The Relative Performance of Spur Gears Manufactured from Steel and PEEK

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Management Summary

Polymer gears offer many advantages over their metal counterparts:

- More cost effective production for large runs
- No need for additional finishing operations
- High resilience and internal damping capacity result in quiet operation
- Lighter, lower inertia
- Good corrosion resistance
- Possible to integrate several components in a single molding operation
- Excellent fatigue performance

Victrex has constructed two gear test rigs capable of running gear combinations at torques up to 60 N-m and speeds up to 6,000 rpm. The rigs are equipped with shaft encoders, resolving to 0.0007 radians, and torque transducers on both input and output shafts. The instrumentation on the rig allows the capture of data related to tooth deflections, gear flank wear and the general performance of the gears.

This paper seeks to compare the data generated from the shaft encoders and torque transducers when using steel-steel, steel-plastic and plastic-plastic gear combinations in order to understand the differences in performance of steel and plastic gears.

Introduction

Plastics have long been used in the production of gears due to their many advantages:

- Thermoplastic gears can be produced by injection molding. This can provide a significant cost saving for large-scale production, the possibility to integrate intricate design features, the ability to reduce part count and short production cycles are possible with minimal requirements for secondary operations.
- The low density of polymers results in potential weight saving.
- Plastic gears have high resilience and internal damping, giving quieter operation.
- Plastic gears have the ability to run successfully with no lubrication.
- Plastics generally have good corrosion resistance.
- Plastic gears can be over-molded onto metal hubs for ease of assembly.

However, the use of plastic gears has so far been limited due to:

- The yield strength and elastic modulus of common plastic gear materials are roughly an order of magnitude and two orders of magnitude respectively lower than steel.
- The mechanical properties of plastics are temperature sensitive, and the usable temperature range is often limited when compared to steel. Frictional heating which occurs in the gear mesh exacerbates this problem.
- Some plastics are sensitive to moisture, resulting in changes in dimensions and mechanical properties.
- Plastics usually have a higher coefficient of expansion than metals and thus dimensional changes need to be considered where applications involve significant temperature variations.
- Plastic gears cannot usually be molded to the same dimensional accuracy as machined metal gears because of post-mold shrinkage.

These factors often limit the load carrying capacity of such gears and so they only tend to be used in lightly loaded applications.

The subject of plastic gears first appeared in the literature in the mid 1950s and was related to the performance of polyamide gears (Ref. 1).

Since then, a considerable amount of research has been published, the literature focusing on polyamide and acetal gears which represent approximately 80–90% of the plastic gear market (Refs. 2–6).

Design data and design methodology is available for these materials and is readily available in standards such as British standards (Ref. 7), Polypenco (Ref. 8) and American standards (Ref. 9). However, it is generally accepted that the only reliable way of predicting gear performance is by testing gears under real life conditions using different applied loads, speeds and lubrication scenarios.

Plastic gear failure often results from either tooth root failure or tooth wear. This paper is aimed at investigating the former and so further discussion will be limited to tooth root failure. Tooth root failure is normally the result of either too high a mechanical stress, the combination of a high mechanical stress with the effects of temperature or simply too high a temperature such that the material softens and can no longer support any load. Theories have been developed to provide a means of determining the thermal effects in gears in relation to direct thermal failure (Refs. 6, 10–11). However, this work seeks to understand the nature of the tooth engagements found with plastic gears in order to attempt to provide some understanding of the effects occurring which may limit tooth lifetime.

Experimental Setup

Victrex, through a knowledge transfer partnership with the University of Birmingham, U.K., designed and constructed a test rig (Ref. 12) to enable the measurement of gear design data. The rig has two 40 kW motors—one driving, the other acting as an electrical brake—and both the input and output shafts are equipped with encoders and torque transducers. The gears used in this work had a module of 2 mm, a pitch circle diameter of 60 mm, a face width of 12 mm, a pressure angle of 20° and 30 teeth.

All tests were carried out under lubricated conditions, and the test temperatures used were at room tempera-

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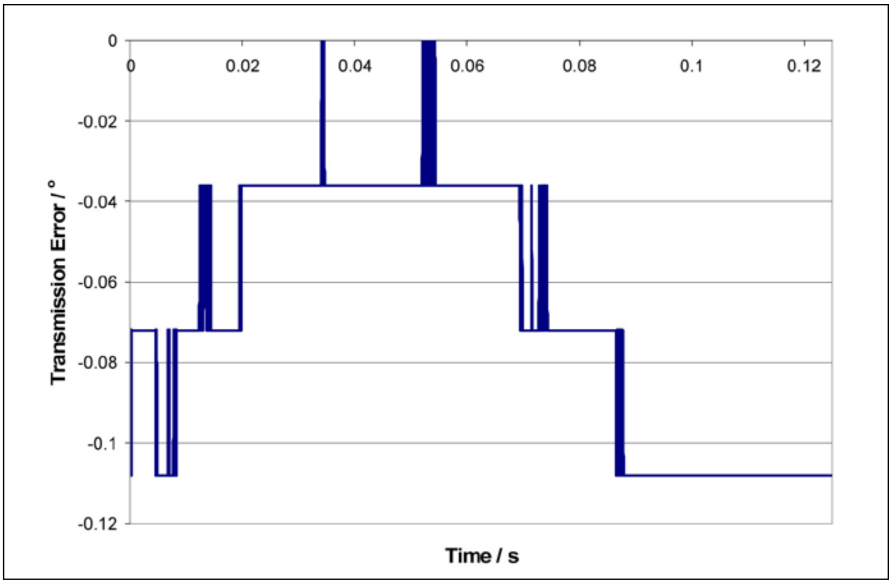

Figure 1—Transmission error with a steel shaft.

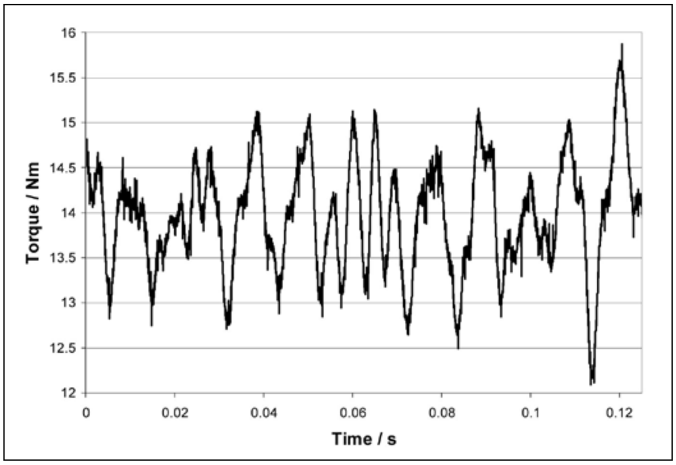

Figure 2—Torque variation with a steel shaft.

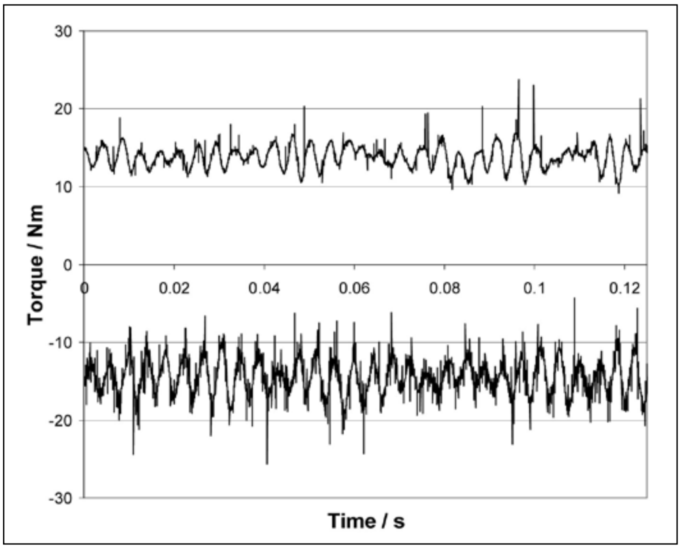

Figure 3—Torque data for the steel-steel gear combination.

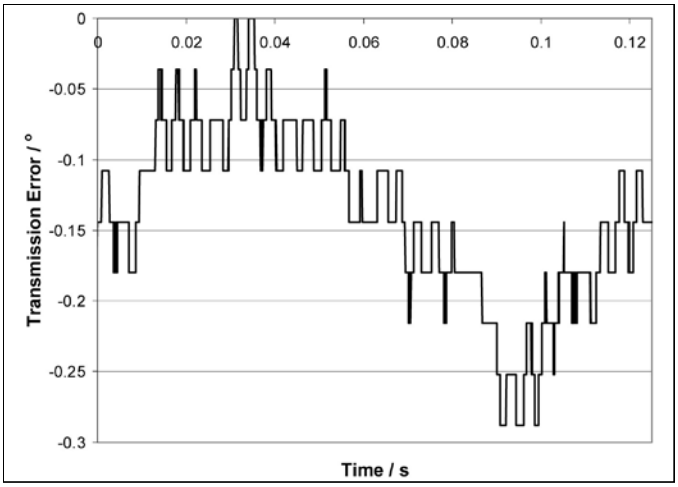

Figure 4—Transmission error data for steel-steel gear combination at room temperature.

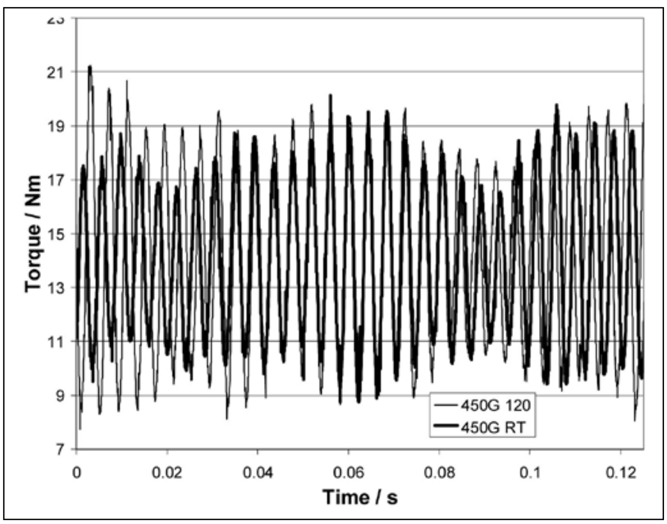

Figure 5—Torque data for Victrex 450G/steel gear combination.

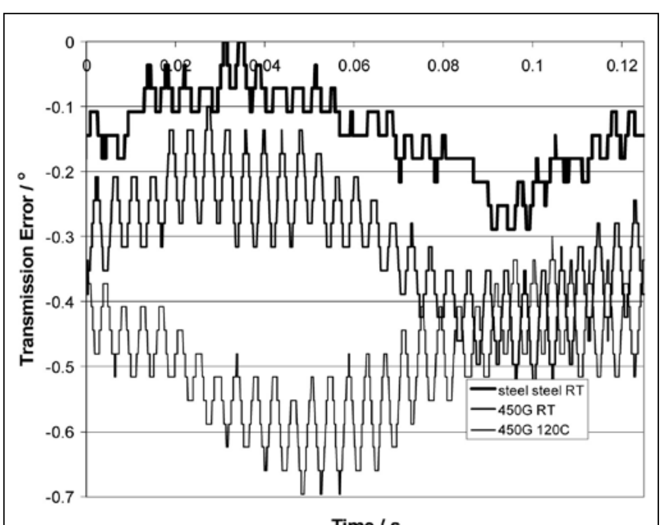

Figure 6—Transmission error data for Victrex 450G/steel gear combination.

ture and 120 °C. However, frictional heating did occur—the gearbox not being actively cooled—and what is classed as room temperature was in fact around 60 °C. The lubricating oil used was Gear Oil S320 supplied in the U.K. by John Neale Ltd.

The transmission error was determined by subtracting the output values from the incremental encoders on the input and output shafts. As the data is relative, it has been arbitrarily offset so that the various data sets can be differentiated on the graphs.

Test data generated for a specific gear pair at different test temperatures were produced using the same gear pair without dismounting the gears between tests.

Testing consisted of running the gear pairs at 500 rpm at a torque of 15 N-m. In cases where one steel gear was used, the steel gear was always mounted on the input shaft.

Test gears were manufactured from Victrex PEEK 450G, Victrex PEEK 450CA30 and Polyamide 4, 6. The plastic gears were molded by IMS Gear (Germany). The gear pairs tested were steel/steel; steel/Victrex 450G; steel/Victrex 450CA30; steel/PA46; Victrex 450G/Victrex 450G and PA46/PA46.

Results

The point at which logging of data commences relative to a specific tooth on a specific gear varies between tests; thus there is a time shift between data sets in that maximum and minimum values for different tests do not coincide in time. Due to the digital nature of the output from the encoders, transmission error plots do exhibit a stepped nature. Where a single torque trace is shown, this is for the output shaft.

Steel shaft. The rig was set up with a solid steel shaft coupling the drive and brake in order to remove any effects related to the gears. The encoder data (Fig. 1) shows a small, cyclic variation in the transmission error equivalent to four bits of data; a mistaken measurement generally is of the order of ±2 bits, this being equivalent to approximately ±0.08° and the angular error being based on the encoders resolving to 10,000 bits/revolution. It thus appears that this may be the cause of the observed variation.

The torque data is shown (Fig. 2). The mechanical load on the system should be constant when the drive and brake are linked with a steel shaft. It seems likely that the variation in torque shown (Fig. 2) arises due to electrical reasons. Two electronic control systems are used—one to control the speed of the drive motor, the other to control the torque on the brake motor.

While a feedback loop is used to trim the torque controller, there will inevitably be some variation due to the drives "fighting" each other.

The data is intended to be used as a reference for subsequent data sets. The variation in torque is mainly in the range 13–15 N-m, although there are some minor excursions beyond these limits.

Steel/steel combination. The steel/steel combination was tested to provide a control data set. Figure 3 shows the torque data (input and output) for one revolution of a gear pair at room temperature. The large spikes are thought to be noise as the related timescale is very short, being of the order of 2×10^{-5}s.

The peaks seen (Fig. 3) appear to correspond to the teeth engagement; it is apparent that the torque is not stable. If the large spikes are ignored, the torque—nominally set at 15 N-m—varies between 11–17 N-m; the variation being greater than that found with the steel shaft. It could thus be concluded that the gears do influence the stability of the torque.

Figure 4 shows the transmission error for the steel gear combination at room temperature. The angular shift of approximately 0.3° corresponds to approximately 2.5% of the tooth pitch. The transmission error shown with the steel gear combination is approximately double that found with the steel shaft. Thus while the transmission error could be considered small, the gears do exhibit some error. The transmission error at 120 °C was the same as that at room temperature—which was expected due to the material properties.

The cyclic variation in the transmission error and torque data is typical of all gears tested. It is unclear at this stage why this cyclic variation occurs.

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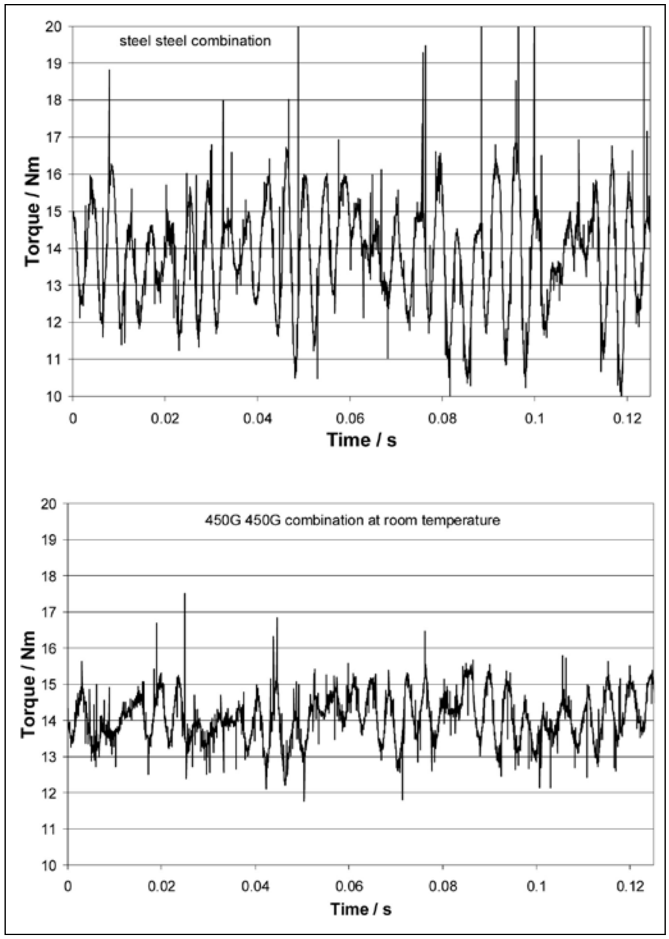

Figure 7—Torque data for steel-steel and Victrex 450G/Victrex 450G gear combinations.

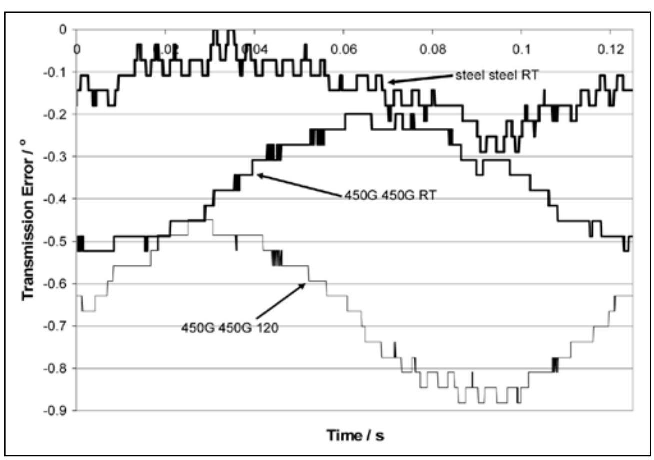

Figure 8—Transmission error data for Victrex 450G/Victrex 450G gear combination.

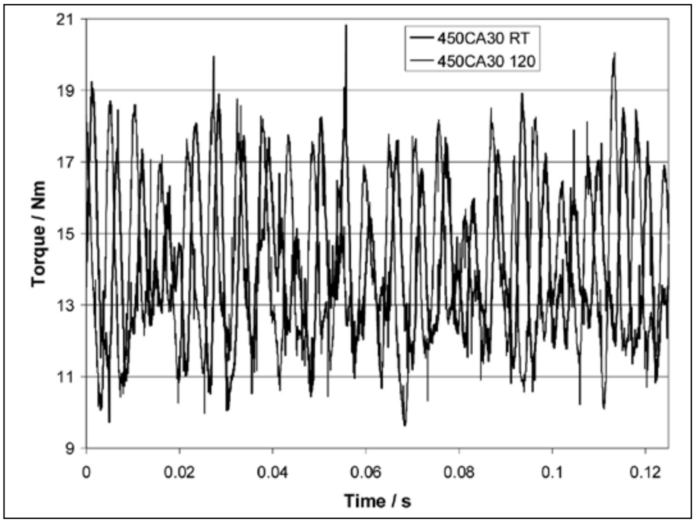

Figure 9—Torque data for Victrex 450CA30/steel gear combination.

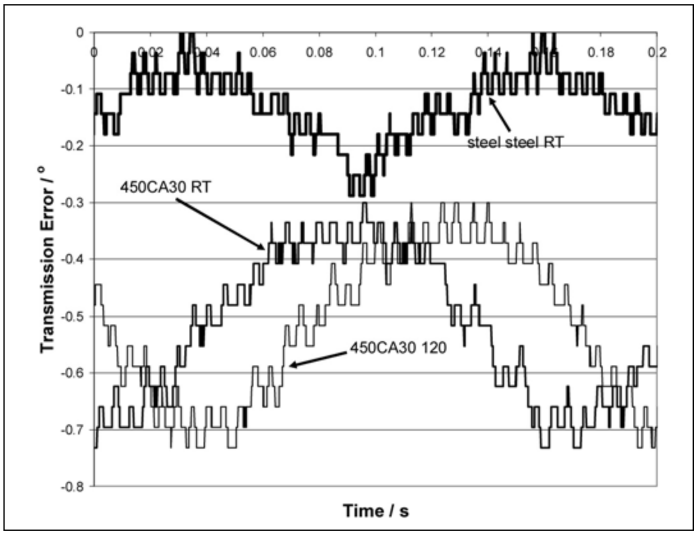

Figure 10—Transmission error for Victrex 450CA30/steel gear combination.

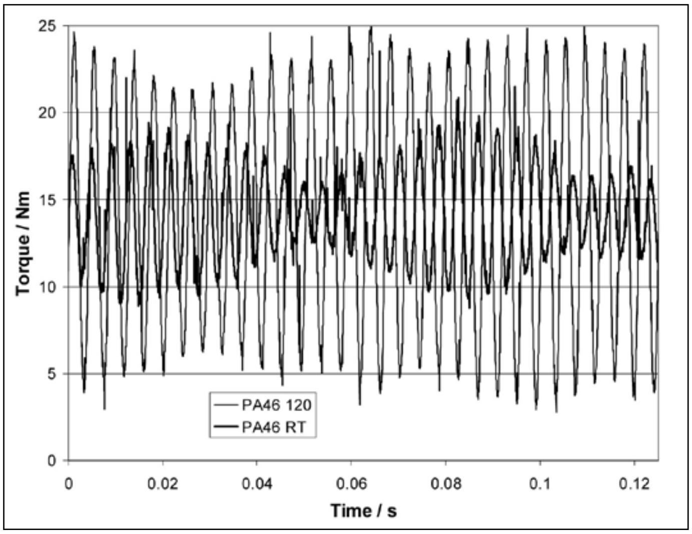

Figure 11—Torque data for PA46/steel gear combination.

There are several possible reasons, including:

- ***Lobed gears***. In the case of the polymer gears this may be possible but seems to be very unlikely with machined steel gears and thus is probably not the cause of the cyclic variation.
- ***Misalignment of the shafts***. If the center lines of the two shafts were not correctly aligned, complex wear patterns on the teeth would result; but the load should remain stable, as should the transmission error.
- ***Eccentric rotation of the input/output shafts***. The gears used in this work have been mounted on a variety of different shafts and so the possibility that the shafts were not machined accurately is unlikely. Run-out on the output shaft has been measured to be 0.002 mm and the run-out on the input shaft was so small it could not be accurately determined. Thus, this does not appear to be a likely cause.
- ***The gears could, due to the mounting, be running eccentrically to the drive shafts***. The shafts on the steel gears were machined as one component and thus any significant misalignment of the gear to the shaft is very unlikely.
- ***An electronic drive instability***. Wider testing has indicated that the frequency of the sinusoidal pattern is always the same as the drive rotation frequency, irrespective of the speed and torque being used. Thus, this explanation also appears to be an unlikely cause for the observations.

Victrex 450G/steel gear combination. The torque data and transmission error data are shown (Figs. 5–6). The torque data shows that the variation associated with tooth engagement is greater than that found with the steel-steel gear combination.

There is limited difference between the Victrex 450G at room temperature and at 120 °C, which is as would be expected as the polymer is below its glass transition temperature **(**T_g**),** which is 143 °C. The torque data shows a regular, higher-frequency variation that occurs once per-tooth-engagement. However, the data does not allow for a direct linking of the relative position of the teeth in relation to the torque variation.

The transmission error (Fig. 6) follows a similar pattern in that there is a variation that is clearly linked to the frequency of tooth engagement.

The magnitude of the torque and transmission error data does seem to be significant and is certainly larger than can be explained through experimental error. The torque variations are happening over a period of around 0.002 s. Assuming that the torque rises from 10 N-m to 20 N-m over this period, and taking the diameter of the gear to be a nominal 60 mm, this results in an increase in force of around 300 N over a period of 0.002 s. Examination of the transmission error would suggest a variation of around 0.2° in the same timescale, this corresponding to an angular acceleration of approximately 100° per second. Such changes could be considered to be significant with respect to the lifetime of a plastic gear.

Victrex 450G/Victrex 450G combination. The torque and transmission data are shown (Figs. 7–8).

The torque data indicates that even though the stiffness of the Victrex 450G gears is lower than that of the equivalent steel gears, the torque variation is significantly smaller with the Victrex 450G/Victrex 450G combination than found with the Victrex 450G/steel combination in terms of both the general cycle-to-cycle variation and tooth-to-tooth variation.

Thus it could be concluded that the torque variations are not related solely to the stiffness of the gears, but rather, to the relative stiffness of the two gear materials.

The variation in the transmission error is reduced with a Victrex 450G/Victrex 450G combination when compared to the Victrex 450G/steel combination. While the overall magnitude of the variation through a cycle is similar, the variation with tooth engagement is much reduced to a level similar to that found with the steel/steel combination of gears.

Victrex 450CA30/steel combination. The torque and transmission error data are shown (Figs. 9–10).

The torque data for the Victrex

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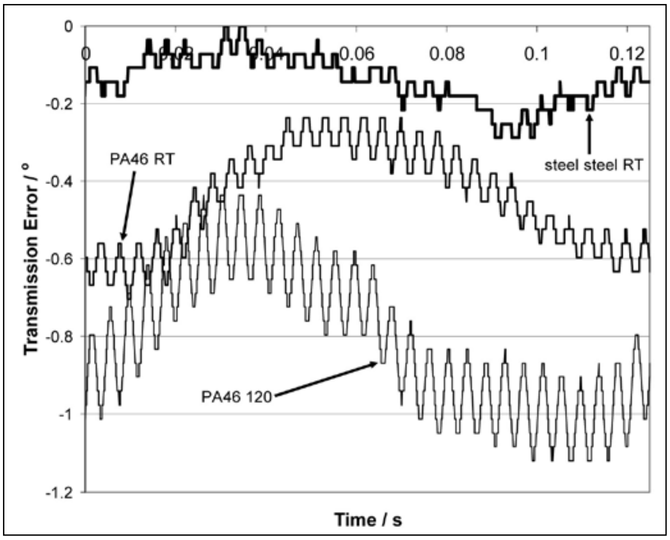

Figure 12—Transmission error data for PA46/steel gear combination.

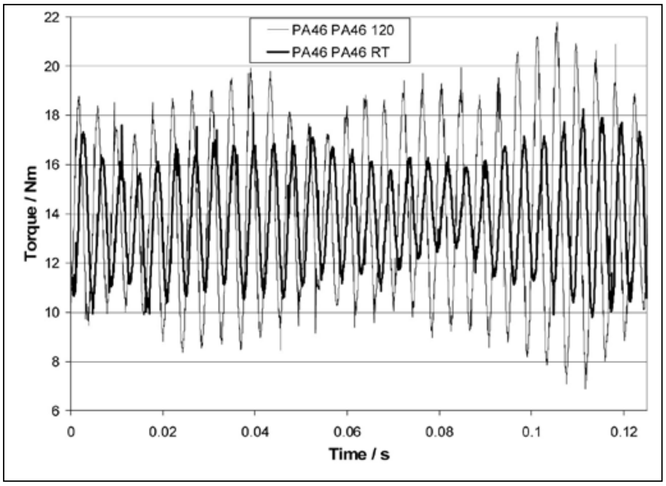

Figure 13—Torque data for PA46/PA46 gear combination.

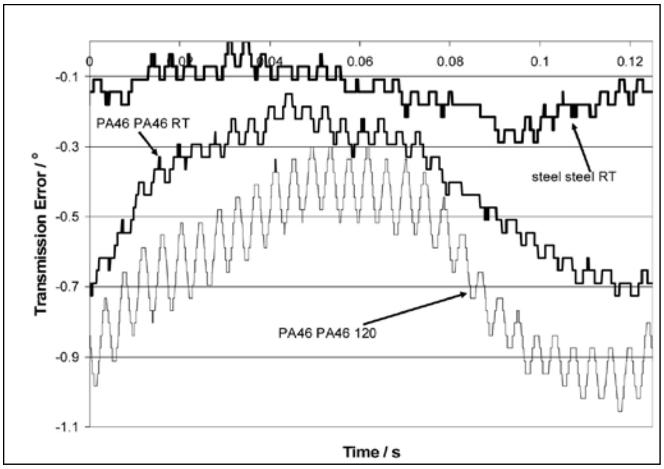

Figure 14—Transmission error data for PA46/PA46 gear combination.

Figure 15—Typical failure found with a Victrex 450G spur gear.

450CA30/steel combination varies slightly more than is found with the Victrex 450G/Victrex 450G or with the steel/steel combination. However, it is slightly reduced when compared to the Victrex 450G/steel combination.

The transmission error data indicates that the gear combination is not subject to the variations related to tooth engagement, as found with the Victrex 450G/steel gear combination. The transmission error with the gears does not change with temperature, as would be expected, the material being below the T_g. However, it is interesting to note that the transmission error for the Victrex 450G/Victrex 450G combination at room temperature is less that than that for the Victrex 450CA30/steel combination, which is similar to that for the Victrex 450G/Victrex 450G combination at 120 °C.

PA46/steel combination. The torque and transmission error data are shown (Figs. 11–12).

The torque data at room temperature shows a slightly increased overall variation when compared to a Victrex 450G/steel combination at room temperature. It is noticeable that the cyclic variation related to the speed of rotation has increased to approximately twice the frequency of rotation. This phenomenon probably requires further investigation in order to determine the cause. The tooth-to-tooth variation still exists. However, the variation in torque increases significantly when the test temperature is increased to 120 °C. The assumption could be made that this is due to the reduction in the stiffness of the gear with increasing temperature. It is noticeable that the higher frequency cyclic variation observed at room temperature no longer exists.

The transmission error data at room temperature is indicative that the variations cycle to cycle are not regular whereas the data at 120 °C indicates some stability. In this case stability is defined as the exit point on the right-hand side of the graph being at a similar value to the entry point on the left-hand side of the graph. The transmission error data shows that the PA46/steel combination gives a slightly poorer performance than the Victrex 450G/steel combination in terms of overall variation. The variation occurring during tooth engagement is, however, slightly less. At 120 °C the transmission error is significantly larger than that for the Victrex 450G/steel combination.

PA46/PA46 combination. The torque and transmission error data are shown (Figs. 13–14).

The room temperature torque results for the PA46/PA46 combination show a smaller overall variation than those found with the PA46/steel combination. Similarly, while the overall variation is greater at 120 °C than at room temperature, the variation with the PA46/PA46 combination is less than that found with the PA46/steel combination. Both sets of data show a slight tendency towards a higher frequency cyclic variation.

The variation in the torque found with the PA46/PA46 combination at room temperature is worse than that found with the Victrex 450G/Victrex 450G combination. Similarly, the transmission error occurring with the PA46/PA46 combination is significantly worse than the steel/steel combination and the Victrex 450G/Victrex 450G combination. It is very noticeable that the variation at the frequency of tooth engagement is still very prominent.

Failure mechanism. The steel/steel combination has not undergone any lifetime tests and so is excluded from the following discussion. In lifetime tests the various gear combinations result in failure of the plastic gear by tooth fracture. A typical fracture is shown (Fig. 15).

Cycles to failure. Table 1 shows the average lifetime for gear combinations featuring Victrex gear materials. The data indicates that using gears made from the same polymer material is advantageous, which suggests that the tooth-to-tooth variation in the torque is an important factor in the lifetime of a gear.

Discussion

There appear to be two main features of the data considered: 1) the cyclic variation of the transmission error data at a frequency equivalent to the rotational frequency of the drive; and 2) the tooth-tooth variation in the torque and transmission error data. The two effects may be linked but the data suggests this is not the case.

Cyclic variation in the transmission error related to the gear rotational speed. The magnitude of the overall variation does seem, in part, to be related to the stiffness of the materials of construction of the gears, the variation being greater with the PA46 gears than with the Victrex 450G and steel gears. However, it seems unlikely that, in the case of the steel/steel combination, there is significant tooth deflection and thus it may be concluded that the fundamental cause of the effect may not be related to tooth deflection. The torque data for the steel/steel combination does show some variation that appears to be related to the tooth engagement process, although the background effects—as determined using the steel shaft—are presumed to be a significant factor in the observations with the steel/steel combination.

If, as mentioned, the stiffness of the gear material does influence the magnitude of the variation, and it is not specifically linked to tooth engagement,

Table 1—Comparative cycles-to-failure for various gear combinations at 25 N-m, 120 °C and 1,020 rpm

Materials	Steel-Polymer	Polymer-Polymer
Victrex 450G	605,000	1,135,000
Victrex 450CA30	2,847,000	11,921,000

then it would seem that the effect is related to deformation of the gear as a whole and this would suggest that the magnitude of the effect is related to deformation of the web joining the central hub and gear tooth hub. In the case of the plastic/steel gear combinations, there does seem to be some cyclic variation of the torque, and so this inference seems plausible.

It therefore seems likely that the variation has a base component, and as shown by the steel shaft, this effect is exacerbated by the deformation of the plastic gears.

Variation related to the tooth engagement. The torque and transmission error variations associated with each tooth engagement can be considered to be imposing significant shock loads on the individual teeth; this effect would be expected to reduce the life of the gear.

It seems likely that the effect is related to the deflection of the individual teeth—i.e., the lower the modulus of the material, the greater the deflection expected.

Where the stiffness of the two gear materials is matched, the variation in transmission error is very much reduced. The torque variation associated with the process is also reduced and therefore any shock loading is likely to be reduced. In the case of the Victrex 450CA30, the stiffness is higher than that of the unfilled polymers and so there is a better match of modulus between the two gears.

Conclusions

Significant variations in torque and transmission error have been observed when plastic gears run against steel gears; the situation improves when plastic gears are run against plastic gears. Gear lifetime data suggests that this tooth-tooth loading variation has a significant effect on the lifetime of a plastic gear. The results indicate that using gears made from the same polymer material is advantageous, as opposed to running plastic gears against metal gears.

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