A COMPARISON OF MICRO-PITTING PERFORMANCE OF IDENTICAL OILS USING STANDARD FZG TEST GEARS AND HELICAL TEST GEARS

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ABSTRACT

The MoD(N), British Gear Association and the DTI are sponsoring a programme of work at *QinetiQ Pyestock* and Design Unit to investigate test procedures to determine the micro-pitting performance of parallel axis gears. This article presents initial results from the work carried out so far. In particular, the micro-pitting performance as determined in the standard FZG test procedure is compared and contrasted with the results obtained using identical oils and larger helical gears run on the Design Unit 160mm Back-To-Back Test Rigs.

Introduction

The problem of micro-pitting has become more apparent over recent years. Micro-pitting (also referred to as grey staining, frosting or peeling) was previously regarded as a secondary wear process that rarely led to actual failure. Nowadays, micro-pitting is increasingly linked with gear failure through the formation of macroscopic pitting, scuffing and flank bending failures[1] in addition to increased levels of vibration and noise (FIG.1).

There has been a general trend over recent years for traditional failure mechanisms (such as macro-pitting and root bending) to become less likely whilst micro-pitting has become more prevalent in a wide range of gearing applications from large marine propulsion systems to smaller automotive transmissions. This change in observed failure mode has coincided with improvements in gear performance and life, which have resulted from a range of factors including:

- Improvements in steel making leading to cleaner steels.[2,3]
- Advances in gear manufacture.
- Design and development of advanced lubricant packages to prevent wear and scuffing.[4,5]

Improvements in steel making methods have led to steels with significantly lower oxygen levels (less than 10ppm) and therefore, large, brittle oxide inclusions are no longer present. It is well established that oxide inclusions can provide nucleation sites for fatigue failure[6,7] and that they can result in subsurface initiated cracking and subsequent macro-pit formation in surface contact fatigue.

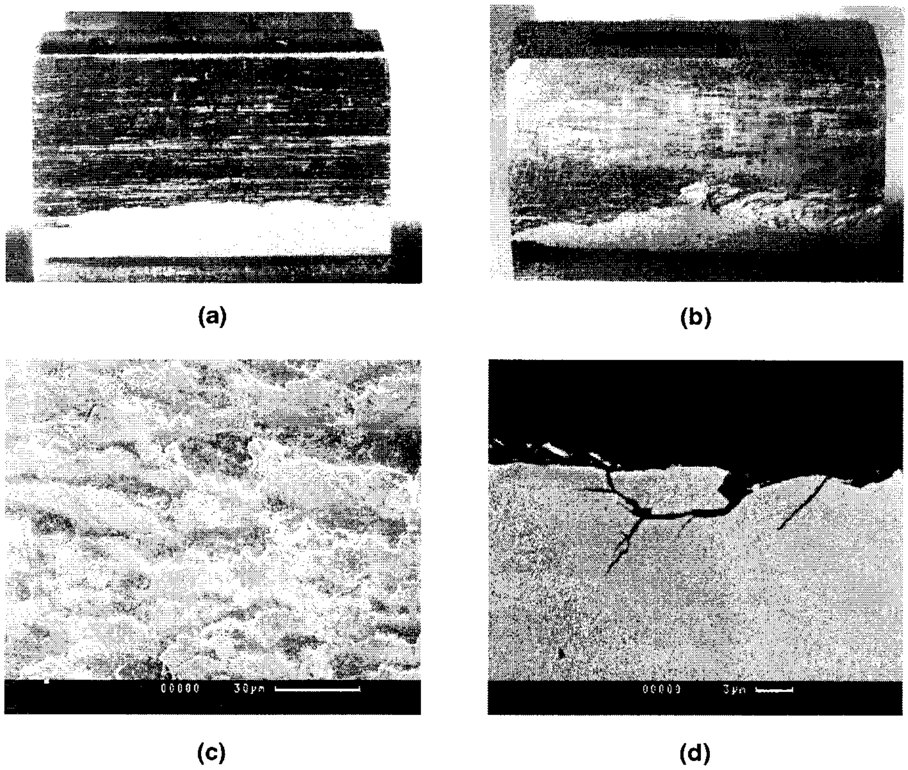


FIG.1:

(a) – DISTRIBUTION OF MICRO-PITTING ON A GEAR FLANK
(b) – DEVELOPMENT OF MACRO-PITS FROM AN EXISTING BANDS OF MICRO-PIT
(c) – MICROGRAPH SHOWING A MICRO-PITTED GEAR FLANK
(d) – MICROGRAPH OF A SECTION TAKEN THROUGH A REGION OF MICRO-PITS SHOWING THE CRACK PATH TAKEN DURING THE MICRO-PITTING PROCESS.

The definition of micro-pitting in the standards for gear failure terminology[8,9] is:

> 'The Degradation of gear tooth working surfaces under lubrication conditions where the film is too thin for the load. It appears under magnification as dense patches of micro-pits or micro-cracks'.

There are a number of features that can distinguish micro-pitting from other wear mechanisms or modes of failure, including:

- A matt grey appearance to the affected surface (giving rise to the term grey staining) (FIG.1(a)).
- Small pits around 5μm in depth (FIG.1(c)), initiated from surface fatigue cracks (5 to 10μm in length) propagating at an oblique angle (approximately 35°) to the gear flank.
- After some growth, these fatigue cracks turn to grow parallel to the gear flank before turning back towards the surface, thus leading to detachment of material from the surface (FIG.1(d)).
- Commonly, micro-pits are observed as a localized narrow band in the dedendum. Although they can also be more generally distributed across the gear flank, it is less common to observe them at the pitch line (i.e. suggests that relative sliding is required for initiation).

Once initiated, micro-pitting can be a progressive process that leads to modification of the gear profile and can promote failure as a result. The development of micro-pitting can also arrest after an initial growth period. However, the precise mechanism and cause of micro-pitting failure is not well understood at present. A number of factors are known to influence the development of micro-pitting, including:

- Gear design (e.g. deviation from the perfect involute).
- Surface roughness.
- Degree of any grinding damage (i.e. hardness and residual stress levels).[10,11]
- Surface treatments (e.g. shot peening, superfinishing and coatings).[12,13]
- Method and type of heat treatment.
- Gear operating conditions (e.g. speed, applied torque and lubricant temperature).
- Lubrication type and additive packages.

Little detail is currently known about the influence of these parameters on micro-pitting although lubrication is known to play a key role and can result in appreciable differences in fatigue life performance. This lack of understanding has aroused great interest in both Industry and Academia because the prevention of micro-pitting could lead to large improvements in the surface endurance and load capacity of gears in a wide range of applications.

This article presents initial results from research work being pursued through the British Gear Association (BGA) which will investigate the effect of test parameters such as:

- Operating speed.
- Applied torque.
- Lubricant conditions.

The work to date has concentrated on validating the repeatability of two different micro-pitting test procedures and generating reference data for a commonly used carburised steel in the 'normal' condition. The aim of this first stage of the research is to gain an improved understanding of the mechanism of micro-pitting with a view to investigating possible methods of prevention in the second phase of the research project.

EXPERIMENTAL METHODS

The programme of work has been carried out at both DERA and Design Unit using two different back-to-back contact fatigue gear test rigs. In each case, the work has investigated the micro-pitting performance of a conventional carburised gear steel (16MnCr5) with two lubricants, referred to as Oil A and Oil B. The aim of the tests is to provide:

- Realistic data that represents the performance of the gear steel and lubricants in-service.
- Data on micro-pitting initiation life.
- Data on micro-pitting wear rate.

DERA test programme

The micro-pitting tests at DERA were conducted on a Strama FZG rig (FIG.2) following the procedure detailed in FVA information sheet number 54/1-IV.

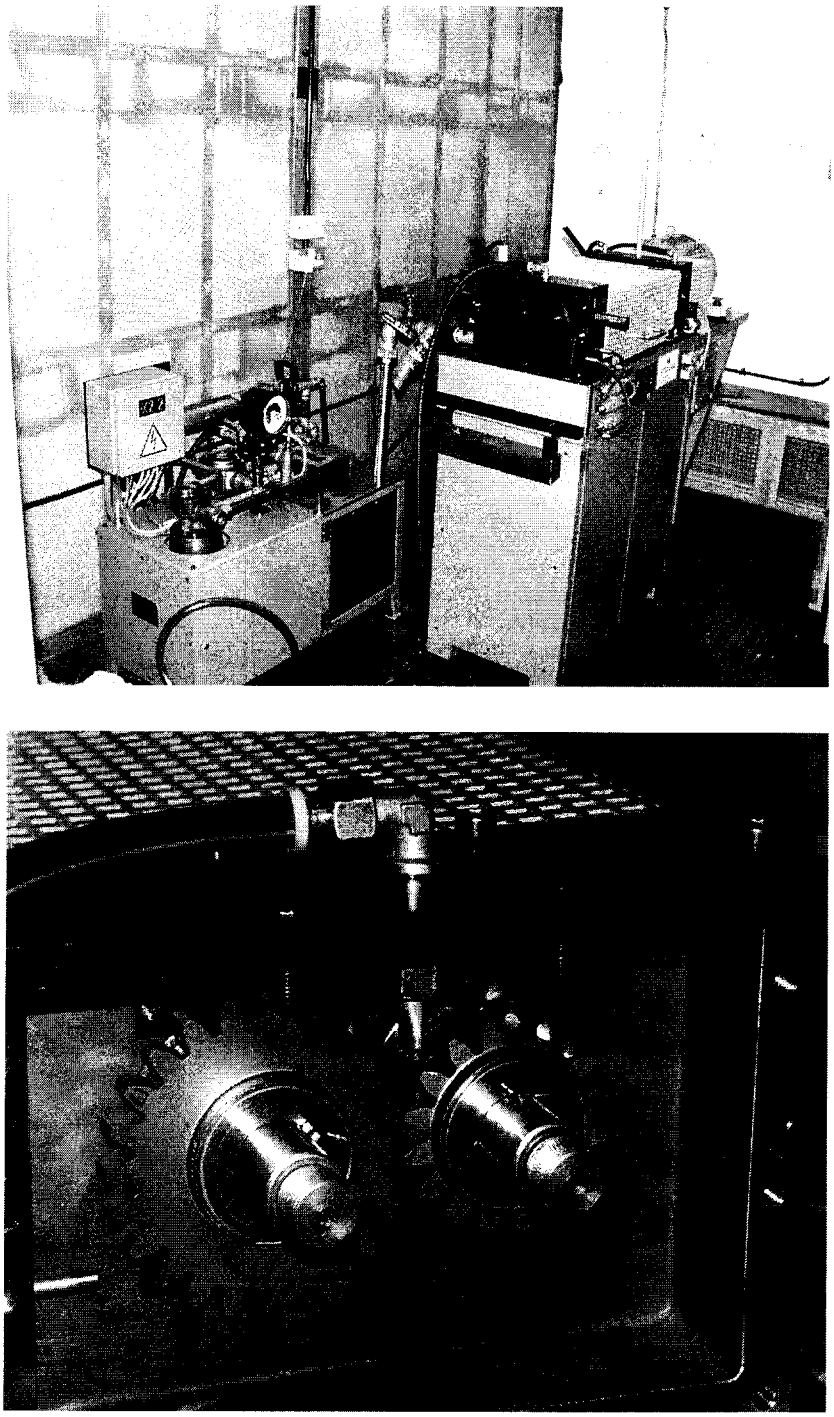


FIG.2 – DERA STRAMA FZC TEST RIG

This test method uses FZG C-GF type gears (91.5mm centres) that are specifically designed to generate micro-pitting under normal contact conditions (Table 1).

TABLE .1 – *Details of type FZG C-GF gears used for the FZG micro-pitting tests*

Dimension		Symbol	Numerical value
Centre distance (mm)		a	91.5
Effective tooth width (mm)		b	14.0
Working pitch diameter (mm)	Pinion	d_{w1}	73.2
	Wheel	d_{w2}	109.8
Tip diameter (mm)	Pinion	d_{a1}	$82.46^{-0.087}$
	Wheel	d_{a2}	$118.36^{-0.087}$
Module		m	4.5
Number of teeth	Pinion	z_1	16
	Wheel	z_2	24
Addendum modification factor	Pinion	x_1	0.1817
	Wheel	x_2	0.1715
Pressure angle (degrees)		α	20.0
Working pressure angle (degrees)		α_w	22.44
Helix angle (degrees)		β	0.0
Tooth correction	Without tip and root relief, no longitudinal crowning		

In each test, a pair of test gears are run for $2.1\text{x}10^6$ pinion cycles (approximately 16hrs) at each of 6 load stages (FZG load stages 5 to 10 inclusive – see Table 2)) followed by endurance testing for 80 hours at load stage 8 (1 cycle) and load stage 10 (up to 4 cycles). An oil inlet temperature of 90°C and a pinion speed of 2250 rpm (giving a pitch line velocity of 8.3ms^{-1}) are used.

TABLE .2 - *Load stages of the FVA micro-pitting test*

Load Stage	Contact cycles (10^6)	Torque on pinion (Nm)	Hertzian contact pressure at pitch point (N/mm^2)
5	2.1	70.0	795.1
6	4.2	98.9	945.1
7	6.3	132.5	1093.9
8	8.4	171.6	1244.9
9	10.5	215.6	1395.4
10	12.6	265.1	1547.3

In view of the time taken to complete a test according to the full FVA method, a shortened test consisting of FZG load stages 5 to 10 has been used for the majority of the work reported here. As well as the standard 90°C test temperature, tests have also been conducted at a reduced oil temperature of 50°C to replicate naval in-service conditions.

DERA classification of performance

The failure criteria for the FVA micro-pitting test is primarily based upon the profile deviation as measured on gear metrology equipment such as the Hofler EMZ 632 CNC gear checking instrument available at the National Gear Metrology Laboratory (Design Unit). The gears are deemed to have failed when the profile deviation exceeds 7.5µm during incremental loading or 20µm during endurance testing. The load stage at which profile deviation exceeds the 7.5µm threshold during incremental loading is termed the damage force stage and is used to classify the micro-pitting resistance of the oil. The classification of the oil is also influenced by the area of the active flank affected by micro-pitting (assessed using an optical microscope and grid foil) and the weight loss from the pinion gear during the test (Table 3).

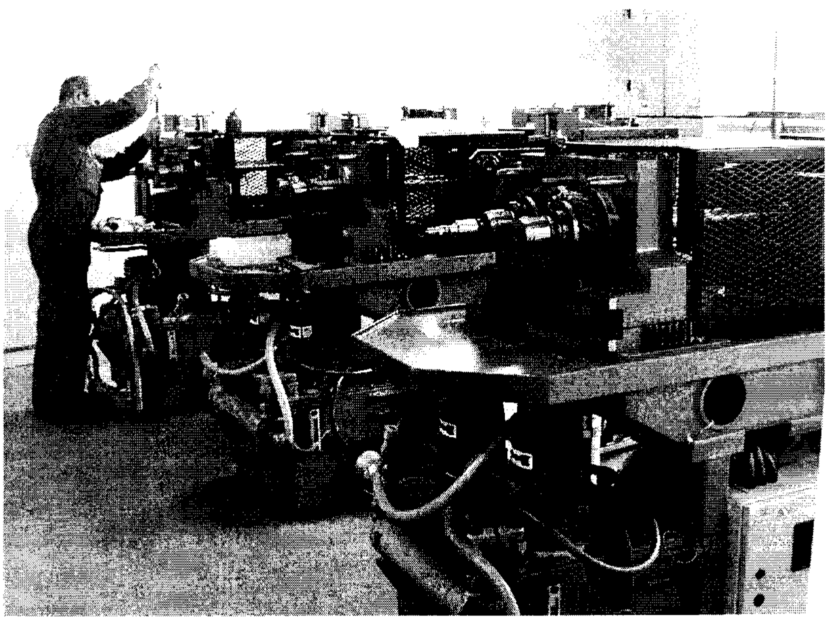
TABLE .3 – *Classification of micro-pitting according to FVA procedure GT-C/8.3/90*

Classification	Behaviour in Stepwise Test	Behaviour in Endurance Test
LOW micro-pitting resistance	DFS[+] ≤ 7 Large area of micro-pitting may be more than 50%.	1×80 hour @ LS10 large profile deviation, clearly more than 20µm
MEDIUM micro-pitting resistance	DFS 8-9 Medium area of micro-pitting, ca. 30%.	$1\text{-}2 \times 80$ hour @ LS10 profile deviation 20+ µm
HIGH micro-pitting resistance	DFS ≥ 10 Small area of micro-pitting, ca. 20%.	$1\text{-}5 \times 80$ hour @ LS10 little profile deviation, less than 20µm

[+]Damage Force Stage – Load stage at which profile deviation $\geq$ 7.5µm

Design Unit test programme

The micro-pitting tests at Design Unit were carried on in-house designed and manufactured 'double-ended' back-to-back gear rigs with a centre distance of 160mm (FIG.3).



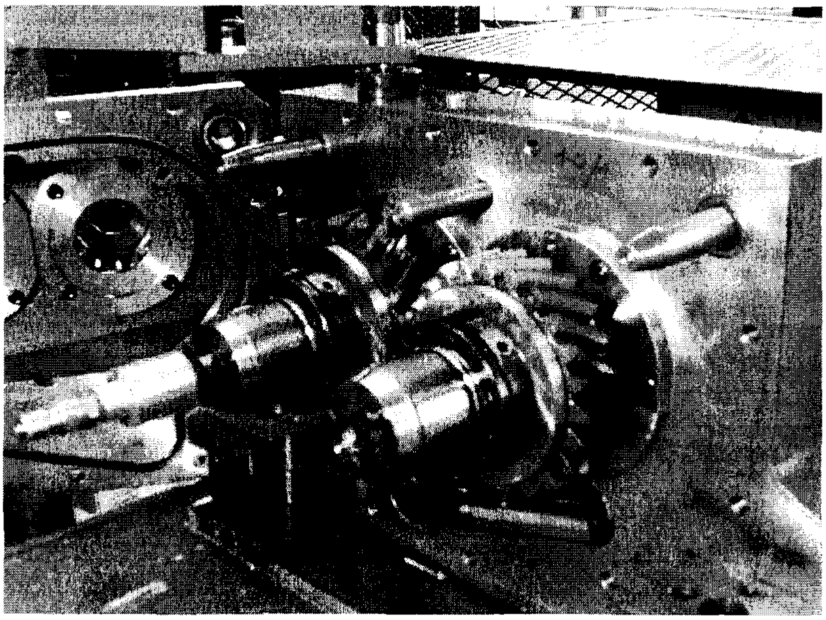


FIG.3 – DESIGN UNIT 160MM CENTRES TEST RIGS

The test gears used in this test rig are 1:1 ratio 6mm module helical gears as detailed in Table 4. All gears were manufactured by Design Unit and heat treated by an experienced project partner.

TABLE.4 – *Details of helical test gears used for Design Unit micro-pitting tests*

Dimension	**Symbol**	**Numerical value**
Centre distance (mm)	A	160
Effective tooth width (mm)	B	38
Working pitch diameter (mm)	d_w	80
Tip diameter (mm)	d_a	171.95
Module	m_n	6
Number of teeth	Z	23
Addendum modification factor	X	0.05
Reference pressure angle (degrees)	α_n	20
Working pressure angle (degrees)	α_w	23.34
Helix angle (Degrees)	β	30
Tooth correction	Chamfered tip relief of 40-50μm over 4mm of roll length, no root relief, no longitudinal crowning	

The test procedure involves two pairs of test gears being run for up to 50×10^6 pinion cycles, in incremental stages, at a constant torque. The test gears were run in 5×10^6 cycle stages up to 10×10^6 pinion cycles and then in 10×10^6 cycle stages up to 50×10^6 pinion cycles. The pinion speed was maintained constant at 3,000 rpm to give a pitch line velocity of $25ms^{-1}$. The oil inlet temperature was regulated to either 50^0C or 90^0C to replicate typical conditions in-service.

Design Unit classification of performance

The test gears were removed at each stage (as detailed above) and then each of the measurements outlined in Table 5 were carried out.

TABLE.5 – *Materials characterisation before, during and after the Design Unit micro-pitting tests*

BEFORE TEST	
Test Method	**Sampling Frequency**
Hardness – portable	20% of gears – 3 teeth, both flanks
Hardness – macro	10% of gears – 3 tests on end face
Hardness – micro profile	1 gear from each heat treatment batch
Barkhausen noise	100% of gears – 3 teeth, both flanks
Nital etch inspection	10% of gears – 4 teeth, both flanks
Retained austenite – surface	10% of gears – 2 teeth, both flanks
Residual stress – surface	10% of gears – 2 teeth, both flanks
Form Talysurf	100% of gears – 2 teeth, both flanks, 3 locations
Gleason gear metrology	100% of gears – lead, pitch and profile
Xantopren replicas	100% of gears – 2 tooth spaces
DURING TEST (5 stages)	
Test Method	**Sampling Frequency**
Gleason gear metrology (profile)	100% of gears – 4 teeth, 3 locations
Xantopren replicas	100% of gears – 2 tooth spaces
Retained austenite – surface	10% of gears – 3 teeth, both flanks
Residual stress – surface	10% of gears – 3 teeth, both flanks
Barkhausen noise	10% of gears – 3 teeth, both flanks
Photography	100% of gears – 2 teeth, both flanks
Microscopy	100% of replicas
AFTER TEST	
Test Method	**Sampling Frequency**
Hardness – micro profile	10% of gears – 1 tooth, both flanks, 3 locations
Residual stress – profile	10% of gears – 1 profiles per gear, 2 directions
Retained austenite – profile	10% of gears – 1 profile per gear
Metallography	20% of gears – 4 teeth
Microscopy	20% of gears – 4 teeth
Scanning electron microscopy	10% of gears – 2 teeth
Optical profilometry	10% of gears – 2 teeth
Gleason gear metrology	100% of gears – 4 teeth, 3 locations
Xantopren replicas	100% of gears – 2 tooth spaces

Involute profile measurements were taken in the National Gear Metrology Laboratory (Design Unit) using a Gleason GMS430 CNC gear checking instrument in order to evaluate the depth of micro-pitting and the micro-pitting roll length (or extent). The gears were deemed to have failed when the profile deviation was greater than or equal to 20µm or if macro-pitting had occurred over an area of 4% or greater on any one tooth. Permanent replicas were taken using Xantopren to evaluate the percentage area of micro-pitting in the dedendum and the gears were also photographed before being refitted. The replicas and photographs were also useful in maintaining a good quality (measurable) record of the damage at each stage of test and this has been useful in examining the initiation stages of the micro-pitted bands.

RESULTS AND DISCUSSION

DERA test data

Eight FZG tests have been conducted as part of this programme (Table 6).

TABLE.6 – *FVA classification of FZG results according to criteria given in Table 3*

Test	Oil	Inlet temperature	Micro-pitted Area (LS10)	Profile deviation (LS10)	FVA rating
A (3/99)	B	90	38	6.7	LOW
B (1/00)	A	90	18	3.4	HIGH
C (2/00)	B	50	23	5.5	MEDIUM
D (3/00)	A	50	54	-	LOW
E (4/00)	B	50	18	-	HIGH
F (5/00)	B	90	52	-	LOW
G (6/00)	A	50	33	-	MEDIUM
H (7/00)	A	50	52	-	LOW

The classification of the micro-pitting resistance of an oil formulation in accordance with the FVA criteria can be complicated. The preferred method, which classifies the oils in terms of the load stage at which profile deviation exceeds 7.5µm, is shown in Table 3. Using this method, all eight of the FZG tests passed load stage 10, giving both oils and conditions an FVA rating of HIGH. However, this classification is also linked with a micro-pitted area of less than 20%, which results in only tests B and E retaining their HIGH rating.

Measurements of profile deviation require access to gear metrology equipment. The fact that these techniques are not readily available within the UK oil industry and that extra time and costs are incurred through sending the gears away to an external body for measuring make the method prohibitive. An alternative method has been developed which uses the Duel Profile facility on a Taylor Hobson Form Talysurf. This method highlights the differences between the current profile and a user defined datum profile (i.e. the original untested profile). Reliable duel profile analysis requires both profiles to be taken over exactly the same section of the tooth flank and at the same orientation relative to the horizontal. Values of profile loss have been compared with profile deviation measurements made on Hofler gear metrology equipment and have resulted in a revised failure criterion being set at 10µm during incremental loading and 22.5µm for endurance testing when using profile deviation measurements. Profile loss measurements for the FZG tests are shown in (FIG.4). In general, tests conducted on Oil A resulted in lower values of profile loss.

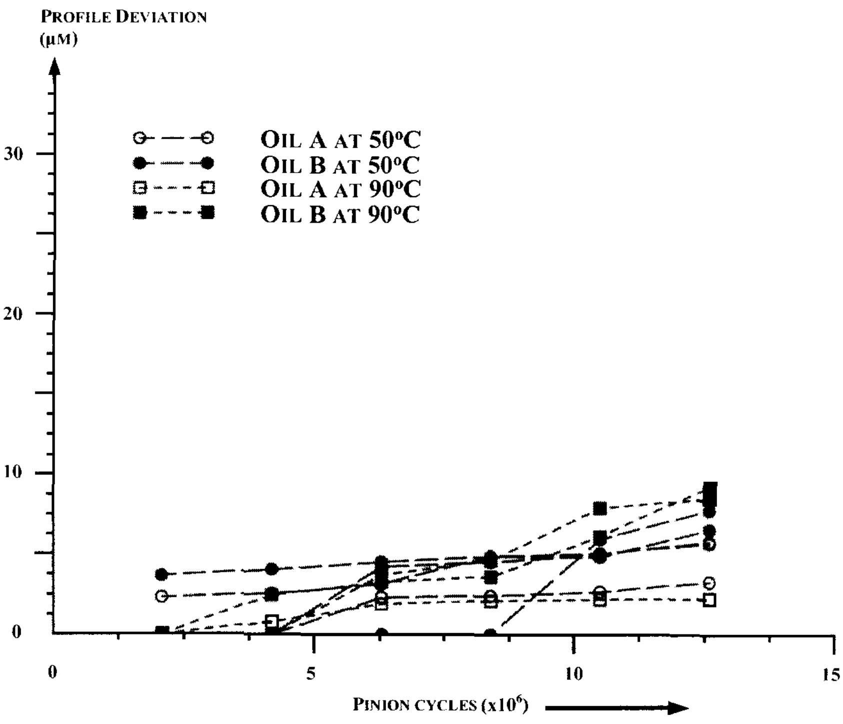


FIG.4 – PROFILE LOSS VALUES FOR FZG TESTS

Micro-pitting was observed to appear firstly as a narrow continuous band, in the dedendum which broadens as the test continues. This is the progressive micro-pitting that is responsible for profile loss or deviation in the dedendum. During the higher load stages, scattered patches of micro-pitting also developed in the addendum and in severe cases, the majority of the tooth eventually became affected. The micro-pitted area is expressed as a percentage of the active flank, as shown in (FIG.5). The apparent lack of correlation between profile loss and the area affected by micro-pitting can be explained by the fact that the profile loss occurs in the dedendum of gear tooth while the micro-pitting area measurement is assessed over the entire flank. It is possible that a better agreement between the levels of micro-pitting area and profile loss may be obtained if the non-progressive micro-pitting in the addendum is disregarded.

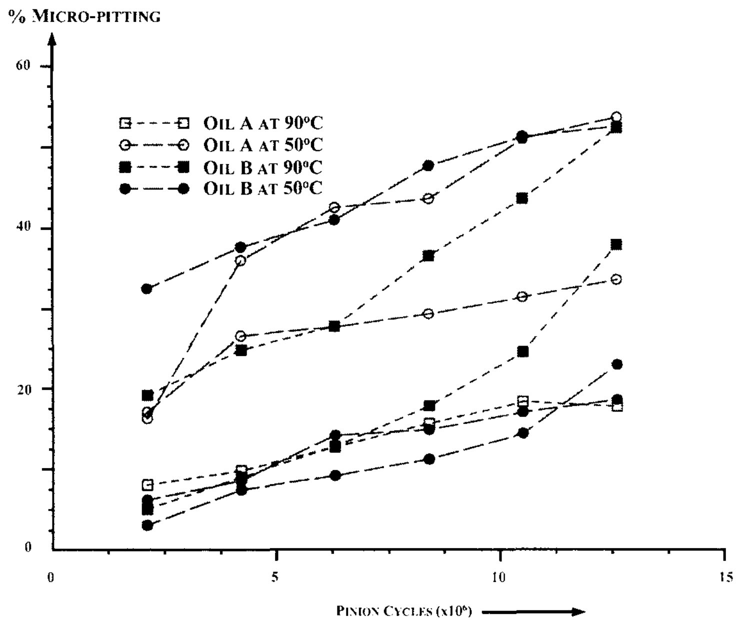


FIG.5 – PERCENTAGE MICRO-PITTING FOR FZG TESTS

The cumulative weight loss for the pinion gears is shown in (Fig.6). Weight loss can provide a valuable indication that wear is taking place. However, it does not differentiate between wear modes or location. Therefore, the lack of correlation between weight loss and profile deviation or micro-pitting area is not surprising.

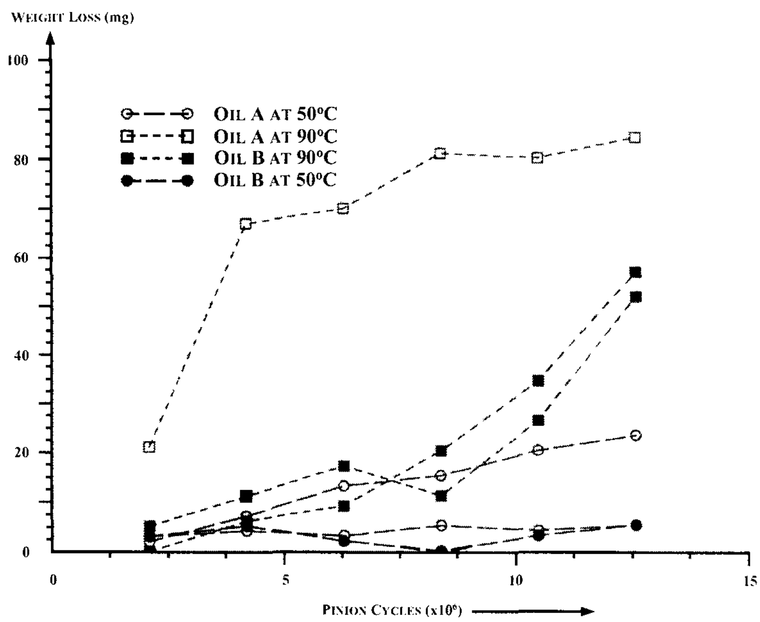


FIG.6 – PINION WEIGHT LOSS FOR FZG TESTS

The DERA FZG results show that there is an observable difference between the two test oils for profile loss measurements with the general trend being for Oil A to result in less progressive micro-pitting than Oil B. The results from the micro-pitting area and weight loss measurements are inconclusive due to the incorporation of non-progressive micro-pits in the calculations.

Design Unit test data

Using the Design Unit 160mm centres helical test rigs, two tests have been completed at 50°C to give a total of four test points per oil and three tests have been completed at 90°C to give a total of eight test points per oil. All tests were carried out under the same conditions in terms of contact stress (1,547N/mm^2 – equivalent to Load Stage 10 in the FZG test) and speed (3,000rpm).

At 50°C it can be seen that there is no appreciable difference in oil performance when comparing profile loss (FIG.7). Both oils gave a maximum profile loss of approximately 10μm after 50x10^6 load cycles (end of test). No significant change in profile loss was observed above 20-30x10^6 load cycles. FIG.7(a) shows that there is no significant change in performance for gears run in Oil A at 90°C. However, at the higher temperature macro-pitting and flank bending failures occasionally occurred on the pinion flanks run in Oil A and these failures led to some tests being stopped after 20-30x10^6 load cycles.

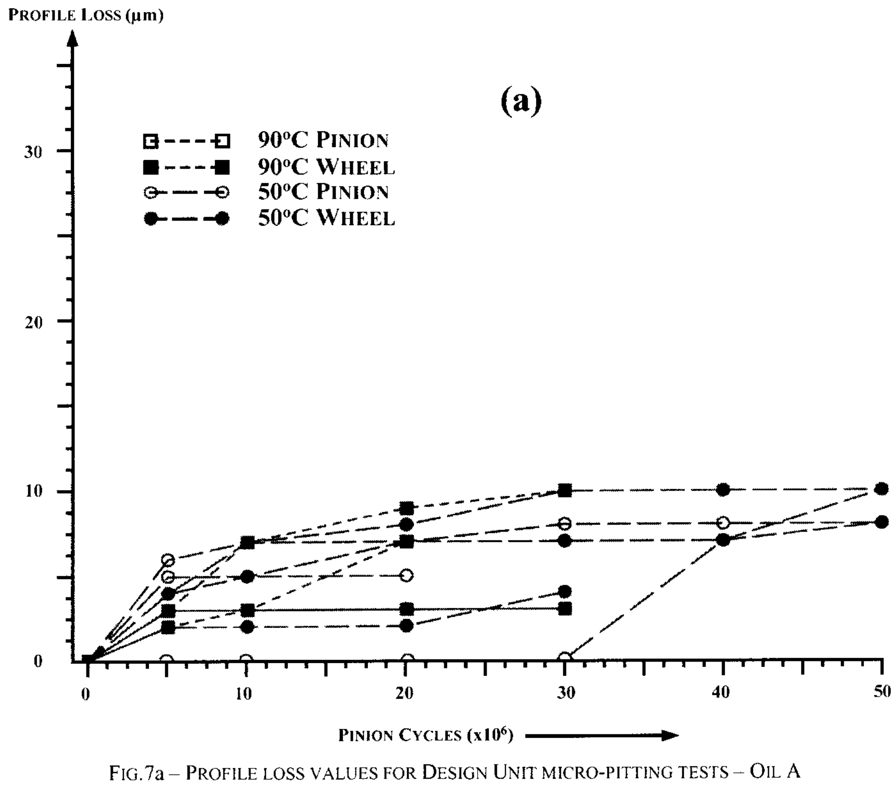


FIG.7a – PROFILE LOSS VALUES FOR DESIGN UNIT MICRO-PITTING TESTS – OIL A

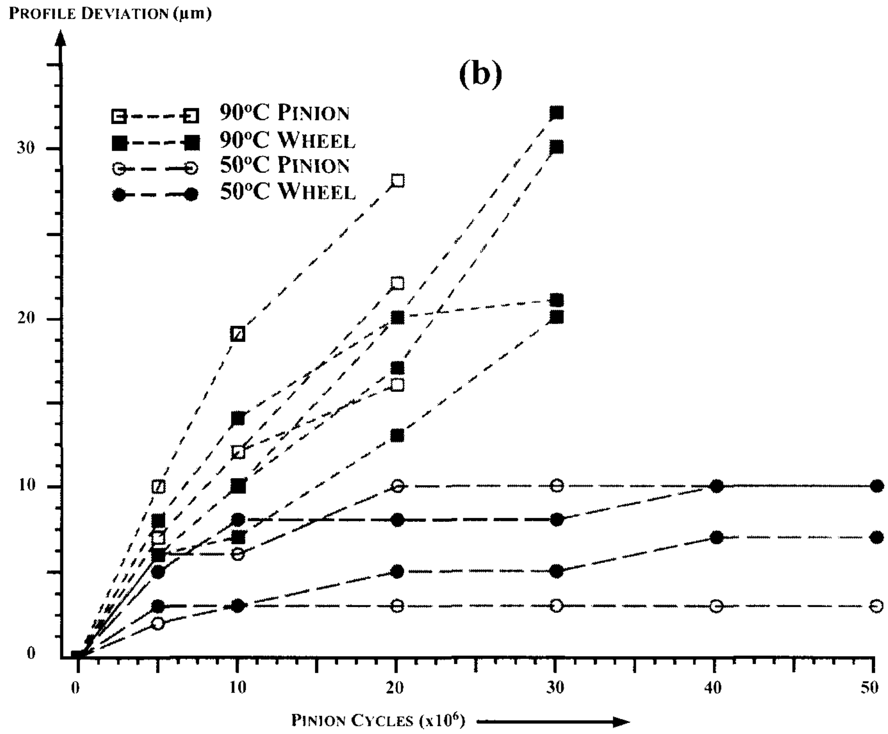


FIG.7b – PROFILE LOSS VALUES FOR DESIGN UNIT MICRO-PITTING TEST – OIL B

The performance of gears run in Oil B at 90°C was significantly worse than identical gears, run in the same oil, at lower temperature FIG.7(b). The profile deviation limit of 20µm was exceeded after 20-30x10^6 load cycles at which point the gears were deemed to have failed. Another significant difference is that the relationship between depth of micro-pitting and number of load cycles is more linear than at 50°C and the data actually suggests the wear rate accelerates prior to the failure limit being exceeded. A likely explanation for the difference in oil performance is that the EP additive package used in Oil B is significantly more 'aggressive' at 90°C than at 50°C resulting in a reduced contact (asperity) fatigue strength.

As for the FZG test gears, micro-pitting first appears as narrow patches in the dedendum which broaden and form a single continuous band as the test progresses (as in FIG.1a). This micro-pitting is progressive and is responsible for the profile loss in the dedendum of the tooth. At higher numbers of pinion cycles, scattered patches of micro-pitting appear in the addendum. This micro-pitting is not progressive and has therefore been neglected when evaluating the percentage coverage (different to the FZG procedure).

A clear distinction in oil performance was seen in terms of the percentage micro-pitting (FIG.8). For gears run in Oil A at 50°C (FIG.8(a)), the maximum area of micro-pitting was approximately 6% after 50x10^6 load cycles with no significant change in the area of micro-pitting after 20x10^6 load cycles. A maximum area of micro-pitting of 25% was seen on gears run in Oil B after 50x10^6 load cycles. As for gears run in Oil A, no significant change in the area of micro-pitting was seen above 20x10^6 load cycles. There is no major difference in performance for gears run in Oil A at 90°C and the maximum area of micro-pitting is very similar to that measured at 50°C, at the same number of load cycles.

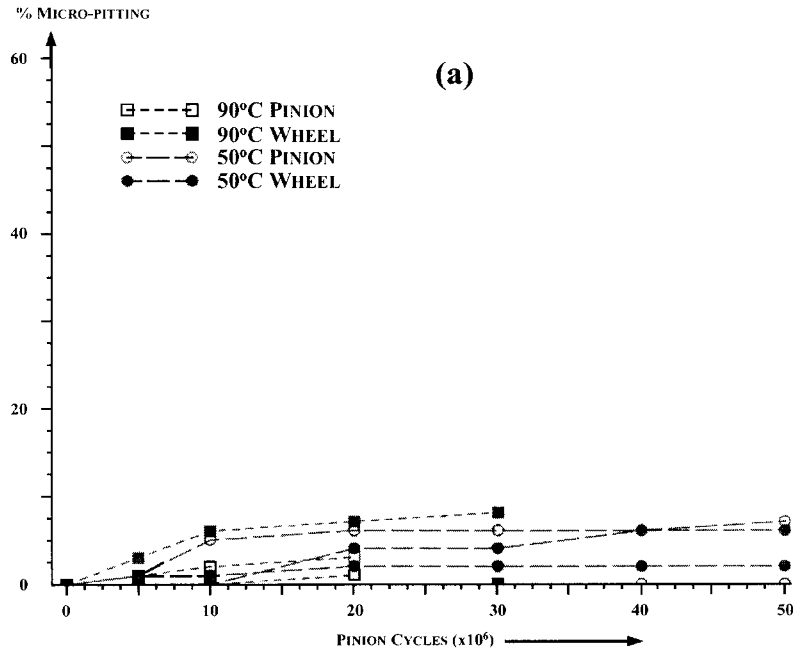


FIG.8A – PERCENTAGE AREA VALUES FIR DESIGN UNIT TESTS – OIL A

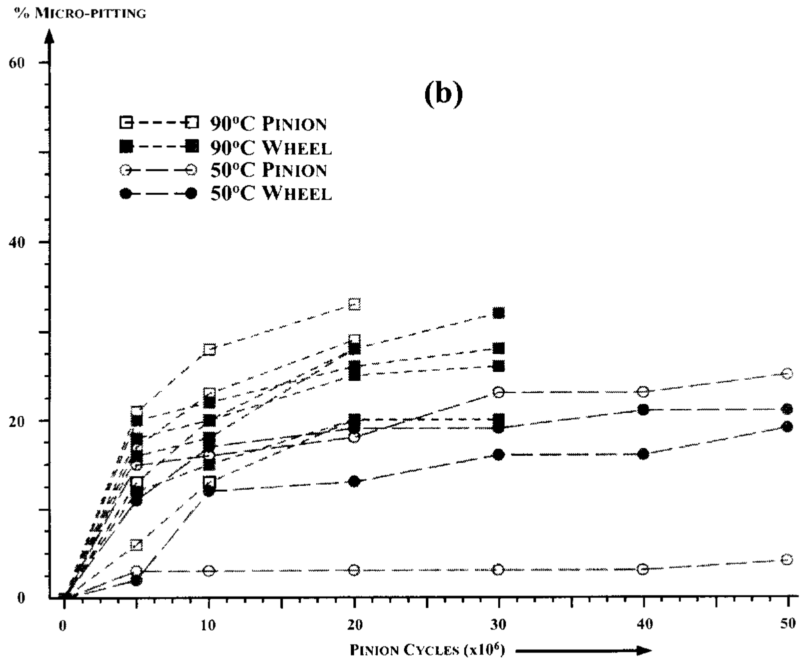


FIG.8B – PERCENTAGE AREA VALUES FOR DESIGN UNIT TESTS – OIL B

For gears tested in Oil B, the maximum area of micro-pitting at 90°C is greater than that measured at 50°C (33% after 20x10^6 load cycles at 90°C compared with 25% after 50x10^6 load cycles at 50°C), as shown in FIG.8(b). The area of micro-pitting increased rapidly in the first 20x10^6 load cycles and then the rate of increase of the area of micro-pitting reduces.

The micro-pitting roll length in the dedendum was slightly higher for gears run in Oil B at 50°C, reaching a maximum of 11mm after 50x10^6 load cycles, compared with a maximum of 8mm for gears run in Oil A (FIG.9).

This trend can be attributed to the higher values of percentage micro-pitting measured on gears run in Oil B. There was no significant change in the extent of micro-pitting above 20x10^6 load cycles for gears run in Oil B. For Oil A, at 90°C, the maximum value of extent of micro-pitting was the same as that measured on gears tested at 50°C (FIG.9(a)) at the same number of load cycles.

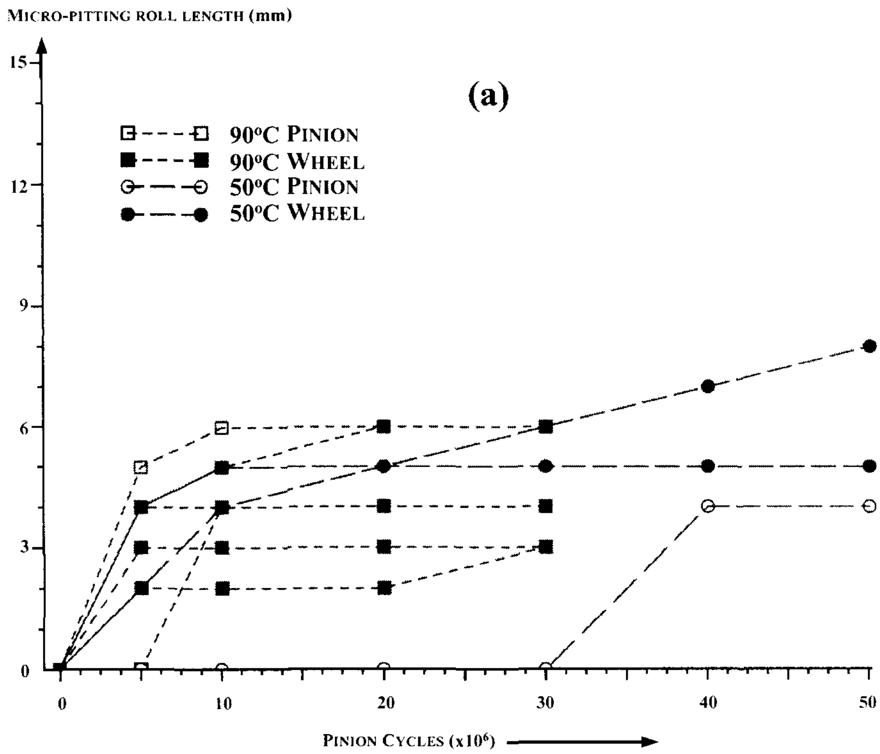


FIG.9A – MICRO-PITTING ROLL LENGTH VALUES FOR DESIGN UNIT TESTS – OIL A

As previously, there was no significant increase in the extent of micro-pitting above 20x10^6 load cycles. FIG.9(b) shows the relationship between extent of micro-pitting and number of load cycles for gears tested in Oil B at 90°C. Again, the maximum value of extent of micro-pitting is the same as that measured on gears tested in the same oil at 50°C, but at a lower number of load cycles. The rate of increase of the extent of micro-pitting is higher than on gears tested in the same oil at 50°C.

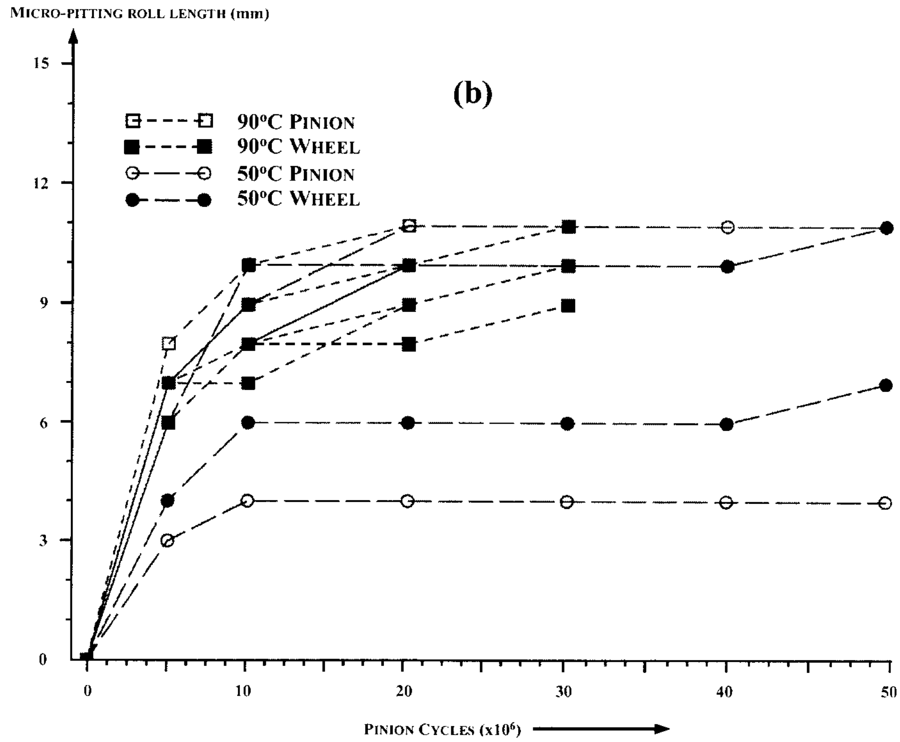


FIG.9B – MICRO-PITTING ROLL LENGTH VALUES FOR DESIGN UNIT TESTS – OIL B

Conclusions and future work

From the testing that has been carried by DERA and Design Unit to investigate the micro-pitting performance of two oils using standard FZG gears and helical gears, it is possible to draw the following conclusions:

1. Both test oils show good micro-pitting resistance at 50^{0}C. There is no appreciable difference in performance between the two oils and all gears reached the end of test.
2. Oil A showed no significant change in performance at 90^{0}C although occasional micro-pitting and flank bending failures occurred on helical test gears.
3. Oil B showed a marked decrease in micro-pitting resistance at 90^{0}C with a profile deviation of greater than 20µm measured after 20-30x10^6 pinion cycles on the helical test gears. No other types of failure occurred.
4. The dense, progressive micro-pitting in the dedendum is responsible for major involute profile loss on both spur and helical gears and ultimately leads to gear failure according to the test procedure.
5. The relationship between profile loss and number of cycles is approximately linear for the FZG spur gears as expected from previous work. This is not the case for helical gears and there is no increase in profile deviation seen above 20-30x10^6 pinion cycles except for gears tested in Oil B at 90^{0}C.

6. There appears to be no correlation between profile loss and percentage micro-pitting or weight loss from the DERA test data.

The work carried out to date has given confidence in the ability of gear test methods to evaluate micro-pitting performance and has shown that measurement of change in involute profile can be used to effectively monitor the micro-pitting fatigue process. The current research programme will continue by attempting to establish the main influencing factors on micro-pit development. The areas being considered for future investigation are:

Flank hardness and any differential gear pair hardness.

(*a*) Surface finish e.g. superfinishing, grinding method, honing, shot peening.

(*b*) Residual stress/retained austenite e.g. changes due to shot peening or deep freeze.

(*c*) Application of 'protective' flank coatings e.g. carbon/tungsten carbide based coatings.

(*d*) Method of heat treatment e.g. nitriding, carbonitriding.

(*e*) Lubrication mode e.g. viscosity, EP additive chemistry.

(*f*) Gear design e.g. effects of involute relief.

(*g*) Steel alloy choice.

(*h*) Running conditions e.g. running-in mode, speed, temperature.

As well as understanding the effect of these processes, the research team will be attempting to understand the mechanism of micro-pit formation and growth, which should assist in directing the future research. The on-going BGA programme of work will examine these areas through collaboration with Imperial College, University of Wales (Cardiff), DERA and Design Unit and will hopefully lead to future improvements in gearing.

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