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An analytical wear model based on CAD measurements in polyamide pinion under different working environments

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1. Introduction

Machined and injection moulded engineering thermoplastics are now commonly used to produce a broad range of mechanical power transmission components. These include gears, cams and bearings for automotive industry, office equipment such as computers, printers and copiers, and domestic electrical appliances like food processors as well as many other applications [1-9]. Meanwhile, in many cases, material selection and design for thermoplastic gears are based on geometrical, environmental and manufacturing factors rather than tooth loadings and contact aspects [1]. It is worth noting that there are many plastic materials and filler combinations available in the market, but data concerning their structure, lifetime and energy consumption are still poor especially when adverse environments are involved [3, 4]. Therefore, research trends are oriented to characterize materials contact circumstances and related mechanical properties evolution for a better gear performance [5, 6].

So far as lifetime is concerned, wear is the most degrading phenomena in polyamide (PA) made gears. Therefore, a large number of wear investigations have been carried out using experimental and/or finite element methods (FEM) in order to explain and model this phenomenon. Experimental work can be achieved using several types of standards or specifically designed laboratory setup. The commonly used testing rig for measuring wear in gear materials is pin-on-disc machine which consists in running a disc made of metal or another polymer against a polyamide specimen [1, 6]. However; this system presents a great disadvantage that geometry of the pin-on-disc test simulates wear on two rolling surfaces rather than on the rolling flanks of the geared teeth. Other types of testing rigs are twin-disc machines which consist of two discs, mounted on parallel shafts, loaded in radial direction against each other and running in opposite directions [7, 8].

Wear results obtained from this approach are alike but not comparable to wear gears. In the above cases, wear measurement is achieved indirectly after interrupting the test by removing the gears, through optical observation of the tooth width reduction on pitch diameter or by determining the wear volume lost by weighting the wheel. Continuous wear measurement is possible using a purpose-designed rig on which wear is measured on a bearing component by recording the movement of the bearing component by means of a non-contacting capacitive transducer [10].

Nevertheless, wear is still measured on rolling contact surfaces rather than on gears. There is also an alternative in measuring wear by using machines in real service conditions, but it is very difficult to appreciate the behaviour and the mechanisms [5]. This could be done by means of sophisticated equipments that are complex and expensive. FEM [10-12] as well as computer aided design methods have also been used to investigate wear resistance of polyamide gears [13-15].

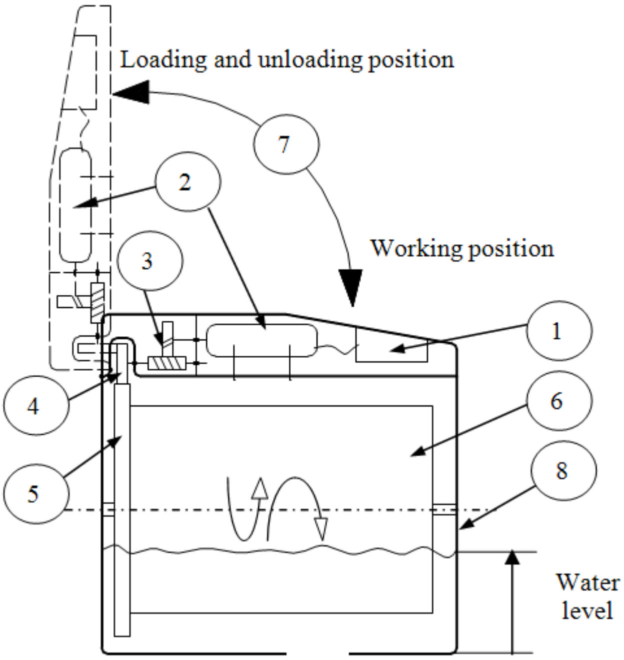
Industrial machines that use rotating gears in clock and counter-clockwise direction create wear on both flanks of the pinion teeth and as a result, it becomes difficult to cope with wear resistance, because of material deformation and associated wear measuring technique. Therefore, the present paper proposes a procedure for measuring wear in polyamide pinions using a method that combines optical microscopy pictures and frame digitalisation analysis via computer-aided design (CAD) system in order to work out the wear-removed volume at each step. On this basis, a model is presented describing wear evolution in dry, water and detergent environments.

2. Experimental procedure

The gears used in this study were bought from the local market together with 2 new washing machines (testing rigs). The geometrical specifications of gears were established in the metrology laboratory (UBMA). Average values are depicted in Table 1. The proposed testing rig puts into contact a PA66 spur gear composed of a 19-teeth and a 132-teeth driven wheel containing the load to be washed as illustrated in Fig. 1. The pinion rotates at a speed of 140 rpm and is driven by 0.1 kW electrical motor [9]. Basically, the rotational movement of the pinion is directly transmitted to the crown wheel of the drum trough the gears. The cycle of the machine is divided into three periods: 10 min in the clockwise direction, followed with 10 min rotation in the counter-clockwise direction and finally, 2 min rotation in the clockwise direction in order to ensure a good washing cycle.

Table 1
Geometrical specification of the PA 66 studied gear

Symbol	Specification	Value
α	Pressure angle, degree	20
m	Contact ratio, mm	3
Z	Number of teeth	19
D_p	Pitch diameter, mm	57
D_0	Outside diameter, mm	63
D_r	Root diameter, mm	49.5
h_t	Whole depth, mm	8
p	Circular pitch, mm	9.42
b	Tooth thickness, mm	15



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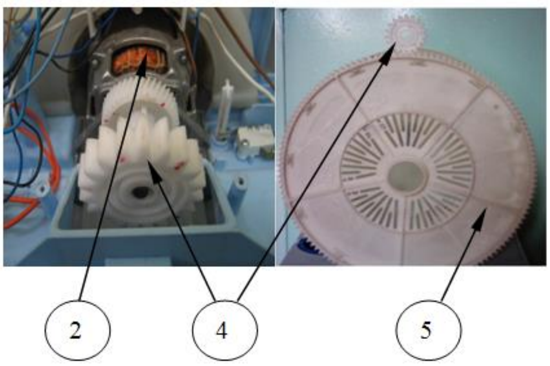

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Fig. 1 a) diagram of testing rig [9]; b) gear views: *1* – rig control; *2* – transmission motor; *3* – helical gear; *4* – Studied pinion; *5* – crown wheel; *6* – driven drum; *7* – Upper cover; *8* – *l*ower barrel

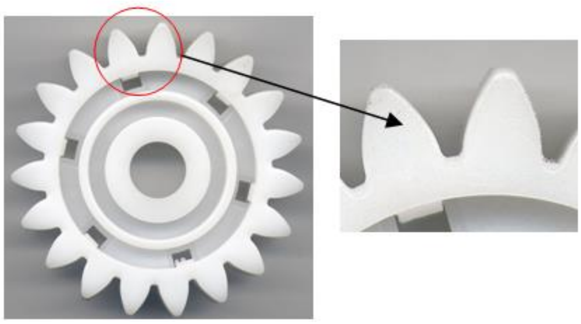
A specific protocol is followed to remove, clean and control each gear at every quarter million cycles. The chosen testing conditions are: 1) water (clear tap drinkable water); 2) detergent water solution (powder detergent containing non-ionic tension-active elements, bleaching agent, phosphates perfume and others); 3) dry condition (no water and no powder used) [9]. When running, usually one third of the drum is filled with the respective solution. Under wet conditions, washing liquid is transported to pinion teeth because of the gearing with the crown wheel during rotation. As a result, the fluid serves as a lubricating agent**.**

3. Wear measurement

Wear measurement has been made on both flanks of the pinion teeth which is shown in Fig. 2. The 19 teeth have been noted 1 to 19 in the clockwise direction. Tooth number 1 is chosen on the basis of a small circular mark caused by the injection process when pressure-moulding the part from the polymer melt. This tooth is referred as the flow moulding injection tooth. The idea was that one expects to find out whether the wear is uniform or not in each tooth of the wheel. Then a procedure for wear measurement is followed in three steps as detailed below:

3.1. Step 1: Tooth observation

A Motic digital compound laboratory microscope with built-in 1/3-inch charge-coupled device (CCD) camera has been used. The microscope has a trinocular 30° inclined heads, an additional tube for mounting a built-in CCD camera, wide field eyepieces WF10X/20mm, quadruple nosepiece, Achromatic Super Contrast (ASC) objectives 4X, 10X, 40X S, 100X S-Oil. It allows both coaxial coarse and fine focusing adjustments. A 5.1 Mega pixel resolution compact and lightweight Canon camera is mounted onto the trinocular eye.



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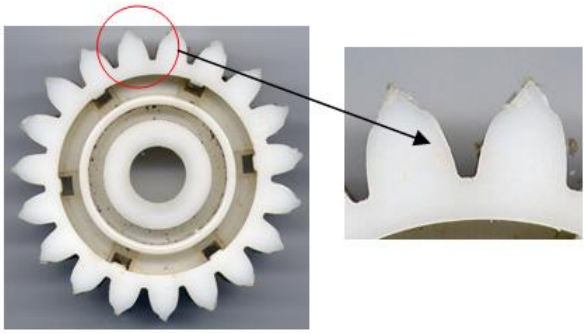

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Fig. 2 a) as-received “PA66” pinion; b) worn pinion after service

Easy plug and play USB2.0 Hi-Speed connection ensures that crisp and clear real-time images are displayed on the computer monitor. Professional application software “Motic Images Plus 2.0” is used to explore the power of the microscope by enabling correct analysis and quantification of the image. In addition, as our work concerns measuring wear in all teeth of a pinion, a purpose built in device consisting of a circular plate, with an axis of rotation and a positioning pin between two teeth, has been constructed in order to get the pinion always with the teeth in the same position, towards the eye of the microscope. Measurement on each flank of the teeth is achieved, tooth-by-tooth simply by rotating the pinion since all the teeth have already been identified. The reference image is a clean and unused pinion. Since, then all the next images on the same pinion being tested are compared to the reference image. This is illustrated in Fig. 3, step 1. A lot of 247 images have been saved in raster graphics digital bitmap format, representing 13 images by tooth for one wheel.

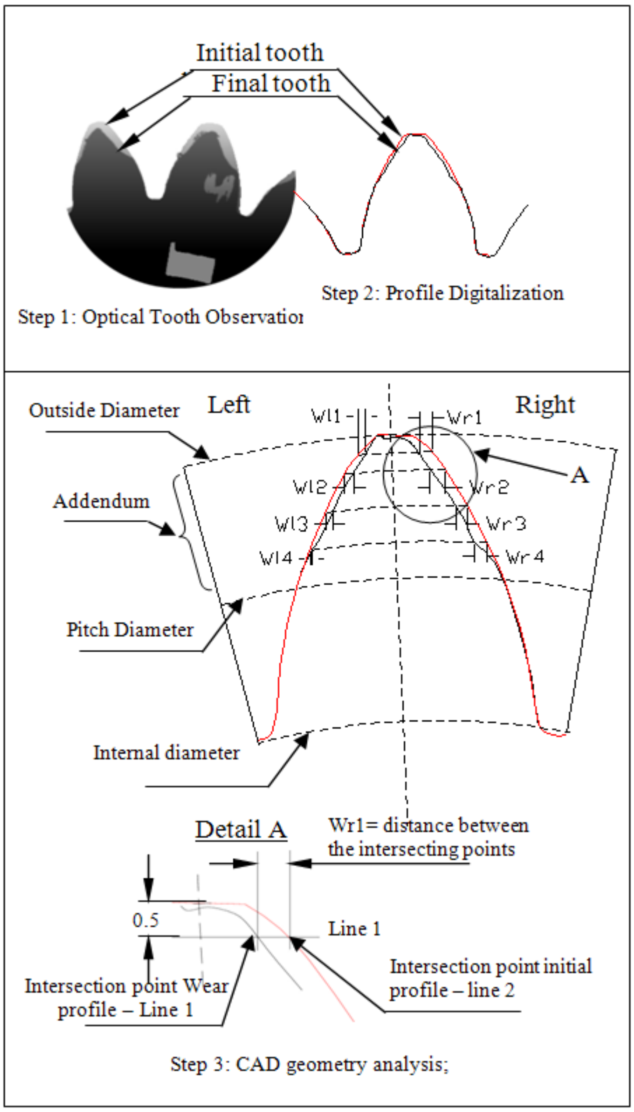


Fig. 3 Wear analysis of a gear using CAD system

3.2. Step 2: Image digitalization

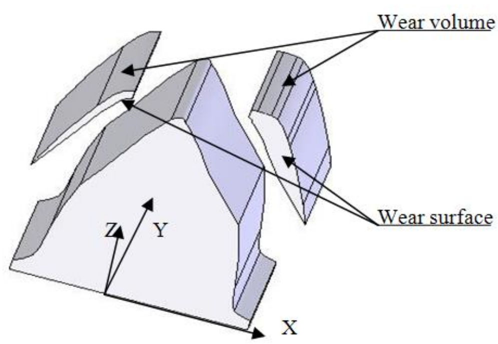
The second step consists in digitalization of the saved images. This is achieved using a free version of Inscape software. The latter is a vector graphics-drawing program published under the Government of National Unity (GNU) General Public License.
Inkscape, made first for Linux, it is now a cross-platform tool and runs on other operating systems.

As of 2007, Inkscape is actively being made better and new features are added all the time [14]. Among this performance is to use the drawing exchange format (DXF) which is a CAD data file format developed by Autodesk, for enabling data interoperability between CAD systems [15]. Subsequently, for this study, each image observed through the microscope is vectorized as to obtain the new profile the tooth generated by wear and saved in DXF format. Fig. 3 illustrates the results for step 2.

3.3. Step 3: CAD analysis

The third step is devoted to computer aided design analyses. As the initial microscope image is saved under DXF file, a computer aided design system can be used to analyze the geometry of the tooth profile. The two-dimensional (2D) analysis is achieved by loading each DXF file of the pinion tooth under robot CAD in ROBOT Millennium environment. The geometrical analysis consists in measuring the wear-removed layer at 4 predefined cross sections in the addendum zone, (Fig. 3, Step 3).

The latter is divided into four parts from the external diameter to the pitch diameter by drawing 4 lines at 0.5 mm, 1 mm, 2 mm and 4 mm deep that are cutting the initial and the wear profiles of the tooth. The distance between the intersecting points is then measured on each of the 4 drawn lines. In this way, wear can be obtained on both flanks of each tooth.



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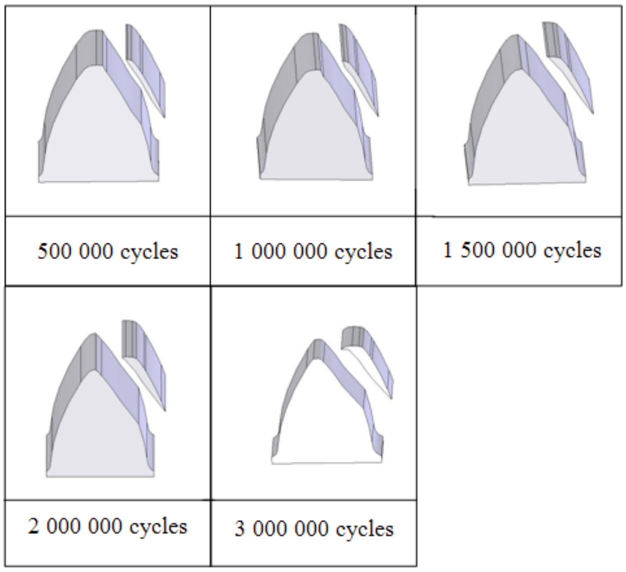

Fig. 4 a) volumetric wears measurement using a CAD system; b) graphical evolution of wear volume removal on a flank

The boundaries of wear in the XY plane are then obtained from the initial tooth shape and the worn tooth shape using the spline function of the CAD system. As the surface shape in the XY plane is now identified, the volume of the removed part can be generated in the Z-axis along the tooth width assuming a fairly uniform layer, Fig. 4, a and b. When multiplied by the specific weight of polyamide, the wear can be expressed in terms of weight. As a result the evolution of wear as a function of the number of revolutions corresponding to number of cycles can be obtained for each flank of the pinion teeth.

4. CAD based analysis of wear in gears

This section presents the different wear analyses resulting from the above CAD based procedure.

A set of 247 raster graphics digital bitmap format images, 494 drawing exchange format data files, 1976 distance measurements, 494 wear profiles and extrusions have been recorded per pinion to reach the following analyses. First the wear morphology on each flank of a tooth is discussed based on raster graphics digital bitmap format images. A distribution of wear around the wheel teeth is then obtained. Secondly, the wear evolution is analyzed in terms of the removed volume in each flank of the wheel teeth. CAD results are then compared to weight data. The fore coming comments are made on a representative tooth, which is similar to all other teeth of the 6 pinions investigated in this work.

4.1. Wear morphology

Microscopic optical observations have been of practical use to follow wear morphology as a function of elapsed number of cycles. It is noted that pinion teeth have been subjected to wear activity just in the addendum zone, between pitch and the outside diameters, as shown in Figs. 2 and 3. It is accepted that applied pressure on the contact zone creates an axial force which results in gear rotation (displacement). Therefore, the surface contact from the first point of contact to the release point is reduced only in the addendum zone. In addition, Public Affairs (PA) gears are known to absorb water as high as 1.5 weight % at 23°C during 24 h. As a consequence, the volume of the teeth of the crown wheel increases leading to push out the meshing teeth of the pinion. The wear shape is then different from that reported in the literature where the wear profile starts well below the contact point in the addendum zone of the tooth, following a smooth trend up to the external diameter [5, 7, 8]. In this case, the wear occurs because of the direction of relative movement when the teeth enter and leave the mesh. Sliding along the reduced contact surface gives the particular wear evolution.

It has been observed that wear is not evolving in the same manner on right and left flanks. Each washing cycle lasts 22 min (10+10+2 min) before the machine stops and it is repeated during experimentation until 250000 revolutions are achieved for wear measurements. Accordingly, in counter-clockwise direction, the number of cycles is about 208330 against 250000 cycles in the clockwise direction, implying higher wear on the right flank. However, the wear at both sides of the flanks is not proportional. This is obviously due to the fact that the weakest area is located in the addendum zone near the external diameter where enough plastic deformations generate deeper wear than in the zones far from the external diameter area.

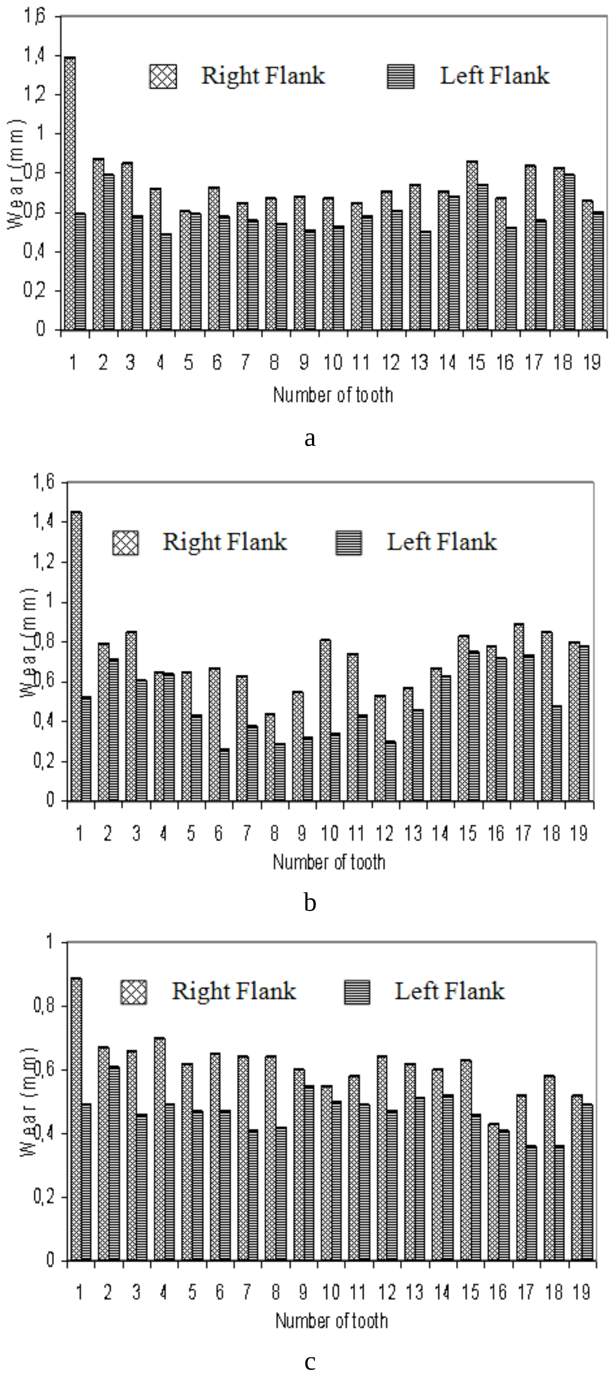

Fig. 5 Wear evolution in a) in dry condition; b) in water-detergent solution; c) in water solution

Fig. 5 shows the evolution of wear on the XY-plane at 0.5 mm from the external diameter, as a function of number of cycles for the 19 teeth, for the 3 conditions. It can be clearly seen that wear behaviour on the right flanks is not the same in all measured cases. For the 3 conditions, it appears that the most sensitive tooth to wear is the flow moulding injection tooth and the less sensitive is the opposite tooth. As far as the teeth are away from the injection tooth position, as they are more resistant to wear. This is due to the fact that during the cooling process of the wheel during the flaw moulding injection, the last tooth to cool down is the injection tooth resulting in a slight difference in material properties around the wheel. This phenomenon is not observed for the left flanks in which wear is almost equitably distributed around the pinion teeth.

This can be explained by the working process cycle of the machine; in the beginning the right flanks are the first to be subjected to wear in the clockwise direction generating elastic deformation in the applied normal force direction, then when rotating in anticlockwise direction, the left flanks relax the elastic deformation before wear process starts on them. In the third part of the working cycling process, during 2 min, rotation in the clockwise direction exposes again the right flanks to wear before the machine stops. The phenomenon is repeated as many times as it is necessary until reaching the wear lifetime.

4.2. Flanks wear evolution

The CAD system allows determining the volume of material removed for each measurement on each flank of the pinion teeth (Fig. 4, a and b). Therefore, isolated material on a tooth can be expressed by the evolution of its volume as a function of the number of cycles. This is achieved by interrupting the test at intervals of 250000 cycles until the final wear where movement transmission is no longer possible under safe conditions. Fig. 6 illustrates the effect of number of cycles on the wear volume on each flank of a representative tooth through the lifetime of the pinion.

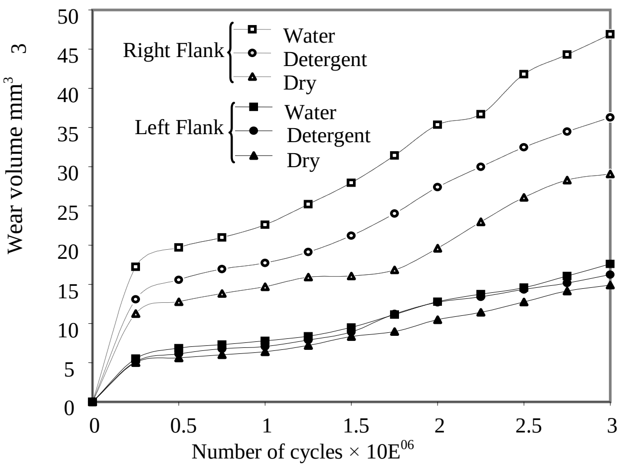

Fig. 6 Wear evolution in volume units (mm^3) as a function of elapsed cycles on both flanks

All values were 4 times higher in the right flank than in the left flank. This is obviously due to the working process cycle in which the right flanks are subjected to 2 min extra revolutions than the left flanks. Moreover, in the first part of the working process cycle corresponding to 10 minutes revolution in the clockwise direction, as the addendum zone is weak, elastic deformations occur within this zone before wear phenomenon starts in the right flank. Then, in the second part of the working process cycle, corresponding to 10 min revolutions in the anti-clockwise direction, there is first, an elastic relaxation of the addendum zone due always to the normal pressure force in the opposite direction, then wear phenomenon can start in the left flank. In the last part of the working process cycle, elastic relaxation takes place again allowing 2 extra minutes revolution on the right flank. Globally, it is observed that wear is faster in wet conditions compared to dry ones as water and detergent play a lubrication role between polyamide gears. After 250000 cycles, results show that a uniformly increasing wear is established before catastrophic failure at approximately 3 million cycles.

4.3. Comparison of CAD and weighting methods

CAD system simulation results are compared to those obtained experimentally by weight measurements using a ± 0.01 g precision electronic balance. However weight measurements have been made on the whole wheel. The volume reduction is determined by subtracting the new weight obtained after testing from the initial weight. Then the lost volume is determined by dividing the obtained weight by the specific weight of the material.

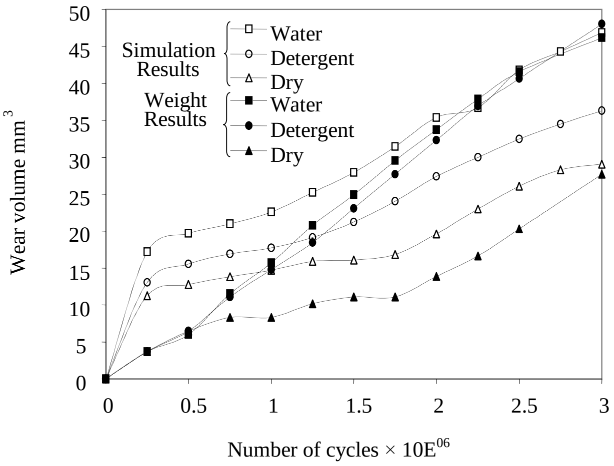

Fig. 7 Comparison between measured and calculated wear volumes

The obtained value should be then divided by the number of teeth, 19, on the wheel and then divided by 2, to determine the wear volume removal on one flank of a tooth. As a consequence a plot of experimental values of wear can be recorded as a function of number of cycles and compared to CAD system simulated curves; Fig. 7. Comparing to simulated results, the running phase is difficult to distinguish in the experimental curves. All the values were below and there is no apparent difference according to the testing environment, until 500000 cycles, when curves obtained in water solutions started to increase rapidly. In dry conditions the trend of the curves was almost the same but all experimental values were 2.5 to 1.5 below as the number of cycles increased. This can be explained by the fact that before each measurement, the tooth should be dry-cleaned and any sticking material generated by wear should be removed. But this is very difficult to ensure because in the early stages of wear, only small amount of material is removed and there is always some debris which could be stuck on the wheel. Therefore despite much care that has been done there are always very tiny ligaments or debris that cannot be removed from the teeth. As a consequence, experimental weights are always over estimated resulting in less reduction in the global teeth volume. After 1.75 million cycles, ligaments and debris become bigger therefore much easier to get rid of and as a result, values approached using microscopic observations and the CAD system are more realistic. However, there is no evident difference in curves obtained in wet solutions by the weight results. In fact, the experimental (weight) data are obtained from the average values on one tooth; dividing these results by two, supposes that wear behaviour is the same on both flanks rather than different as observed under microscope and revealed by the simulated results.

4.4. Wear model

At this stage, it is important to figure out a model for wear evolution which does not call upon finite elements [11, 12]. Based on the right maximum flank wear, the obtained data are statistically fitted to an exponential function. The following equations are obtained:

water: $$W_{wat} = 15.97\, e^{3.7\times10^{-7} Nc}; \quad (1, a)$$

detergent: $$W_{det} = 12.43\, e^{3.7\times10^{-7} Nc}; \quad (1, b)$$

dry: $$W_{dry} = 10.26\, e^{3.4\times10^{-7} Nc}, \quad (1, c)$$

where W is the wear volume (mm^3) and N_C is the number of cycles. Basically, since wear is proportional to the applied load, the proportionality coefficient can be divided by the nominal friction force F = 29.92 N, calculated from the nominal torque, pitch diameter and friction coefficient, according to the relationship:

$$F = \frac{\mu T}{D_p}, \quad (2)$$

with μ is the friction coefficient, T is the torque (N m) and D_p is the pitch diameter, mm. By substitution of Eq. (2) into Eqs. (1, a, b and c), we can rewrite the equations in the following form:

water: $$W_{wat} = 0.534 \frac{\mu T}{D_p} e^{3.7\times10^{-7} Nc}; \quad (3, a)$$

detergent: $$W_{det} = 0.415 \frac{\mu T}{D_p} e^{3.7\times10^{-7} Nc}; \quad (3, b)$$

dry: $$W_{dry} = 0.343 \frac{\mu T}{D_p} e^{3.4\times10^{-7} Nc}. \quad (3, c)$$

The comparison between the wear volume and the maximum wear depth for the three cases allows us to determine the geometrical relationship as:

$$W = 0.3\, w_r\, b\, \frac{D_0 - D_r}{2}, \quad (4)$$

where W is the wear volume per tooth, w_r is the maximum wear depth for the same tooth, b is the tooth thickness, and D_r and D_0 are respectively root and outer diameters. Combining Eqs. (2, a, b and c) with Eq. 3, an explicit wear model is proposed based on the maximum flank wear per tooth:

water: $$w_{r,wat} = 3.56 \frac{\mu T}{D_p b \left(D_0 - D_r\right)} e^{3.7\times10^{-7} Nc}; \quad (5.a)$$

detergent: $$w_{r,det} = 2.77 \frac{\mu T}{D_p b \left(D_0 - D_r\right)} e^{3.7\times10^{-7} Nc}; \quad (5.b)$$

dry: $$w_{r,dry} = 2.29 \frac{\mu T}{D_p b \left(D_0 - D_r\right)} e^{3.4\times10^{-7} Nc}. \quad (5.c)$$

This wear model allows us to compute the wear depth as a function of the pinion geometry, applied torque, friction coefficient and number of applied cycles. Such model, valid only the PA gears tested in our conditions, is very useful for the estimation of the lifetime of such parts under service conditions. It opens the way to carry out reliability studies using wear as a limit function for lifetime and to learn about importance of involved variables.

5. Conclusion

The proposed CAD-based wear measurement is a more accurate method to assess wear on the flanks of wheel teeth in this case. It is important to note that wear is difficult to apprehend when using industrial machines and that is why indirect methods are usually preferred. Apart that, much care should be taken when using CAD systems in order to obtain significant measurements. The wear results are more approaching the reality than those obtained by weight measurement. Fitting curves on the wear behaviour allowed also determining a mathematical model to be used in the estimation of the lifetime assessment and optimization.

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ĮVAIRIOMIS SĄLYGOMIS DIRBANČIO POLIAMIDINIO KRUMPLIARAČIO ANALITINIS MODELIS, PAREMTAS CAD MATAVIMAIS

R e z i u m ė

Ši studija skirta poliamidinio krumpliaračio dilimui nustatyti matuojant nuo krumplių šoninių paviršių nudilusios medžiagos tūrį eilinės profilaktikos metu. Matavimai atliekami mikroskopu ir kompiuterinio projektavimo CAD įranga. Pirmiausia rastrinis krumplio vaizdas registruojamas optiniu mikroskopu mikrokompiuteryje, paskui naudojama skaitmeninė programinė įranga naujiems krumplio kontūrams sudaryti ir galiausiai kiekvieno danties šoninio paviršiaus profilis nustatomas naudojant CAD programinės įrangos splaino funkciją dilimo raidai tirti. Rezultatai rodo, kad pasiūlytoji CAD technika teikia atkuriamą ir pakankamai tikslią informaciją apie dilimą, palyginti su tradiciniu svorio praradimo vertinimo metodu. Dilimo analizė atliekama dilimo morfologijos terminais abiejuose krumplio šoniniuose paviršiuose kaip ciklų skaičiaus funkcija. Parametrinis modelis, apimantis sukimo momentą, krumpliaračio geometriją ir trinties koeficientą, yra nustatytas esant įvairioms darbo sąlygoms – kai naudojamas vanduo, kai naudojamos tepimo priemonės ir esant sausai aplinkai.

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AN ANALYTICAL WEAR MODEL BASED ON CAD MEASUREMENTS IN POLYAMIDE PINION UNDER DIFFERENT WORKING ENVIRONMENTS

S u m m a r y

This study proposes a method to assess wear in polyamide gears by measuring the volume of worn material from teeth flanks of a pinion under actual service conditions. Measurements are conducted using a microscope combined with a computer aided design “CAD” technique. First, a raster image of a tooth is recorded through an optical microscope linked to a microcomputer; then, digitalisation software is used to sort out the tooth new boundaries and finally, each tooth flank profile is obtained using spline function of the CAD software and wear evolution is deduced. Results show that the proposed CAD technique gives reproducible and sufficiently precise wear data compared to conventional weight loss approaches. Wear analyses are achieved in terms of wear morphology on both flanks as a function of number of cycles. A parametric model involving torque, pinion geometry and friction coefficient is deduced for water, detergent and dry environments.

Key words: polyamide, gears, flank, wear, CAD system, analytical wear model.

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