An Investigation of Misalignment Effects on the Performance of Acetal Gears

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Abstract

This paper concentrates on the effects of misalignment on meshing behaviour of acetal gears as hardly any misalignment investigations on polymer gears in the existing literatures. The experimental results show that the wear of acetal gears is insensitive to radial and axial misalignments but sensitive to yaw and pitch misalignments which degrade the conjugate contact action. Yaw misalignment leads to 'scoop' wear marks near tooth pitch points. Pitch misalignment causes 'superimposed palisade' wear marks and micro cracks near tooth roots. Compared with metal gears, the effects of small pitch angle on acetal gears are insignificant which may be linked closely to polymer's low elastic modulus. Strikingly different wear striations and various debris morphologies are observed by using scanning electronic and optical microscope (SEM, OM) and misalignment effects can be noted.

Keywords: Acetal spur gear; Misalignment; Wear debris morphology; Micro cracks

1. Introduction

The increasing use of polymer and polymer composite gears in transmission system such as acetal, polycarbonate, PEEK, and carbon/glass fibre reinforced PEEK gears is driving manufacturing industry into a new energy-saving era. Great efforts have been made to investigate and understand the wear mechanisms of polymer and polymer composite gears in the past 40 years such as design standard [1-5], sources of heat generation [6], varying temperature effect [7-12] and effect of sliding-rolling contact [13-19] and so on.

However, almost no literature has been found on the subject of polymer gear tooth contact under misaligned condition although in depth research has been conducted on metal gears. Houser et al [20] listed major sources of misalignment, defined three categories of misalignment for metal helical gears and presented some possible methods such as lead crowning and end relief to reduce the detrimental effects of misalignment; Li [21-23] developed a finite element method (FEM) to investigate the effects of shaft misalignment. It is found that misalignment on the plane of action exerts significant effect on contact stress (CS) and tooth root bending stress (TRBS) while misalignment on the vertical plane of action exerts minimal effect. Prabhakaran et al [24] calculated and modelled the variations of the bending stress (BS) and CS of a spur gear pair which are exerted by misalignment on the plane of action. Lias et al [25] attempted to use FEM to analyse theoretical forces that create stresses due to misalignment in a spur gear pair. It is found that the CS is proportional with the misalignment deviation and its concentration is higher in tooth contact region and root as an increase in misalignment angle. Ameen [26] used distributed point loads to describe the non-uniformity in load distribution under misalignment and found an increase in angular misalignment results in an increase in maximum BS and stress concentration (SC) on the edge of tooth. Driot and Liaudet [27] modelled the dynamic behaviour of a spur gear pair due to shaft misalignments. Velex and Maatar [28] introduced a comprehensive mathematical model. Saxena et al [29] calculated the mesh stiffness of a spur gear pair subject to yaw misalignment using potential energy method considering the effect of friction force. Jones [30] investigate the static effects of misalignments through using FEM on the LSR and reaction force under contact to approximate contact in dynamic model. A similar method with computer aid was applied by Simon [31-33]. It is found that the misalignments degenerate conjugate action and result in an increase of CS, BS and transmission error (TE).

In practice, the occurrence of misalignment is inevitable for meshing gear pairs due to the elastic deformation, manufacture error, assembling of gears and shafts and so on [20]. Currently solely the field of transmission errors of plastic gears is found to be investigated by Tsai et al [34] and Meuleman et al [35]. However they are not directly linked to misalignment. Polymer has an elasticity modulus approximately 100 times less than metal, and a lower thermal conductivity and softening/melting temperature. As a consequence, it is more flexible than its metallic counterparts. No publications are available highlighting the particular issue of the misalignment effect on non-metallic gears, therefore it is essential to investigate into the effect of misalignment on polymer gears.

Vibration monitor, oil debris analysis and oil temperature analysis are three major sources of information to monitor the metal geared system [30]. Analysis of wear particle morphology can aid to understand wear mechanism, tribology system diagnosis and fault diagnosis [36-38]. Compared with metal gears, the wear particle can be detected and obtained straight due to no need of lubricant for most polymer gears. The wear debris morphology of polymer gears is associated with wear mechanism and operating condition such as rubbing, scratching, CS, local contact temperature and mesh misalignment. Varieties in morphology of polymer wear debris and their effects have not received enough attention [14-16].

A novel design of polymer gear test rig has been developed to investigate the effects of gear misalignment, however detailed research was not conducted [39]. This paper describes the operation of the test rig to continuously measure the wear behaviour of the misaligned polymer gear pairs. To demonstrate clearly the interaction between the wear and misalignment, extensive experiments with great misalignments are conducted. The preliminary aligned and misaligned experimental results include wear rate, load distribution, noticeable various morphologies of wear debris and SEM micrographs of worn tooth surfaces. Some possible causal wear mechanisms, and general conclusions are presented in this paper.

2. Experiment

2.1 Misalignment

A gear pair mesh alignment is the ideal condition. There are four main categories of misalignment for gear engagement in imperfect condition shown in Fig.1 [30]:

- Axial misalignment (AM)- (Fig.1(a))
- Radial misalignment (RM)- (Fig.1(b))
- Pitch misalignment (PM) - (Fig.1(c))
- Yaw misalignment (YM) - (Fig.1(d))

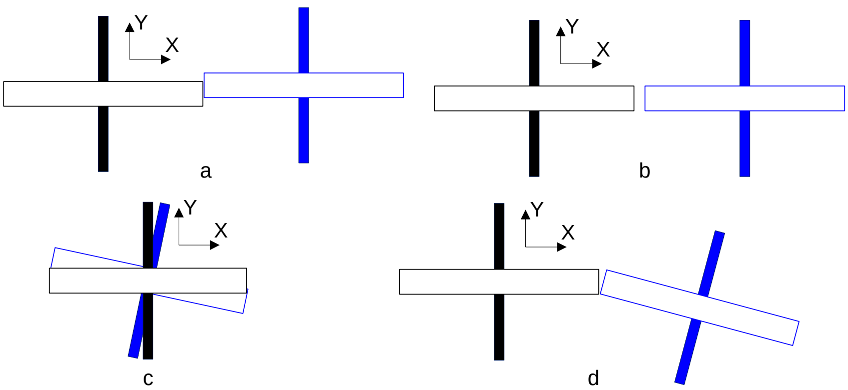


Fig.1 Schematic of a gear pair mesh misalignment [39]:
(a) Axial misalignment, (b) Radial misalignment, (c) Pitch misalignment, (d) Yaw misalignment

Apart from the AM (reduction in tooth mating length along tooth face width) and RM (variations in centre distance), the PM and YM (angular misalignment on the plane of action) tend to cause an uneven load distribution [25, 29] and the wear rate rise sharply. The causes of gear mesh misalignment may be due to many factors, e.g. bearing and housing deflections, shaft bending or torsional deflections, gear blank deflections and assembly errors [20].

2.2 Experimental method

A unique gear test rig shown in Fig.2, was designed and manufactured at the University of Warwick with a capacity to continuously measure the gear surface wear, and also conduct the test in both alignment and misalignment modes. The assembly photos of gear test rig and its wear mechanism are presented in detail in [39]. To continuously measure and record the wear in real-time, an exclusive data-logging system was designed and made, consisting of a displacement measurement device and a data-logging software. The non-contact displacement measurement device was designed by applying the principle that output voltage of Hall Effect sensor varies in response to an applied magnetic field. The transducer is able to move in three dimensions according to the experimental requirement. The gear wear is indirectly measured through the rotation of the pivot block. The details of wear definition and wear measurement method are explained in [8, 39].

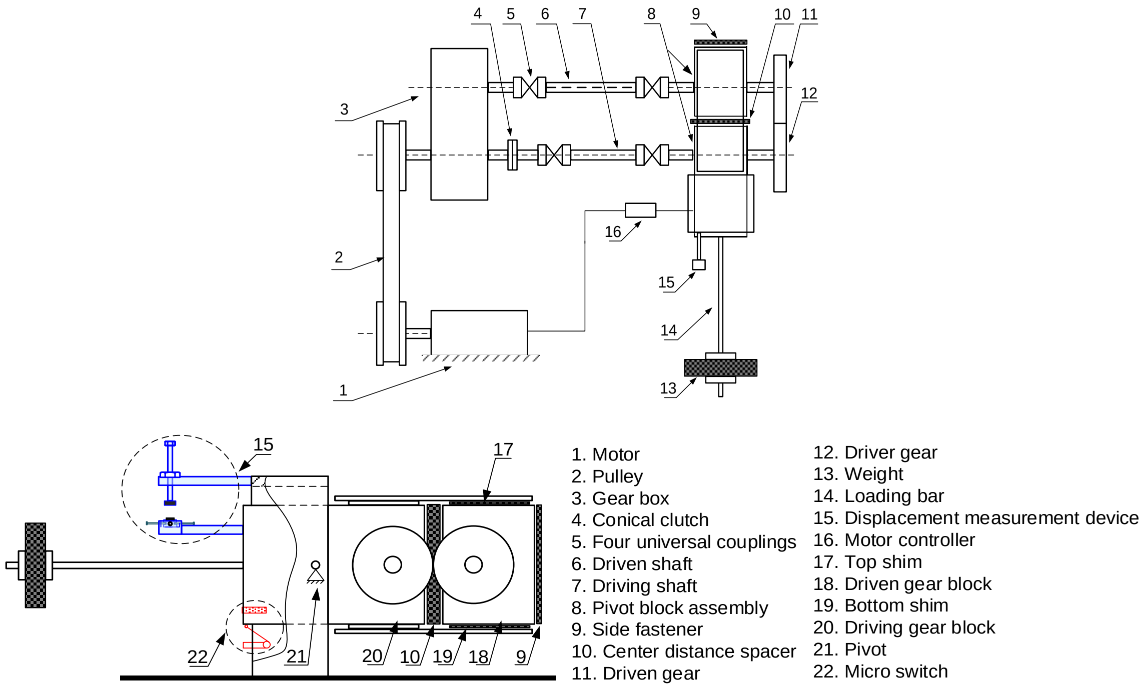


Fig.2 Schematic diagram of polymer gear test rig

Tab.1 Experimental specifications

Parameters	Value
Gear material	Acetal
Gear category	Spur gear
Module(mm)	2
Pressure angle (º)	20
Tooth number	30
Pitch circle radius r_p (mm)	30
Tooth thickness at r_p (mm)	3.14
Face width (mm)	15
Center distance (mm)	60
Contact ratio	1.67
Elasticity modulus at 23°C (MPa)	2200
Melting point (°C)	165
Rotation speed (rpm)	1000
Torque (Nm)	7.2

Throughout this paper, acetal spur gears with no addendum modification defined in Tab.1 were used. All the test data presented in this paper are obtained from machine cut acetal gear pairs running at a speed of 1000 rpm and a torque of 7.2 Nm.

3. Experimental results and discussions

The wear phenomena of a nominally properly aligned gear pair is described in Section 3.1, and the results compared with those of misalignment tests outlined in Sections 3.2 to 3.5.

3.1 Perfect alignment test

In the alignment test, two regimes of debris shown in Fig.3 were observed by using an OM. Powdery debris dominated through all the test and granular-like debris emerged around the transitional wear phase. There were no wood-shavings-like wear debris and large snowflake-like wear debris mentioned in tests of AM and PM, although the load was increased to 12NM. SEM examinations of the driving and driven teeth shown in Fig.4 (a) demonstrate markedly different wear features on the worn surfaces. A 'groove' forms at the pitch line on the driving tooth and a 'ridge' on the driven tooth. Many wear striations-ploughing-are observed on the wear surface of the dedendum area than that of the addendum on the driving tooth, and vice versa for the driven tooth.

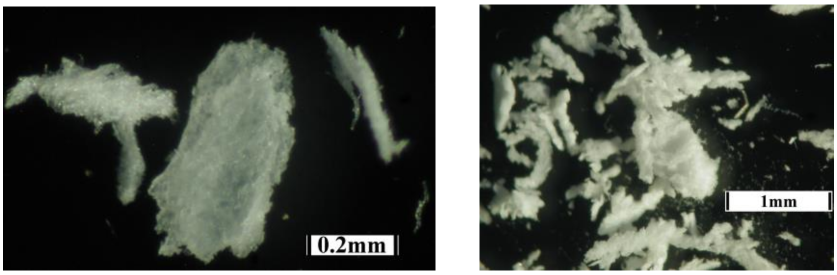
3.2. Test results on axial misalignment and discussions

AM test results presented in Fig.5 (a) indicate three main wear phases: initial (wear-in), transitional and steady wear phases, having very similar wear curves. Wear rate discussed in the following paragraphs is achieved through averaging the total wear by its corresponding operating revolutions. The wear rate calculated prior to steady wear phase is defined as initial wear rate and the one within steady phase is referred as linear wear rate. Taking the results of alignment (see Fig.5 (a)) as an example, the expression of initial wear rate is $(Y_a\text{-}Y_o)/(X_a\text{-}X_o)$ and the linear one is $(Y_b\text{-}Y_a)/(X_b\text{-}X_a)$.

In contrast to alignment test, the initial wear of AM is sharper and wear loss is heavier. The initial wear loss increases as axial gap widens. Fig.5 (b) shows that the wear rate tends to increase as axial gap increases. It is noted that the initial wear rate is directly proportional to the axial gap and the linear wear rate appears slightly less linear to the axial gap.

In addition to powdery wear debris, handful of long strip-like wear debris shown in Fig.6 appeared in these tests. The strip-like wear debris resembles wood shavings and small flake-like wear debris is like thin slice of snow. Noticeable load distribution shift could be seen from SEM micrographs of worn tooth surfaces shown in Fig.4 (b). Obvious characteristics are that the worn tooth surfaces are much rougher (coarse furrows) and more debris distributes on them. Compared with alignment (Fig.4 (a)) considerably more debris evenly scatters over the dedendum of the driving teeth and over the addendum of the driven.

With regard to the disproportional relationship of linear wear rate and axial gap, one possible reason is the test measurement and data calculation error; one might be due to a disproportionally accumulative gear bulk and flash temperature during the long term operation, another maybe an increase in surface roughness owing to the trapped debris and consequently it further affects the wear as stated in [14-16]. Fig.4 (b) demonstrates that AM leads to edge loading, resulting in a contact area reduction, subsequently contact pressure increase. The unworn edge tends to prevent debris escaping from uncontacted tooth ends. The increase in debris size might be caused by a high volume of powdery debris trapped on tooth contact surfaces and be recirculated many cycles, finally the powdery debris is compacted into large piece. It In turn makes contact surfaces rougher.



(a) Powdery debris (b) Granular debris

Fig.3 OM micrographs of debris morphologies from alignment test

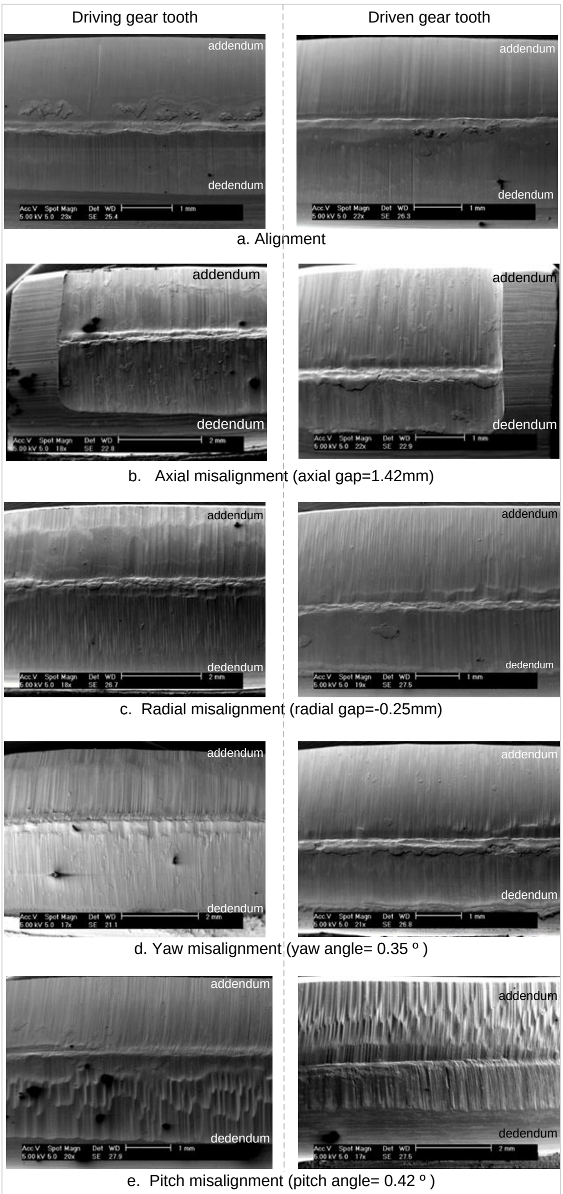


Fig.4 SEM micrographs of gears mesh alignment and misalignment

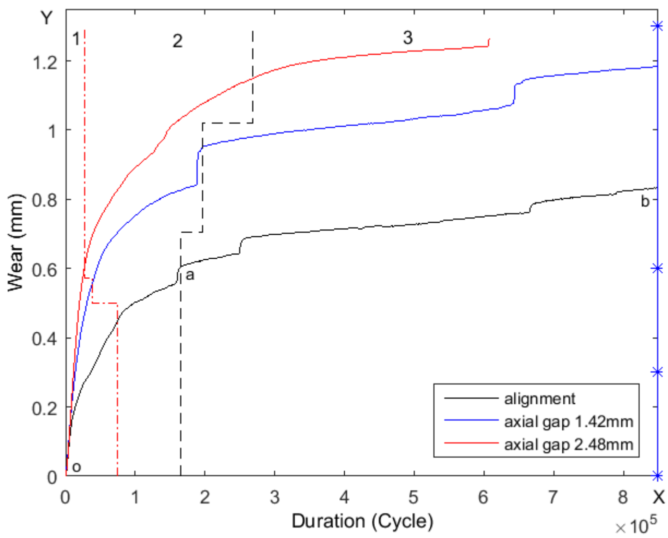


Fig.5 (a) Wear curve of axial misalignment: 1-initial (wear-in) phase, 2-transitioal wear phase, 3-steady wear phase (remove)

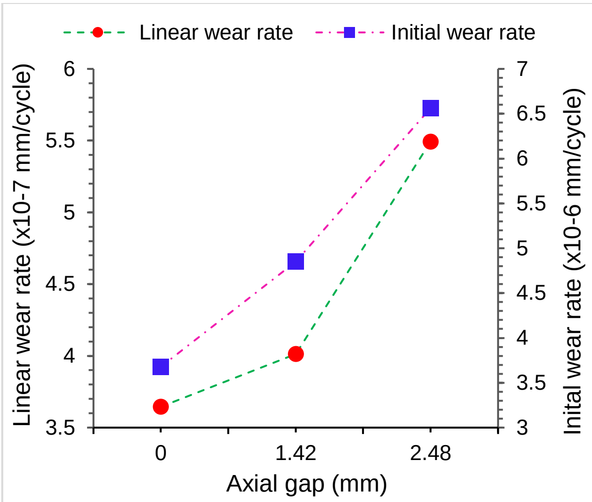


Fig.5 (b) Wear rate against axial gap

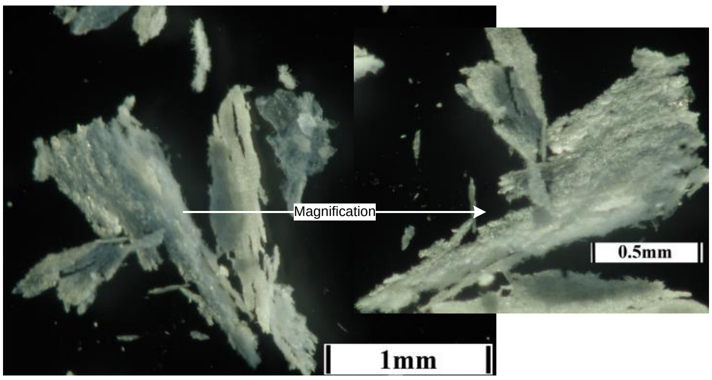
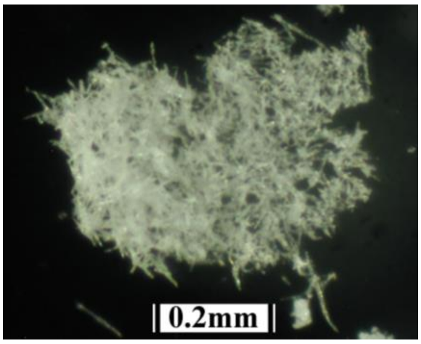


Fig.6 (a) Wood shavings-like wear debris



(b) Small round flake-like wear debris

Fig.6 OM micrographs of wear debris from axial gap =1.42 mm test

3.3. Test results on radial misalignment and discussions

RM has two cases that actual centre distance (CD) is less than and greater than the nominal CD. The RM test results are shown in Fig.7.The wear curve (d=+0.45mm) shown in Fig.7(a) is parallel to that of alignment, and its initial wear rate is close to that of alignment but linear wear rate is slightly lower than that of alignment as shown in Fig.7(b). The RM wear curves (d=-0.25 and -0.3 mm) shown in Fig.7(a) are steep in initial phase, and their initial wear rates shown in Fig.7(b) are over twelve times that alignment. However their linear wear rates are not greater than that of alignment.

As with alignment test, almost no visible differences of debris morphology was found when actual CD increases (d=+0.45 mm). However when actual CD diminishes, a strikingly different debris regime was observed. Long strip-like debris shown in Fig.8 (a) dropped instantly once initiated and needle-like debris shown in Fig.8 (b) generated in steady phase. SEM micrographs of worn tooth surfaces are shown in Fig.4(c).

A slight increase in CD almost does not greatly impact acetal gears' performance, but a reduction in CD does affect significantly. The former introducing backlash could allow thermal expansion and moves load forwards tooth tip. The later results in an increase in the gear profile contact ratio, which could be proved by Fig.4(c). It is interesting to note that the worn tooth surfaces (Fig.4(c)) are as rough (wear striations) as those subject to AM (Fig.4 (b)), but without much debris. As with alignment and AM, it seems that substantial wear occurs over driving tooth tip. The long strip-like debris and needle-like debris reveal that the material is possibly torn from the wear surfaces. This may be due to the interference fit of teeth, where the material is scratched once relative motion occurs between contacting teeth. Hence the amount of backlash should be considered in polymer gearing application.

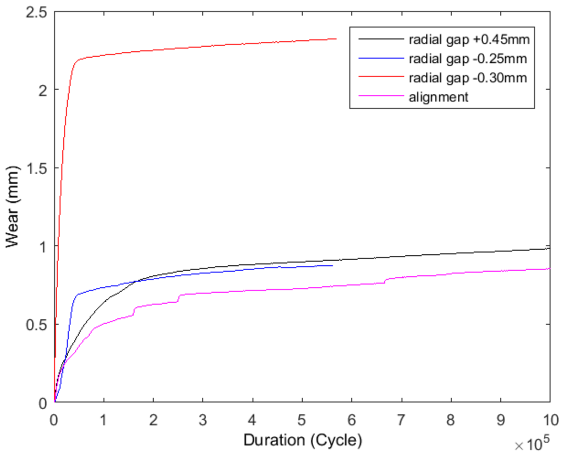


Fig.7 (a) Wear curve of radial misalignment

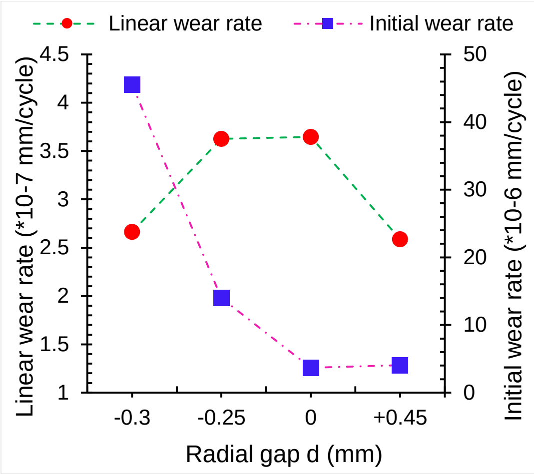


Fig.7 (b) Wear rate against radial gap *d*

Note: CD is nominal centre distance 60 mm, CD' is the actual centre distance, d presents radial gap, thus CD'=CD+*d* alignment *d*=0 mm

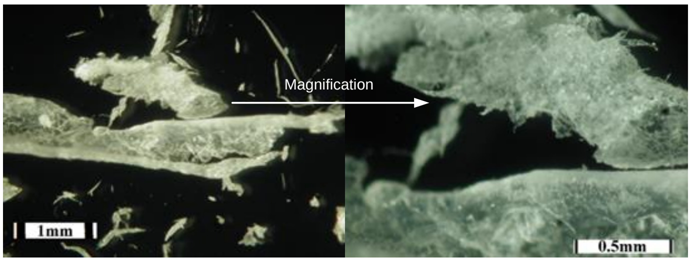


Fig.8 (a) OM micrograph of long strip-like debris - radial gap d= -0.3mm

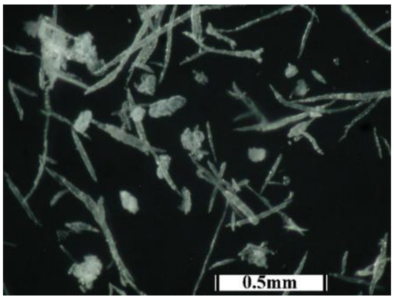


Fig.8 (b) OM micrograph of needle-like debris - radial gap d= -0.3mm

3.4 Test results on yaw misalignment and discussions

Three different sets of acetal gear tests subjected to YM were conducted, at yaw angles α of 0.35°, 0.45° and 1.16° respectively. The YM wear curves and wear rates are plotted in Fig.9. Fig.9 (a) shows that the wear curves with yaw angles of 0.35º and 0.45º are similar to that of alignment except relatively steep wear gradient and high wear loss in initial wear-in phase. Fig.9 (b) shows that wear rates increase as yaw angle increases. Note that when a yaw angle α=1.16°, the wear curve gradient is steep almost no transitional wear phase and linear wear rate is over fifty fold that of the other three.

The wear debris of YM tests is similar to that of RM (d=-0.3mm), spindly needle-like wear debris shown in Fig.10 dropped instantly once initiated and powdery debris dominated in steady wear phase. Striking wear characterises can be seen clearly from SEM micrograph in Fig.4 (d). 'Scoops' wear marks formed closely along the bottom of the driver's pitch point and the top of the driven. Coarse wear furrows can be seen and much wear occurs over addendum of driving gear as RM tests (Fig.4 (c)). Copious debris scatters over driving tooth roots and driven tooth tips, however, not much as AM test (Fig.4 (b)).

Non-conformal contact form subject to YM tends to change from full active (tooth width) line contact to short active line contact. Consequently it leads to wear rate increases as yaw angle increases. The appearance of spindly needle-like debris (Fig.10) is much likely to be caused by cyclic scratches due to imperfect conjugate contact action and short line contact. Perfect gear involute profile does not exist due to YM, which is a possible reason for scoops of material being removed from the surfaces near pitch point.

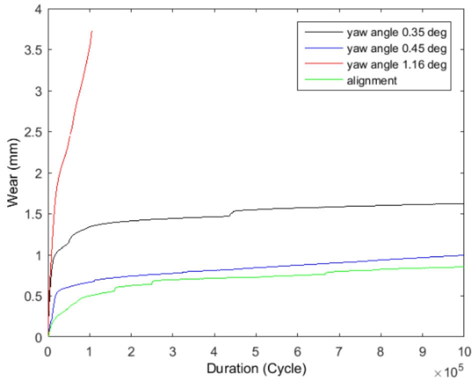


Fig.9 (a) Wear curve of yaw misalignment

Note: the plot of yaw angle α=0.45° does not conform to others due to the testing device and environment variations. However it still shows the wear trend. The wear loss is the sum of driving and driven teeth.

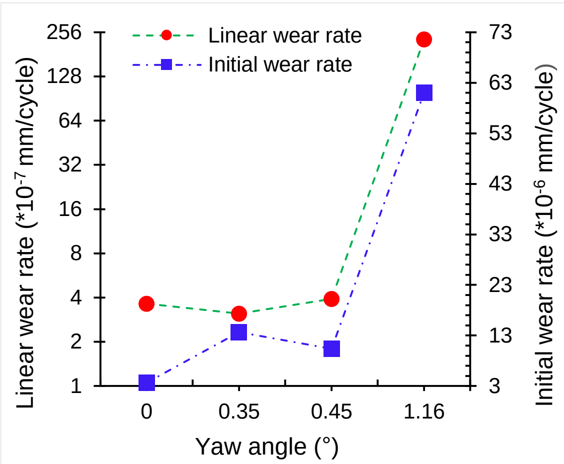


Fig.9 (b) Wear rate against YM angle

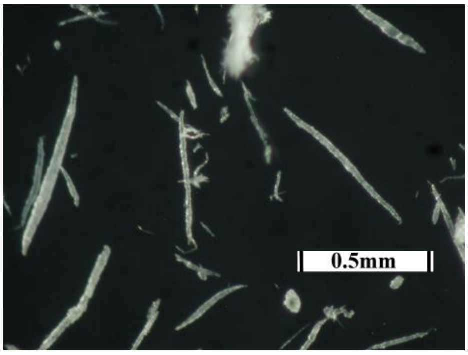


Fig.10 OM micrograph of spindly needle-like debris of 0.35° YM test

3.5 Test results on pitch misalignment and discussions

Three different sets of pitch misalignment (PM) experiment were carried out respectively at pitch angles of β=0.42°, β=0.60° and β=0.86°. PM test results are presented in Fig.11. Fig11 (a) shows that PM wear curves are similar to that of alignment when pitch angle does not exceed a threshold value. A steep wear gradient would be initiated once the pitch angle β reaches a threshold value, such as β=0.86°.Its initial wear loss approaches 1.6 mm per tooth, nearly half of tooth thickness (at pitch point). This will reduce the tooth strength resulting in gears failing prematurely. Wear rates plotted in Fig.11 (b) shows that initial wear rate approaches a linear relationship with PM angle. However, linear wear rate increases as PM angle increases within 0.6°, and possibly decreases as PM angle greater than 0.6°.

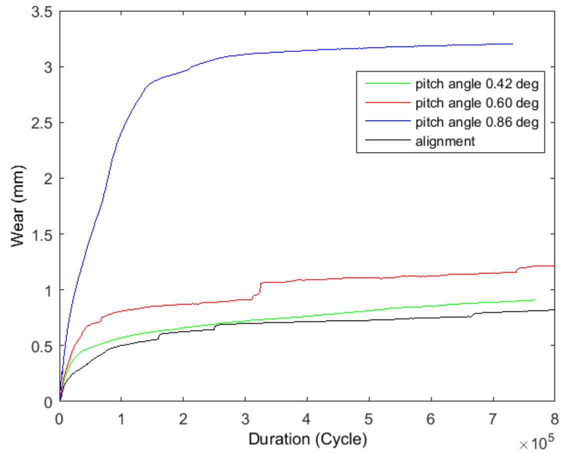


Fig.11 (a) Wear curve of pitch misalignment (pitch angle β)

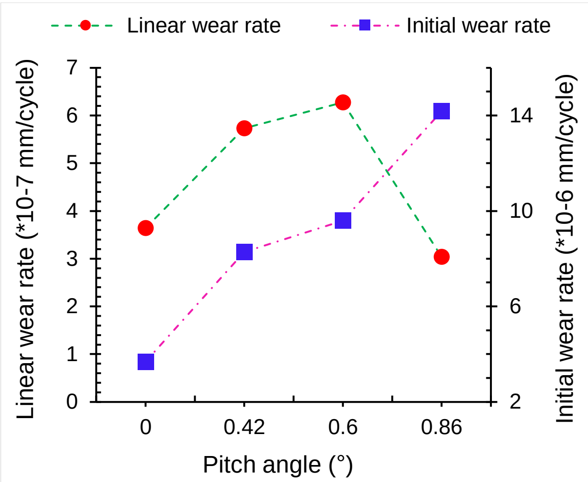
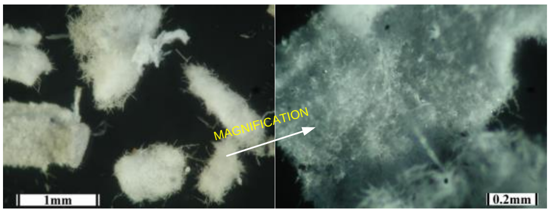


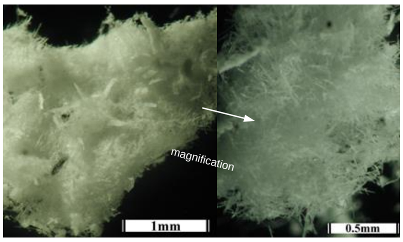
Fig.11 (b) Wear rate against pitch angle

High volume of large snowflake-like were debris was produced prior to steady wear phase. The powdery wear debris took dominant in the steady wear phase as other tests. Fig.12 shows the OM micrographs of snowflake-like wear debris. It reveals that the size of snowflake-like debris increase as PM angle increases. Coarser wear 'ploughing' can be seen from SEM in Fig.4 (e), where a series of 'palisade' wear marks across the dedendum of the driver and addendum of the driven. A visible difference is that 'groove' forms along the pitch line on the driven tooth and a 'ridge' on the driving tooth. Fig.13 shows the pitting over driving root, the intersection of 'superimposed palisade' wear marks and micro cracks on tooth root respectively.

Linear wear rate is less proportional to PM angle. A possible reason might be its contact formation alters greatly from the initial wear-in phase to a steady wear phase. Namely tooth active contact line tends to become short line or even point contact as the pitch angle increases. It results in an increase in local CS and hence the initial wear rate increases greatly. In addition the uniform load distribution changes into parabolic distribution along tooth due to PM. Copious material is removed from contact surfaces and elastic deformation may occur owing to temperature rise. The short line contact gradually develops into long active line contact or even into interfacial contact which subsequently reduces wear in the linear wear phase. In brief, while gear teeth were in mesh, the non-conformal line contact evolved into conformal contact. Fig.11 (a) indicates that when pitch angle is great, such as 0.86°, initial wear loss should be taken into account. Otherwise gear may fail prematurely. The snowflake like debris is found solely in PM tests. From the OM magnification micrograph, it is similar to chunk snow, piling up by copious small flake-like wear debris of AM. The superimposed layers of 'palisade' wear striations tend to trap powdery debris which is recirculated in many revolutions and is squeezed into large snowflake-like wear debris.

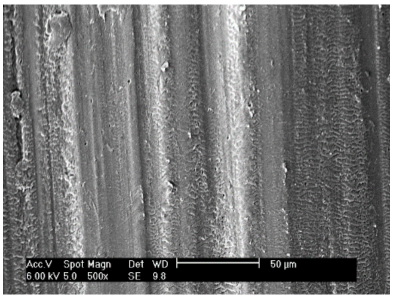


(a) Snowflake like debris (pitch angle 0.42º)

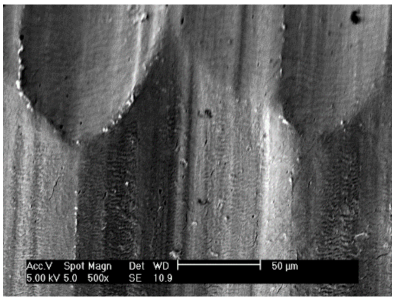


(b) Snowflake like debris (pitch angle 0.86º)

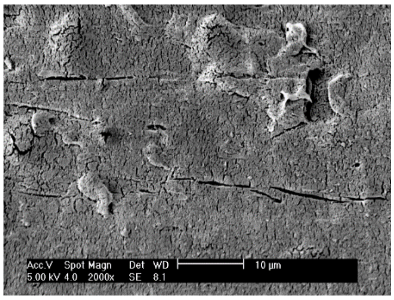
Fig.12 OM micrographs of snowflake like debris from PM tests



(a) Pitting on root of driving gear



(b) Junction of multi-layers palisade



(c) Micro cracks of driving gear tooth root

Fig.13 SEM micrographs of a gear pair with pitch angle 0.42º

It is concluded that of four types of misalignment, pitch misalignment has significant effect on the wear of acetal gears. pitch misalignment has greatly changed the size, shape and position of contact area [30]. A unique wear mark-a superimposed layer of 'palisade' (Fig.4(e)) was noticed, which resembled the wear striation described in [14]. It may contribute to the generation of snowflake-like wear debris. It is very possibly developed in initial wear phase. Micro cracks (Fig.13 (c)) were observed near tooth roots. Further tests are underway to establish its origin.

4. General conclusions

The wear behaviours of machine cut acetal gears subject to radial, axial, yaw and pitch misalignments have been investigated. Detailed experiment results are presented and discussed. A number of conclusions may be drawn from this work.

a) The similar wear behaviours have been observed for acetal gear under both aligned and misaligned engagements.

b) An increase in axial gap, pitch and yaw angles results in an increase in wear rate. Of the four categories of misalignment, acetal gears are most sensitive to pitch misalignment in view of its unique wear marks-superimposed ‘palisade’, micro cracks near tooth roots and steep initial wear gradient. And the second susceptible could be yaw misalignment judging from high initial wear rate, the ‘scoop’ wear marks closely along pitch point and the rough worn tooth surfaces.

c) Strikingly various morphologies of wear debris could have close relationships with misalignment. In addition to powder wear debris, needle-like wear debris appeared in radial and yaw misalignment tests, wood-shavings-like wear debris in axial misalignment tests and large snowflake-like wear debris in pitch misalignment tests.

d) Uneven wear is shown in the SEM micrographs of axial misalignment tests due to edge loading. Superimposed layers of ‘palisade’ wear marks exhibit on pitch misaligned worn tooth surfaces.

e) Acknowledgments

The authors acknowledge Warwick University for test facilities’ support. Also the authors would like to thank SMT (Smart Manufacturing Technology) support for the testing gears.

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