Acoustic Emissions from Polymeric Gears

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This paper presents a study of the role of materials in the generation of noise made by plastic gears. Sound levels were recorded for gears running in various running combinations. Frequency analyses were conducted on all the noise measurements and these showed that the harmonics for plastic gears mainly occur at multiples of the tooth meshing frequency. Materials such as Polyoxymethylene (POM), when run against itself were very noisy, but when run against a dissimilar material or steel they became quiet. Gears made from a polymer composite were the quietest. Measurements of surface roughness showed that the nosiest gears were those that developed high surface roughness when run-in.

Keywords **- Noise, polymer, composites, spur gears, surface roughness**

I. Introduction

The main advantages of plastic over steel gears are their low weight, high resilience and their ability to run under dry, unlubricated conditions. For high volume production the cost of plastic gears is low if manufactured by injection moulding. As more is understood about the behaviour of plastic gears and with advances in plastic materials the demand for these gears continues to grow. While ten years ago, plastic gears were mainly used in office and domestic machines, due to continuous improvements, plastic gears are gradually advancing into power transmission and are able to run at relatively high torque and speeds. With this change from low to high transmissible power levels comes a need to study the noise of plastic gears and, in particular, to investigate the effect of different materials and material combinations.

Noise generation is a major concern in all types of machines. Gear noise can be a particular problem either because of unpleasant audible noise or because of the effect noise has on the operating characteristics of the machine, e.g. noise generated in high precision copying machines leads to inaccuracies in the picture being copied. Gear noise is caused by either changes in load or in the direction of the force or a combination of these. The prime causes of gear noise are inaccuracies caused by manufacture and by the elasticity of the gear system, i.e. tooth stiffness and the elasticity of the shafts, bearings and bearing housings (1). Considering only gear noise, the main causes are out-of-roundness and transmission error due to tooth-to-tooth inaccuracies. These will cause non-conjugate motion resulting in local accelerations, which in turn will induce vibration of the teeth and may also cause gear body vibrations. Unlike steel gears which, when run under normal lubrication and hence experience low friction, the coefficient of friction of unlubricated plastic gears can be very high, as much as 0.8 (2). This leads to high friction forces at the point of mesh and, as the friction force changes direction during the mesh cycle, this is an additional cause of noise in plastic gears. The problem is complicated by the high temperatures caused by the friction and consequent changes in material properties, such as the elastic modulus, which decreases with temperature and hence alters the stiffness of the teeth.

Relatively little has been published on the noise of plastic compared to steel gears although some papers written ostensibly for steel gears (3) are a very useful source. Polyamide (PA) gears running against steel were investigated and noise was measured against running time where considerable wear had occurred on the PA gear (4). Their main conclusion was that noise did not correlate well with wear, with very little change in noise level over time, even when the wear became gross. Also observed was the higher initial noise level when the gears were new. It was also noted that for steel/steel pairs noise levels were higher than plastic/steel pairs, a result that might be expected due to the lower damping capacity of steel/steel pairs.

A study on the effect of noise due to transmission error for PA/PA, POM/POM and steel/steel gears (5) showed that correlation between transmission error and sound pressure level on load are very similar. This was found to be consistent with variations in load. However, the ratio of sound to transmission error varied from one material to the next. More recently, research has focused on matters such as the surface finish of plastic gears, where (6) showed that for POM gears the surface roughness was crucial, with smooth surfaces leading to low intrusive noise levels. Slip modified POM, to give lower friction, resulted in quieter gears. Attention has also been given to gear body vibration and the associated noise that this creates and the effect of the elastic modulus on the frequency of vibration (6), (7).

This paper is concerned with the effect of different polymers on gear noise. The most commonly used plastic gear materials are PA 6.6 and POM, used either in pairs or against one another and noise levels for these materials are reported in this paper. In many applications, plastics are run against steel and measurements were carried out for these combinations. For high power applications these gears are often lubricated with grease and one case for lubricated plastic gears is reported here. Large improvements in transmissible power can be achieved by the use of polymer composites, such as PA with glass or carbon fibre reinforcements. These significantly increase the strength and stiffness and also the permissible operating temperature. Running temperatures can be reduced by the inclusion of an internal lubricant, such as PTFE. Noise levels for a composite material gear pair consisting of glass fibre reinforced PA with an internal PTFE lubricant is also reported.

II. Material and Gear Geometry

In this study the following materials combinations were tested: PA 6.6, POM, PA against POM, steel against POM, and PA composite containing 30% by weight of glass fibre and 15% PTFE. POM was also tested against itself and steel but with grease lubrication instead of running dry.

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Gear design was decided on the basis of compatibility with previous work [8]. The geometry was chosen to be module 2mm, 30 teeth with 20˚ nominal pressure angle and a facewidth of 17mm. All gear teeth forms had an addendum equal to the module and a dedendum equal to 1.5 times the module. Figure 1 shows the gear geometry illustrating the web and flange. All gears were moulded with a steel hub insert to avoid failures at the mounting. This geometry has been tested at The University of Birmingham for a wide range of polymers and polymer composites over a fifteen-year period [9].

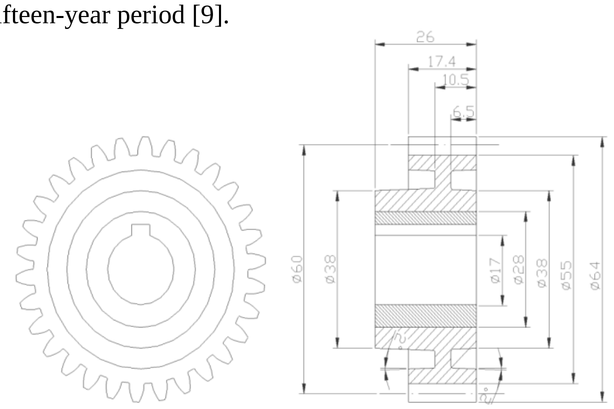

Figure 1 Showing the gear geometry (dimensions in mm)

III. EXPERIMENTATION

Figure 2 (a) shows a schematic diagram of the power re-circulating test rig used for the gear noise experiments. Instead of the more common method of loading test gears where the torque is wound in and the drive shafts locked, in this design the test gears are loaded by a pivoted bearing block (8) containing a load arm (10) with a moveable weight (11) to permit changes in torque. This method of loading is essential for plastic gears whose teeth tend to wear with running time as well as deflect due to the viscoelastic nature of plastics. Speed changes were affected by an inverter controlled electric motor (1) used to drive the master gearbox containing lubricated steel gears (3). The closed loop drive shafts (5, 6) have universal couplings at each end (7) to allow for the rotation of the load block as the gears wear and creep. The test rig is more fully described in [10].

To minimise the noise emitted by the bearings in the loading block and seals, universal couplings, electric motor noise and drive pulley, the test gears were enclosed in a soundproof box, made from wood lined with noise absorbing plastic foam. A similar anechoic chamber was made to surround the whole of the test rig. These chambers are shown in figure 2 (b).

A microphone was placed facing directly at the test gears' meshing pitch point, 50mm away from the gears (items (4) and (5) respectively in figure 2 (a)). The microphone was connected to a laptop computer to collect and analyse the noise using a software package [11]. This package is able to store the basic noise pressure levels and to analyse the signals to give a fast Fourier frequency analysis. Also an infrared thermocouple was placed 5mm away from driver test gear to measure the bulk body temperature (shown as (3) in figure 2 (a)). Noise measurements were taken at various torques and speeds when the bulk temperature had stabilised to a constant value. This would simulate a steady, run-in operating condition. The test gears were loaded to torques of 3, 5, 7 and 10 Nm. At each torque the gears were run at speeds ranging from 500 revs/min up to 2000 revs/min in increments of 500 revs/min.

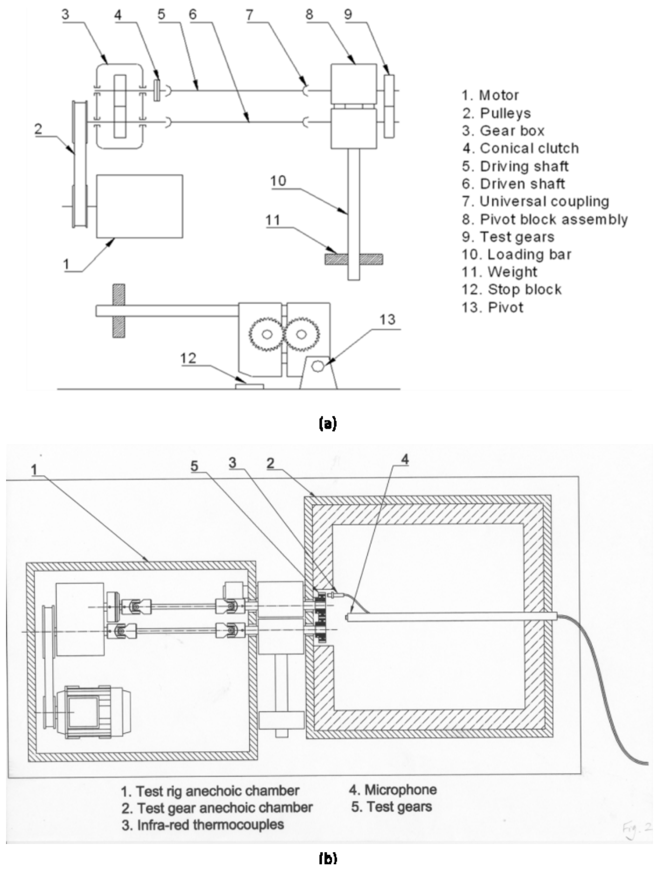

Figure 2 Showing (a) the test rig (b) anechoic chambers

IV. RESULTS AND DISCUSSION

Figure 3 shows noise recordings (sound pressure [SP] in N/m^2) with running time for the PA gear pair. Figure 3 (a) shows recordings at a low torque of 3 Nm for speeds of 500, 1000, 1500 and 2000 revs/min and figure 3 (b) for a torque of 7 Nm. In both figures it can be seen that the noise amplitude increases with speed, probably due to the increase in tooth collisions.

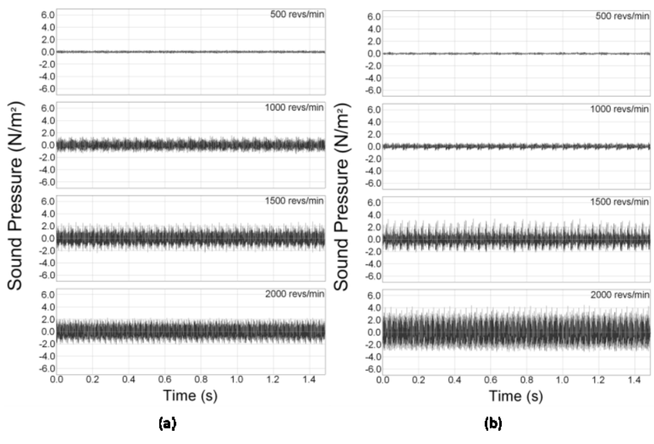

Figure 3 Showing the SP of PA gears carrying (a) 3 Nm and (b) 7 Nm

Generally the noise amplitude decreased with load, a result that may not be expected. There are a number of probable reasons for this. For plastics the coefficient of friction decreases with load, thereby reducing the friction forces acting between the meshing teeth acting to excite the teeth [12]. It has also been observed that due to the high flexibility of plastic gear teeth, the transmission error will change with load [13]. This is a complex phenomenon where the teeth deflect due to a combination of load and temperature, as most plastics are highly temperature sensitive with respect to their modulus of elasticity. Finally, it has been noted that most plastic gears experience a "running-in period" when new where the initial rate of wear is high. As noted by [4] gear noise decreased as the gears wore, and this may explain why at a higher torque where the wear is increased but the noise level is reduced.

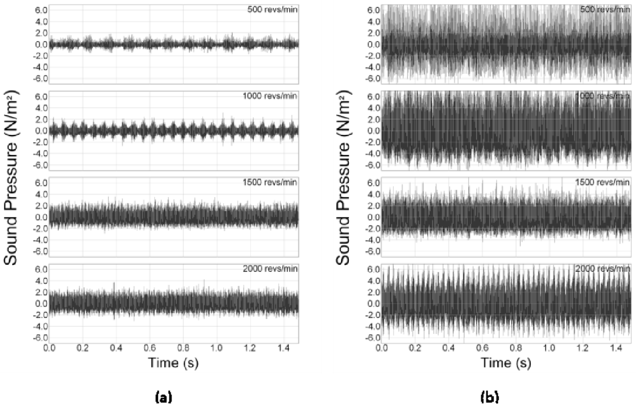

Figure 4 Showing SP of POM gears carrying (a) 3 Nm and (b) 7 Nm

For POM gears SP exhibited very different results compared to PA. Figure 4 (a) shows the recorded noise for POM gears at 3 Nm for speeds of 500, 1000, 1500 and 2000 revs/min. Figure 4 (b) shows the recorded noise at 7 Nm. At the lower torque the noise increased only slightly with speed, but at the higher torque the noise amplitude was very high at low speed. The noise then increased from 500 to 1000 revs/min, then reduced up to 1500 revs/min. At 2000 revs/min the noise began to increase again but was still lower than at 1000 revs/min. POM is known to be "squeaky" [6] due to stick-slip, especially at low speeds where the surfaces have longer to adhere and this might explain why for gears made from POM the noise is high at low speeds.

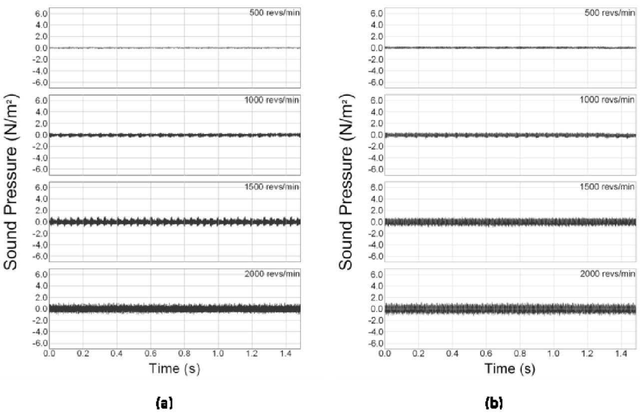

Figure 5 Showing SP of PA comp' gears carrying (a) 3 Nm and (b) 7 Nm

Figure 5 shows the recorded noise levels for gears made from PA composite containing glass fibre reinforcements and internally lubricated by PTFE. It is immediately evident that the signals are much "cleaner" than those for PA and POM and with virtually no change in amplitude for different torques at a given speed. The higher stiffness coupled with lower friction has resulted in the low noise levels.

All the above results are summarised in figure 6, where (a) shows Sound Pressure Level (SPL) in dB against torque for two test speeds. These graphs clearly show the relative noise levels for each of the three materials examined. With the possible exception of POM, the noise levels show little variation with torque. The glass fibre filled PA with PTFE is quieter at all speeds and torques than either PA or POM pairs and the difference in noise levels is significant.

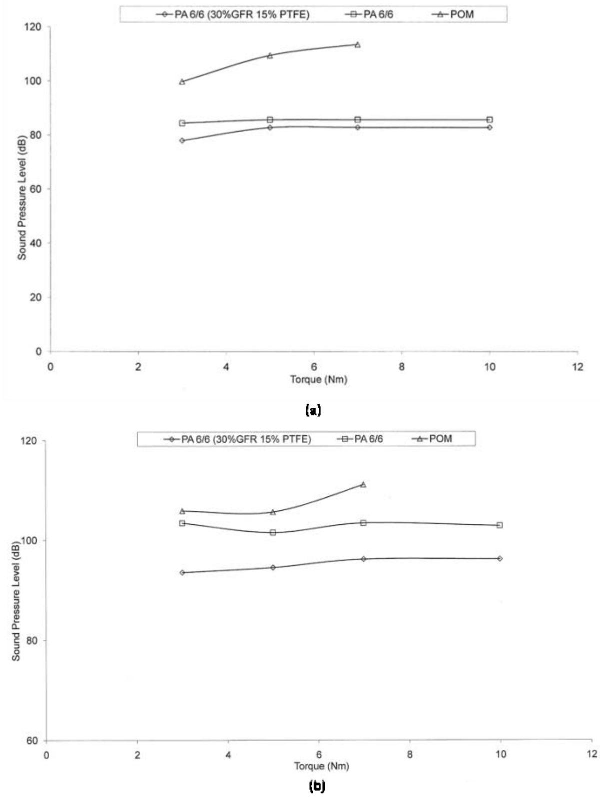

Figure 6 Showing (a) SPL against torque (b) SPL against speed

The results described above can be further processed by Fast Fourier Transform (FFT) techniques to pinpoint sources of excitation. In the analyses, all measurements were made at a torque of 7 Nm. Figure 7 shows a FFT for PA 6.6 where the vertical axis represents the SPL and the horizontal axis the sound frequency. Superimposed on the figure are lines indicating harmonics of meshing frequency, starting from 1fz (the tooth meshing frequency) up to 13 times fz. At 500 revs/min only four harmonics of mesh are observed. As the speed was increased the number of multiples of mesh frequency also increased, but the number of sidebands also increased, particularly around 2500 Hz.

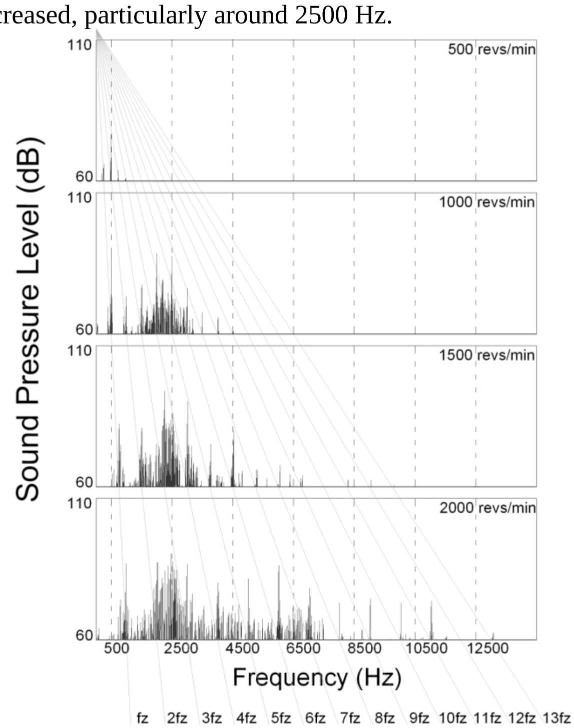

Figure 7 Showing frequency analysis for a PA gear pair

Figure 8 shows the FFT analysis for the POM gears. The analysis reflects the extremely high range of SPL's recorded for these gears as shown in figure 4.

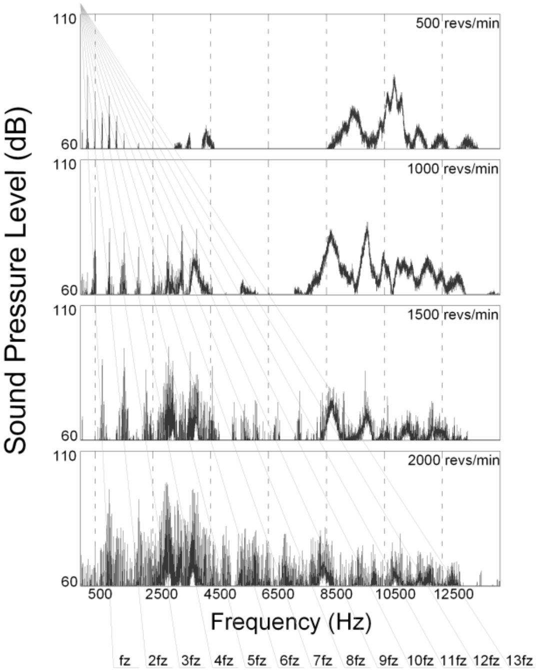

Figure 8 Showing FFT analysis for a POM gear pair

At 500 revs/min the noise appears at meshing frequencies up to around 2000 Hz and then at very high frequencies (8000-12000 Hz) the SPL rises in a wide band without any particular peak. This occurs on a wider band at 1000 revs/min and at speeds above 1000 revs/min this phenomena is less dominant as the SPL is spread over a very wide range of frequencies.

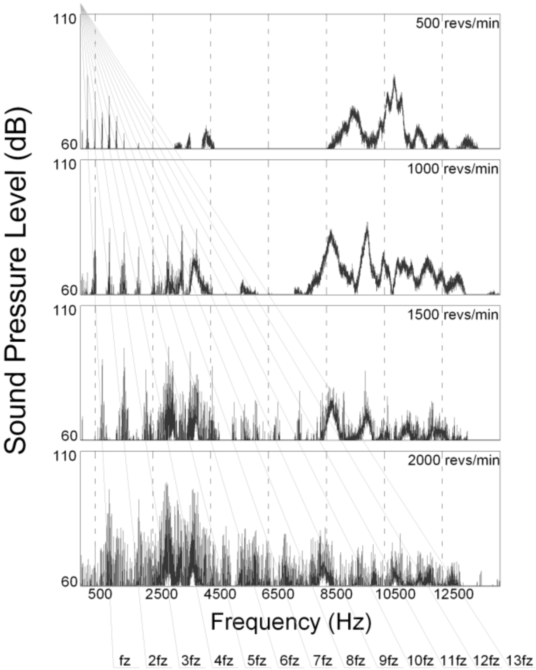

Figure 8 Showing frequency analysis for a POM gear pair

Figure 9 shows the FFT analysis for the glass fibre reinforced and internally lubricated PA composite gears. The analyses show very distinct harmonics at multiples of meshing frequencies with very few sidebands. As far as audible noise was concerned, the composite gears were very quiet compared to both PA and POM.

Tests to investigate the effects of running dissimilar materials began by testing PA against POM, with PA as the driver, figure 10. A comparison with figure 3 shows that a considerable reduction in noise results from running PA against POM and a further comparison of figure 4 shows that much greater reductions in noise are achieved by running POM against PA rather than against itself. Running POM against PA eliminated the high noise frequencies.

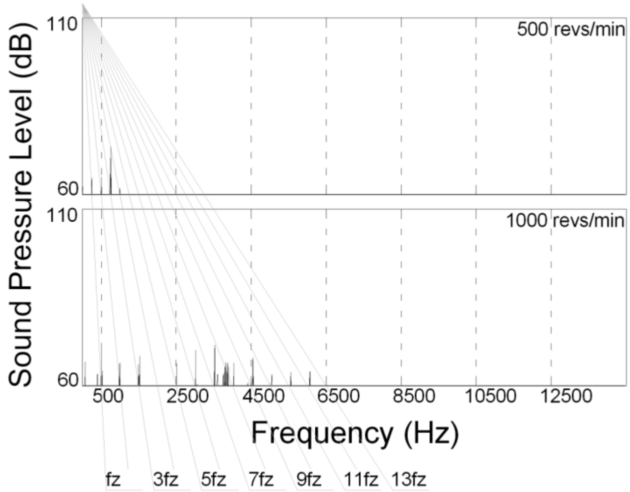

Figure 10 FFT analysis for a PA gear running against a POM gear

Figure 11 (a) shows the FFT analysis for PA running against steel, where the driver was the steel gear. Comparing this figure with the results of the PA/PA pair (figure 3), the amplitude and sidebands are lower for the plastic/steel combination.

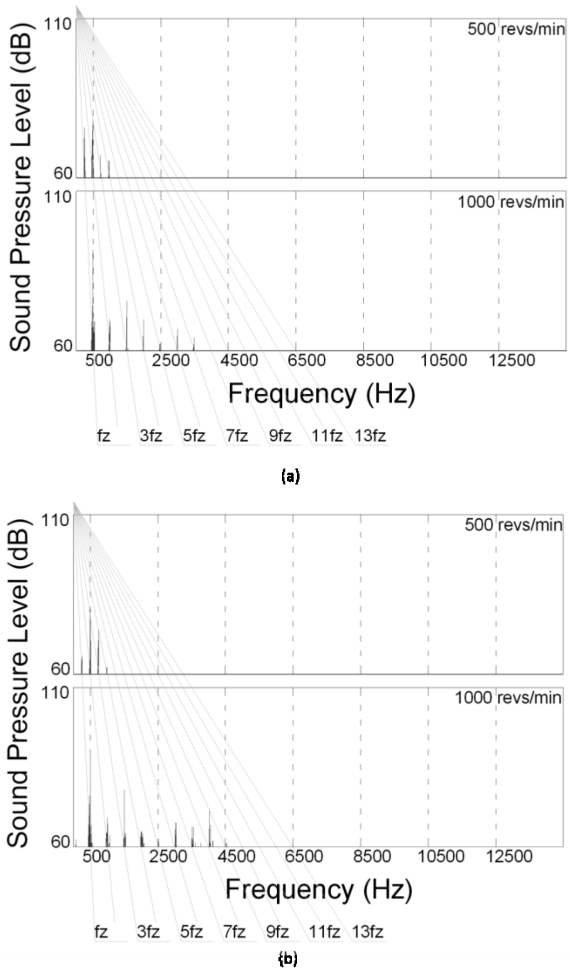

Figure 11 Showing FFT analysis for (a) PA/steel (b) POM/steel gears

Figure 11 (b) shows POM running against steel, where again the plastic/steel combination produces much less noise and considerably fewer harmonics and high frequency sidebands compared to POM running against itself. Both PA and POM against steel show hardly any difference in noise levels and frequency distribution. When the results for PA and POM against steel are compared with PA against POM, the all-plastic combination was slightly quieter than any of the plastic/steel combinations.

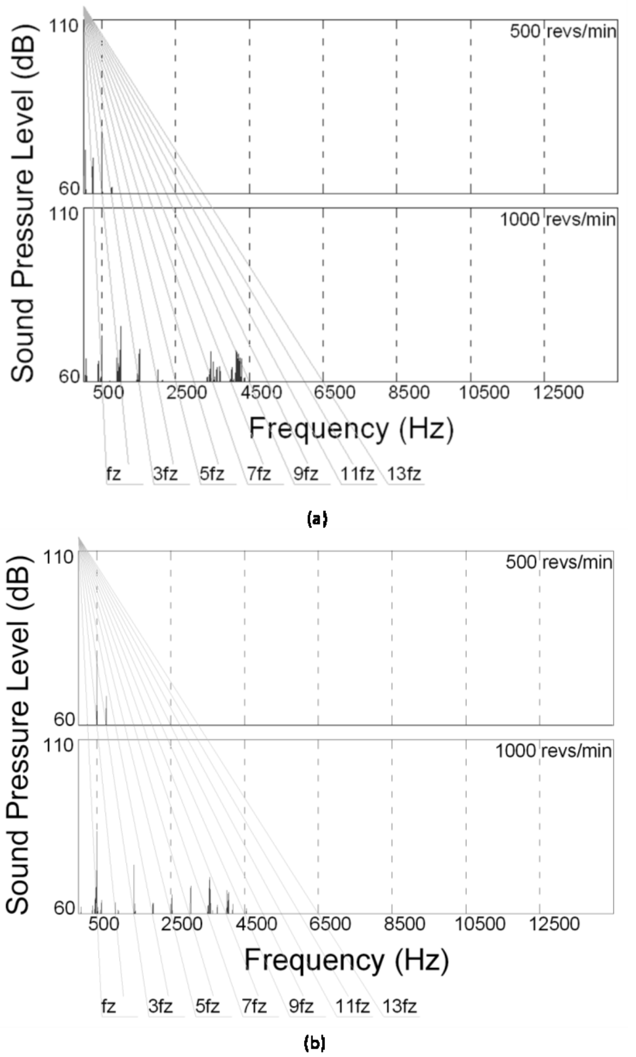

Figure 12 Showing FFT analysis for greased (a) POM (b) POM/steel

Finally, tests were carried out to investigate the effect of a single application of grease to gear noise. Figure 12 (a) shows the FFT for POM/POM pairs grease lubricated at speeds of 500 and 1000 revs/min. Figure 12 (b) shows the FFT for steel/POM gears grease lubricated. The results are similar. Neither of these tests shows significant differences over non-greased steel/POM combinations (figure 11). When figure 12 (a) is compared to figure 4 it can be seen that the lubrication has reduced the noise very considerably. This supports the view that high friction and stick/slip is the prime cause of noise for POM/POM and other gears made from plastics when running against themselves.

Figure 13 (a) shows the surface roughness for the PA, POM and composite gears measured before the gears had run. The roughness was measured on the pitch line, half way along the face width of the gears in each case. The roughness is about the same for all the gears. Figure 13 (b) shows the roughness measured at the same points after running. Here it will be observed that for POM the surface is rough with high peak to trough distances. The RMS roughness, B_a, is the highest of the three materials. PA has the next roughest surface while the composite has low peak to trough undulations and a smooth surface with low B_a.

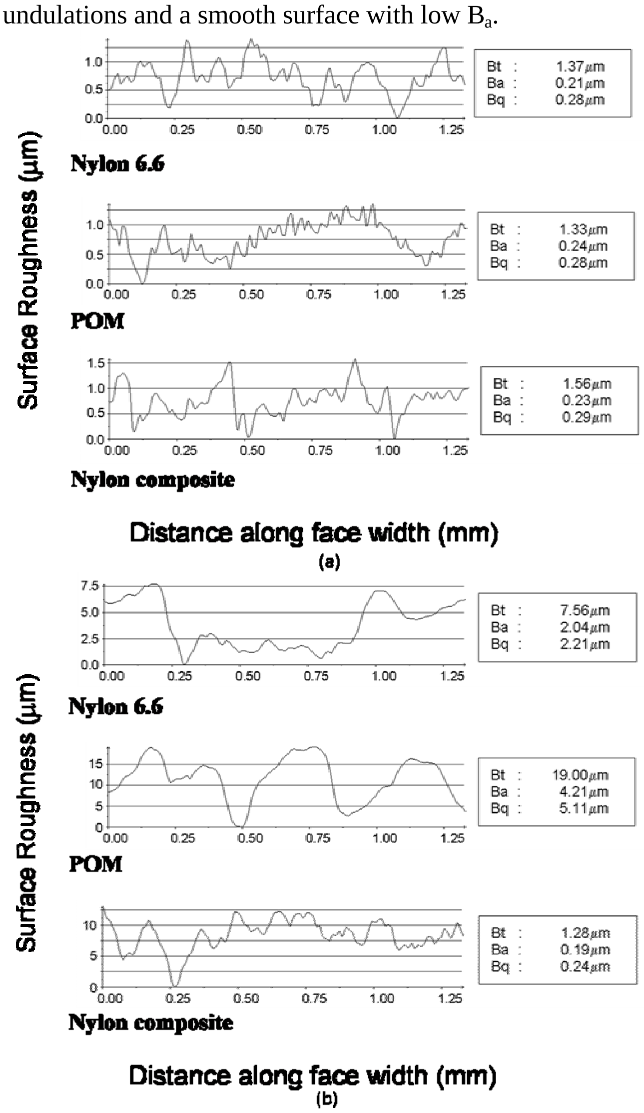

Figure 13 Showing surface roughnesses for (a) PA, POM and the PA comp gears measured before running and (b), after running

POM/POM combinations are known to promote high wear [14] and this is shown by these measurements. The wear is adhesive but the process is not stable and large powdery particles fall away from the surface and the wear is continuous. The roughness promotes high friction and as a consequence, high noise. The composite gears experienced some wear, which is a mixture of adhesive and abrasive wear (caused by the exposed glass fibres on the gear flank) but the surfaces are effectively polished and friction is low and so too is the noise. The bulk body temperature of the composite gear was noticeably lower than either the PA or POM gears. Figure 14 (a) shows the roughness of the steel gear used to run against POM. Figure 14 (b) shows the surface roughness of the PA and steel gear after running, where it can be seen that the changes in surface roughness is small. The surface roughness of the steel gear appears to be smoother, probably due to a transfer layer of PA onto the steel tooth flank. Figure 14 (c) shows the worn tooth surface of the POM gear, which, when compared with figure 13(b), is much smoother and hardly different from the new surface. Surface measurements taken for the PA/POM pair showed similar results, with the

PA gear showing a smoother surface after running (figure 15).

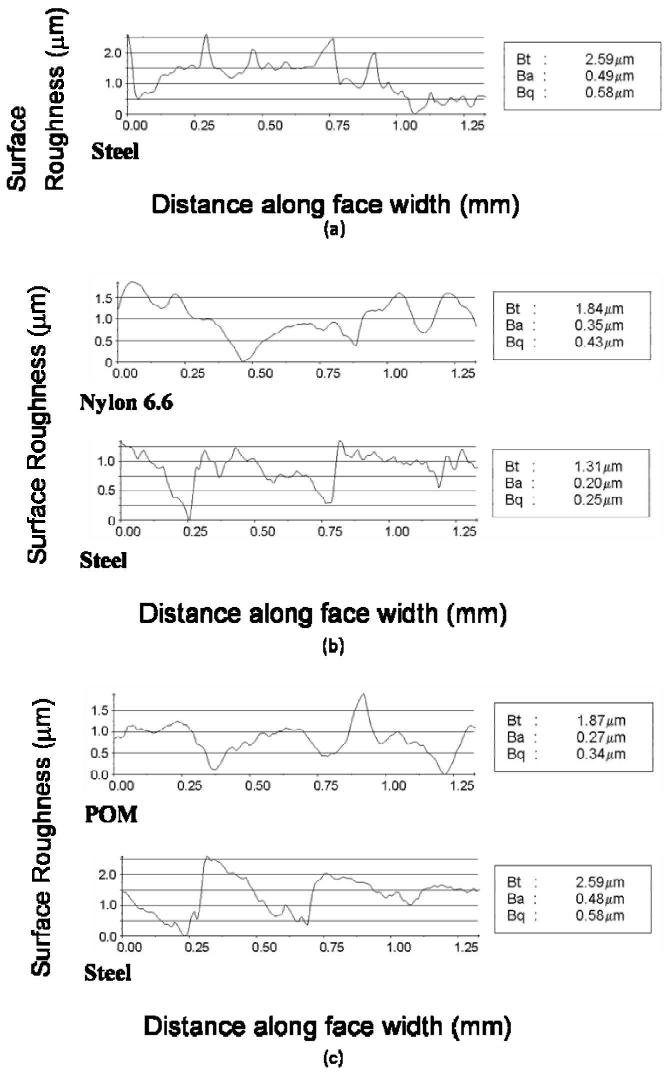

Figure 14 Showing surface roughness for (a) steel gear measured before running (b) PA and steel gears measured after running (c) POM and steel gears measured after running

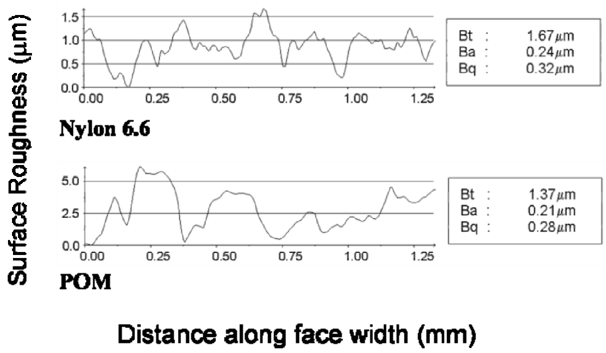

Figure 15 showing surface roughnesses for PA and POM gears measured after running

V. CONCLUSIONS

The following conclusions can be drawn from the results of measurements of noise with variations in torque, speeds and for different combinations of materials for plastic gears. PA gears were quieter than POM gears and showed none of the higher harmonics that were seen in the POM tests. Noise levels were shown to be virtually independent of torque but much more dependent on speed. Of the materials tested, POM against POM was the noisiest combination. Compared to the other materials, POM showed a greater sensitivity to changes in torque. A PA composite gear pair gave the lowest noise levels, which were also shown to be virtually independent of torque. Running a PA gear against a POM gear resulted in very low noise levels. Running PA or POM gears against steel also resulted in low noise. When POM was run against itself but with grease lubrication noise was also low. Running POM against steel gear but in a greased condition resulted in no significant difference between the noises in an unlubricated state. All the plastic gears tested had similar tooth flank roughness when new. Measurements in the changes in surface roughness as the gear wore correlated with the noise levels recorded. Rougher surfaces resulted in louder gear noise.

The results reported in this paper have focused on the effects of different materials on the noise of plastic spur gears. Wear and fracture are also important and have not been mentioned, but the wear of the composite material was markedly less than the other materials tested. Other factors, such as gear tooth geometry are likely to affect gear noise as well, but it is probable that the materials tested here and shown to be the quietest will also be the quietest in different geometries.

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