most effective way to reduce friction and wear is to lubricate the surfaces in contact in all cases where this is possible. The purpose of lubrication is to reduce the friction and wear of the surfaces in contact, to prevent the premature destruction of these surfaces, to increase the permissible load, their service life and reliability.

In practice, lubrication is found only during assembly, periodic lubrication and continuous lubrication. The lubricant, which can be liquid (oil), thick (vaseline) or solid (powder) reaches the lubrication site using lubrication devices. There are practical situations in which lubrication cannot be done, namely:

– lubricant is not available;
– the lubricant pollutes the environment;
– the environment prevents obtaining the lubrication effect (for example extreme temperatures, food industry);
– lubrication cannot be done economically.

In such situations, the correct choice of the material coupling has a particular importance for obtaining a proper reliability.

4 USE OF GEARS WITH PLASTIC TOOTHED WHEELS

Due to its advantages, plastic toothed wheels are used in various branches of industry and especially where noise removal, vibration damping, abrasion resistance, corrosion resistance, etc. are required.

In the textile industry, plastic toothed wheels are used in spinning, twisting, winding, debugging, automatic weaving machines, washing and dyeing machines.

The special advantage of these toothed wheels, used in the textile industry, is that since they do not require lubrication, the lubrication of threads and fabrics is eliminated with lubricants.

Plastic toothed wheels are also used in the construction of agricultural machines but only for low transmission loads. These toothed wheels behave particularly well in the environment with dust and vibrations from the machines, even in conditions where their lubrication is not done regularly.

In the food and pharmaceutical industry, the advantage of plastic toothed wheels is that they can function without lubrication and that in the fog they can come into direct contact with food or medicine. In such situations plastics are used that are physiologically inert.

Plastic gears are also used in the chemical industry (many plastics are resistant to acids or bases), in construction (in various mechanisms), in the wood industry, as well as in maintenance, repair or modernization of existing equipment.

In recent years there has been a favorable evolution of the price of plastics in relation to that of metallic materials (steel, bronze, copper, etc.), which leads to the extension of their use to more and more technical applications.

5 SPEED OF ADHESIVE WEARING OF GEARS WITH PASTIC MATERIALS AND STEEL

Given that there is no lubrication during the operation of a gear (a common situation with gears with plastic and steel gears), the wear of the flanges of the teeth usually limits the operation of the gear.

For the calculation of the thickness of the layer of used material by worn adhesion, the relation can be used:

$$h_{uz} = 0{,}0375 \cdot t_h \cdot n_1 / \rho_{2/}u - \rho_2 / \left(F_n\theta_\rho\right)^{\ 1/2} \left(I_{uh1} \cdot \frac{n_{z1}}{\rho_1} + I_{uh2} \cdot \frac{n_{z2}}{\rho_2}\right) = v_{uad} \cdot t_h \text{ [mm]} \quad (3)$$

where:

t_h is the operating time of the gear [h]; n_1 - gear speed [rpm];

ρ_1, ρ_2 - radiuses of curvature at the given point [mm];

u - transmission coefficient;

F_n - normal unit force per unit length [N/mm];

θ - the elasticity parameter of the materials [Mpa^{-1}];

$$\theta = \frac{(1-\mu_1^2)}{E_1} + \frac{(1-\mu_2^2)}{E_2} \quad (4)$$

μ_1, μ_2 - Poisson's ratio;

E_1, E_2 - modulus of elasticity of gear materials [MPa];

I_{uh1}, I_{uh2} - the wear intensities of the materials, for the given operating conditions;

n_{z1}, n_{z2} - the number of toothed wheels with which the wheel in question is in contact (for a gear consisting of two gears $n_{z1}=n_{z2}=1$);

v_{uad} - overall speed of adhesive wear of the gear [mm/h].

In the above expression, for a given gear, the following quantities can be considered constant: wheel speed n_1, elasticity parameter θ, transmission ratio u, wheel numbers n_{z1}, n_{z2} and radius of curvature ρ_1, ρ_2.

The variable working conditions during gearing require the variation of the normal unit force F_{n1}, of the wear intensities I_{uh1}, I_{uh2} and implicitly of the v_{uad} wear speed.

The normal unit force can be determined by the relationship

$$F_{n1} = \frac{F_n}{b_w} \left[\frac{N}{mm}\right] \quad (5)$$

in which:

F_n is the normal force on the tooth [N];

b_w - active tooth width [mm].

The wear intensities I_{uh1}, I_{uh2} can be determined for a certain quality of the flanks (microgeometry, material, roughness, etc.).

There are a number of mechanical characteristics of plastics that have an influence on the adhesive wear mechanisms, namely: breaking strength / flow limit σr/σc, hardness HRM, longitudinal modulus of elasticity E, elongation at break A, etc.

To correct this, a material factor, dimensionless, k, is defined with the following relation:

$$k = \frac{R_c \cdot HRM}{E \cdot A} \quad (6)$$

where:

R_c is flow resistance [N/mm^2];

HRM - Rockwell hardness of plastic (on M hardness scale);

E - longitudinal modulus of elasticity [N/mm^2];

A - elongation at break [%].

Thus, for the 5 (five) types of plastics recommended for toothed wheels, the following values presented in table 1 are obtained for the material factor k.

Table 1. Material factor values k.

Plastic type	PA6-Mg	PA6-Na	PA66 GF 30	POM-C	PETF-Tx
Factorul k	0,061	0,085	0,498	0,067	0,275

For the calculation of the adhesive wear speed vuad of the gears the following calculation relation is proposed, using the coefficient of the material factor k.

$$v_{uad} = 0{,}375 \cdot k^{\frac{1}{2}} \cdot n_1 \cdot / \rho_2 / u - \rho_1 / \left(F_{n1}\theta_\rho\right)^{\ 1/2} \left(I_{uh1} \cdot \frac{n_{z1}}{\rho_1} + I_{uh2} \cdot \frac{n_{z2}}{\rho_2}\right) \text{ [mm/h]} \quad (7)$$

In relation (7) the notations ρ_1, ρ_2, F_{n1}, θ, I_{uh1}, I_{uh2}, n_{z1}, n_{z2} have the same meanings as in formula (3).

Consider a straight-tooth gear consisting of an S355JR steel sprocket (without heat treatment) and a POM-C polyacetal wheel, characterized by the following geometric and kinematic elements – figure 1:

- axial distance a=45 mm;
- active tooth width b_w=12.5 mm;
- modulus m=1.25 mm;
- number of teeth $z_1=z_2$=36 teeth;
- coefficients of displacement of the profile $x_1=x_2=0$;
- head diameters $d_{a1}=d_{a2}$=47.5 mm;
- rolling diameters $d_{w1}=d_{w2}$=45 mm;
- foot diameters $d_{b1}=d_{b2}$=41.88 mm;
- gearing angle a1 of the reference rack α=20°;
- precision class 5-C.

The adhesive wear speed at the gear entry point (A) and at the gear exit point (E) shall be determined, characterized by a normal force F_n = 288.4 N and speed n = 1300 rpm.

The following data are considered known:

- the parameter of elasticity of the materials $\theta=2.91 \cdot 10^{-4}$ mm^2/N;
- wear intensities I_{uah1} (plastic)=7.06 10^{-8}, I_{uah2} (steel)=$2.54 \cdot 10^{-10}$.

In points A and E, of entry and exit of gear, respectively, the radiuses of curvature are determined with the following relations:

$$\rho_{2A} = 0{,}5 \cdot z_2 \cdot m \cdot \cos\alpha \cdot tg(\arccos d_{b2}/d_{a2}) \quad (8)$$

$$\rho_{1A} = a_w \cdot \sin\alpha_w - \rho_{2A} \quad (9)$$

$$\rho_A = \frac{\rho_{1A} \cdot \rho_{2A}}{\rho_{1A} + \rho_{2A}} \quad (10)$$

$$\rho_{1E} = 0{,}5 \cdot z_1 \cdot m \cdot \cos\alpha \cdot tg(\arccos d_{b1}/d_{a1}) \quad (11)$$

$$\rho_{2E} = a_w \cdot \sin\alpha_w - \rho_{1E} \quad (12)$$

$$\rho_E = \frac{\rho_{1E} \cdot \rho_{2E}}{\rho_{1E} + \rho_{2E}} \quad (13)$$

Performing the calculations obtains the following values: $\rho_{2A}=\rho_{1E}=12.03$ *mm;* $\rho_{1A}=\rho_{2E}=3.36$ *mm;* $\rho_A=\rho_E=2.63$*mm.*

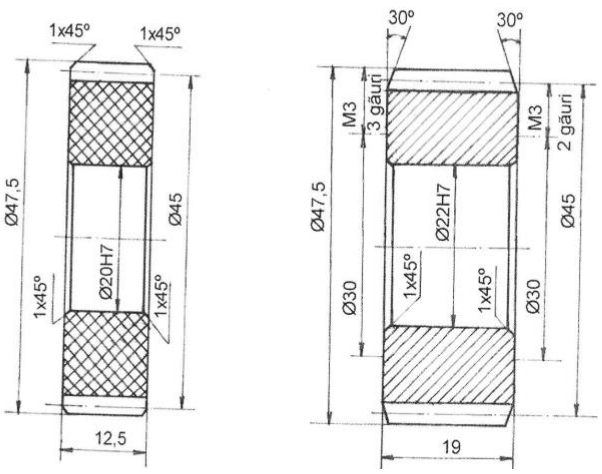

Fig. 1. Plastic and steel toothed wheels that form the gear.

Using the relation (7) it is possible to determine the adhesive wear speeds for the two toothed wheels that compose the gear, the calculated values being:

- POM-C $v_{uadA}=v_{uadE}=4.52 \cdot 10^{-6}$ mm/h;
- Steel $v_{uadA}=v_{uadE}=2.18 \cdot 10^{-7}$ mm/h.

The adhesive wear speeds, for a certain toothed wheel, calculated at the point of entry and exit of the gear are equal to each other.

It is also observed that the adhesive wear speed of the steel toothed wheel is approximately 21 times lower than the wear speed of the plastic wheel. The difference between the wear speeds was predictable but through these determinations it is also known what is, numerically, the difference between the two adhesive wear speeds.

6 CONCLUSIONS

Due to the advantage it offers, plastic toothed wheels are increasingly used in different sectors of activity: food industry, textile industry, construction, wood industry, etc. Frequently plastic toothed wheels are used in gearing with steel toothed wheels. Given the areas of use, frequently, the friction between the two toothed wheels is a dry friction, without lubrication. In this case, adhesive wear is predominant.

The paper establishes an algorithm for calculating the adhesive wear rate and calculates the value of these speed for plastic and steel toothed wheel. For the established materials and conditions, it is observed that the wear speed of the plastic toothed wheel is 21 times higher than that of the steel wheel, which will allow it to be replaced, predictably, before affecting the proper operation of the gear.

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