Wear Mechanisms in Polyoxymethylene (POM) Spur Gears

Mike Evans[1)*], Sam Akehurst[1)] and Patrick Keogh[1)]

1) Department of Mechanical Engineering, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom

*Corresponding author: smme20@bath.ac.uk

1. Introduction

The involute gear form is a gear tooth profile that allows constant and smooth power transmission from the driving gear to the driven gear. The involute profile is generated by sweeping an arc from the base circle of the gear out beyond the outer diameter of the gear, which produces the characteristic involute shape. This gear form is often described as being extremely efficient at transmitting power as it involves mainly a rolling contact between the teeth. However, there also exists sliding motion between the teeth. This sliding motion gives rise to a particular contact mechanism between the teeth, and in the case of a steel pinion driving a plastic gear, several distinct wear mechanisms. This paper identifies one of these mechanisms through Scanning Electron Microscopy images and provides a model to predict the quantity of material that is removed from the bulk of the gear by it during continuous operation of the gear pair under load. *Figure 1* illustrates how the sliding between the two faces occurs, the small opposing arrows at the contact interface show the driving gear flanks sliding direction with respect to the driven gear.

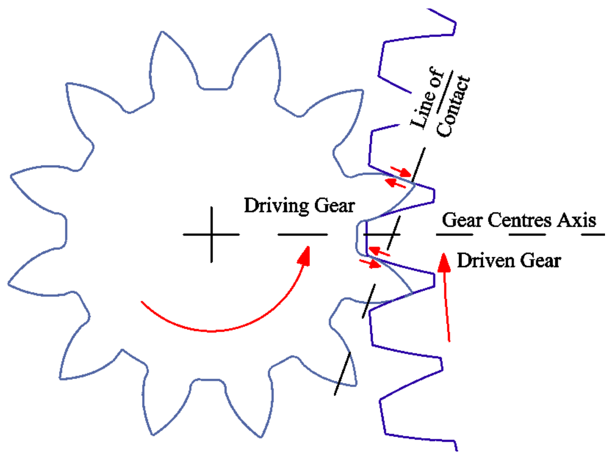

Figure 1: Gear Contact and Sliding

The contact between the two gear teeth can be thought of as analogous to a pair of contacting equivalent cylinders whose diameters vary through the line of contact as described by Hamrock *et al* [1]. The rotational speed of these equivalent cylinders varies through the line of contact and so the slip speed can be calculated as the difference between their speeds thus:

$$\beta = \left[\left((r_b \sin\psi + S) \times 2\pi\right) \times \omega_1\right] - \left[\left((r_a \sin\psi - S) \times 2\pi\right) \times \omega_2\right] \quad (1)$$

where:

- β = Slip speed (mm/s)
- r_a = Pinion radius (mm)
- r_b = Gear radius (mm)
- ψ = Pressure angle (radians)
- ω_1 = Rotational speed of gear (rev/s)
- ω_2 = Rotational speed of pinion (rev/s)
- S = Distance along the line of contact from the gear centre axis

From equation (1) it can be seen that the slip speed β will be positive until the S becomes zero, at which point there will be no slip speed. The slip speed then becomes increasingly negative as the contact point moves away from the gear centre axis along the line of contact.

The contact and wear of a polymer gear has been identified as a complex mixture of material characteristics and contact mechanics. Breeds *et al* [2] have identified that the driving and driven gears are moving in opposing directions and Kukureka *et al* [3] present images of a wear mechanism between the gear teeth that is described as lateral cracking. However, these works were concerned predominantly with wear rates rather than the specific wear mechanism that is operating on a microscopic level. The wear mechanism identified by this research has been observed in Polyoxymethylene (POM - Delrin 100, a type of nylon) gears that have been operated for many cycles in an industrial product. The product was undergoing durability testing, hence the large number of cycles. The wear mechanism has also been replicated in the laboratory by the use of purpose built equipment. The mechanism itself consists of distinct areas of asperities that appear to have been generated by the operation of the gears under load. These areas can be large or small in relation to the tooth flank area, but appear consistently across the flank of the tooth.

2. Observed Smearing Mechanism

Figure 2 shows a POM gear tooth flank that has been in continuous operation for ~ $6\mathrm{x}10^6$ cycles and then has been sectioned, processed and imaged using a Scanning Electron Microscope. As the imbedded footer shows, the image is at 600 times magnification and is tilted at an angle of 40° to show the surface structures more clearly. The direction of slip is from the top right of the image to the bottom left. In the centre of the image several smears are seen as created by the contact conditions as the gears are driven together. They range in size and are approximately 10-40 µm in length and are in the order of 1-3 µm high. The swept forms of the features would appear to be a function of the sliding contact between the gear teeth.

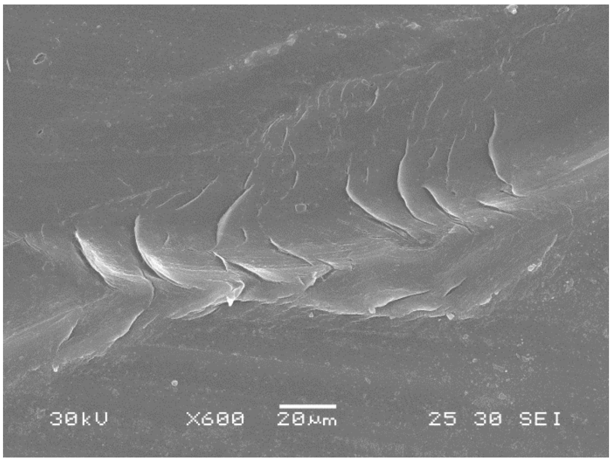

Figure 2: Smearing of Gear Flanks 6x10^{6} Cycles

These smears are evident on all teeth observed from the industrial product that was tested, but in order to determine that they had not been produced by some other effect of the products system (rather than the contact between the teeth) an experiment was devised to attempt to reproduce these features in the laboratory. *Figure 3* shows the experiment arrangement, which consists of a steel pinion running against a POM gear. The pinion is driven by an electric motor and the POM gear reaction load is controlled by an electric magnetic particle brake, which can be seen at the far left of the image. The assembly is mounted in such a way that the reaction to loading is directed though a thin steel beam that is strain gauged and calibrated to measure the torque delivered through the POM gear to the magnetic particle brake. The speed of rotation is also measured accurately by way of an encoder mounted to the rear shaft of the motor. Using this hardware it was possible to run the gears together for a known period of time at an accurately measurable torque and speed.

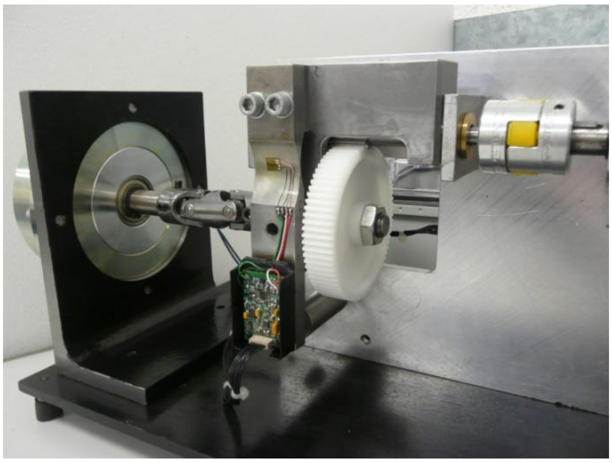

Figure 3: Gear Wear Experiment Hardware

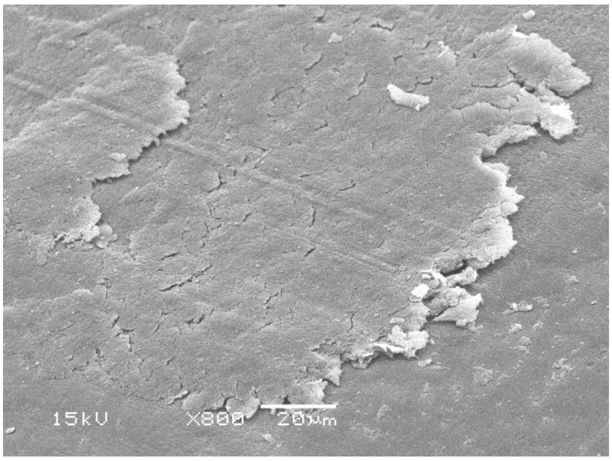

Figure 4: Smearing Created by Experiment

Figure 4 shows a smear feature that was created by this experimentation. The structure of the feature is different from the previous image in that it is approximately 5 times longer and has a rougher leading edge than the 6x10^{6} cycle gear. However, due to the extremely long timescales that the 6x10^{6} cycles gear had endured (1 year), it was necessary to attempt to accelerate the process somewhat. The smear created by experiment was run at around 4 times the pressure seen on the long timescale running gear. However, smearing is seen to be taking place in the gear surface and in addition to this, small pieces of material can be seen in the process of being ejected from the leading edge of the smear. It is proposed that this is indeed the process by which material is worn away from the surface of the gear. The smear is initiated and as the gear runs, this feature is then augmented by the repeated action of the steel gear sliding and rolling over it again and again. After many operations the smear becomes elongated and more pronounced until it reaches the point where the material finally fails and breaks away from the leading edge of the smear, thus removing material.

3. Prediction of Wear Volume

An individual smear can be modelled as a block of material with dimensions corresponding to the smear sizes observed through the SEM images. If this analogous block were to be subject to a cyclic force of the same magnitude as the force applied due to the torque generated by the gear interaction then it would be deformed to a certain degree. If the stress generated in the block exceeds its elastic limit then the block would not return to its original dimensions and given a sufficient number of cycles, then would naturally fail. A mathematical model has been developed that applies this scenario to a block of dimensions 20×40×3 µm (length, width, height) and uses a looping function to iterate until failure has occurred. *Figure 5* shows the output from this model for the single smear block. As the area is diminished by the cyclic loading, the stress increases at each iteration and so the area reduces rapidly to failure. The number of cycles to fail an individual smear is small (~25) in this model. However, the smear must also have been created in the first place and so the actual number of cycles to initiate, grow and ultimately fail the smear will be greater than this.

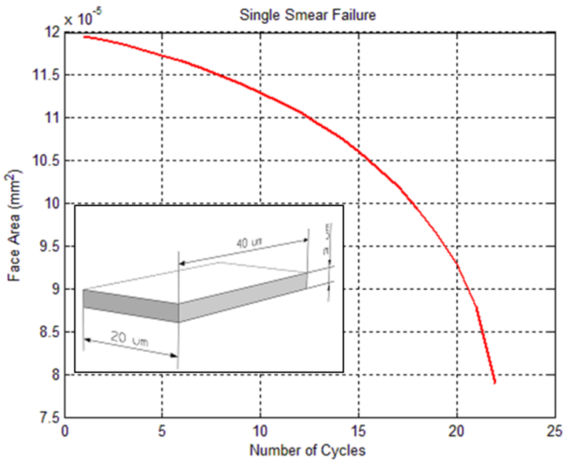

Figure 5: Single Smear Failure Model

There are a number of assumptions made in the model, namely the percentage area of material that is actually in contact and the percentage area that is actually a smear to be failed. Greenwood and Williamson [4] provide a substantial theory on the statistical quantity of asperities in contact at a surface interface and they find that this value is very low in comparison the perceived area of contact.

The product of the variables used in the proposed model is 15% and although this is a much higher figure than determined by Greenwood and Williamson, their work was concerned entirely with hard metallic surfaces and in this case the polymer will deform significantly and plastically under the load to give a far greater real contact area. This value should be validated through further research. For $6x10^6$ cycles, the model returns a total wear mass for the whole gear of 67 mg.

4. Measurement of Wear Volume

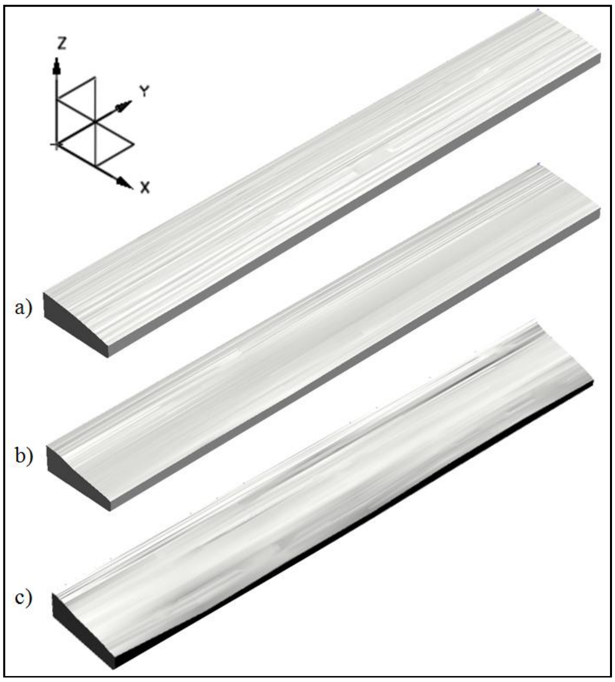

Figure 6: Scanned Gear Teeth

The gear teeth were scanned to find the exact shape and the quantity of material that had been worn away during operation of the $6x10^6$ cycle gears. *Figure 6* shows 3 gear teeth that have been scanned. The process of scanning was first to carefully cut the gear tooth away from the gear wheel and then to use a profile measurement machine to measure the tooth profile as a series of lines along the tooth from front to back. The profile measurement was done along the *x*-axis as depicted in the coordinate system in the figure. These profile data were then used to build a computer model from whence the images in *Figure 6* came. A series of profiles along the *y*-axis were generated at distances matching the measurement planes and were then swept together to form a solid model. The lighting has been manipulated to more clearly show the features on the surface of each of the gear teeth. Tooth a) is from an unused gear tooth, the surface of this scan shows the machining marks from the manufacturing operation running in the *y*-axis direction and it can be seen that the profile is consistent along the *y*-axis. Teeth b) and c) are scans of teeth that have been worn by $6x10^6$ cycles of operation and the worn profile can be seen as markedly different from the unused gear tooth.

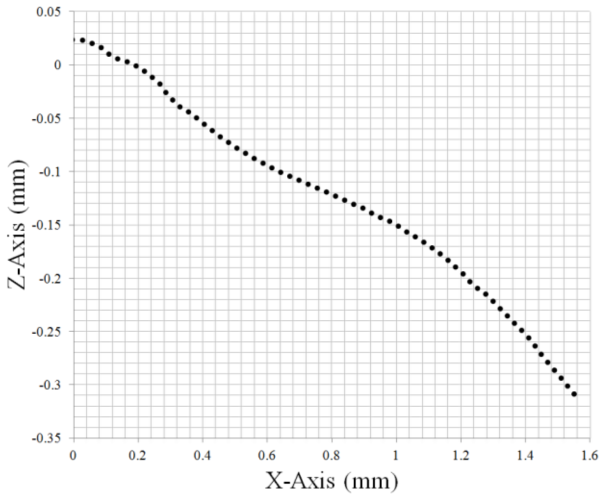

Figure 7: Tooth Profile Measurement Data

Figure 7 shows one set of measurement data taken during the scanning process. A dip in the profile is seen at x = 0.4 mm, this is as the steel tooth is slipping in the positive x direction. The slip speed reduces to zero as the contact point moves through the gear centre axis on the line of contact, which is x = 1.1 mm and then alters direction so slip in the negative x direction to the tip of the tooth at x = 1.6 mm.

The models allow the analysis of the surface of the gear teeth to measure the quantity of material removed by wear. An average of the worn teeth was taken in terms of volume and was then subtracted from the unworn tooth volume and multiplied by the number of gear teeth in the complete gear (75). This figure came to 77 mg of material worn away from the complete gear.

5. Conclusions

A wear mechanism in POM spur gears has been identified by Scanning Electron Microscopy. A simple modeling has been presented which can be used to predict the quantity of material removed by that process of wear, although the premise of the model must be validated. The mass of material removed from the gears during realistic operational conditions has been measured using the technique of profile measurement and the modeled wear mass has shown to be of a similar order as that of the physical measurements taken. The profile measured mass of worn material value was 77 mg, while the modelled value was 67 mg. Although superficially there appears to be a good correlation between the model and experimental results, this is dominated by the constants used to describe the real contact area and number of smears on the gear tooth surface. In the continuation of this research, this value will be confirmed by further experimentation. Further validation of this technique will now be undertaken by repetition of the experimental results and by analysis. In particular, a statistically significant number of measurements of the size and quantity of smears found on the surface of a worn gear should be taken. This will allow a more accurate assumption to be made for the model inputs.

6. References

[1] Hamrock, B. J. *et al*, "Fundamentals of fluid film lubrication". Vol 169. CRC Press, 2004.

[2] Breeds, A.R. *et al*, "Wear behavior of acetal gear pairs", Wear, **166**, 1993, 85-89.

[3] Kukureka, S. N., Y. K. Chen, C. J. Hooke, and P. Liao. "Surface failure mechanisms in polymer gears." Proc. Int. Gearing Conf., London, 1994, 13-18.

[4] Greenwood, J.A. and Williamson J.B.P., "Contact of nominally flat surfaces", Proc. R. Soc. Lond. A 1966 **295**, 300-319.

[5] Bowden, F.P. and Tabor, D., "Friction, lubrication and wear: a survey of work during the last decade", Br. J. Applied Physics **17**, 1966, 1521

[6] Hooke, C.J. *et al*, "The friction and wear of polymers in non-conformal contacts", Wear, **200**, 1996, 83-94.

[7] Mao, K. *et al*, "Friction and wear behavior of acetal and nylon gears", Wear, **267**, 2009, 639-645.