MICROPITTING OF AUSTEMPERED DUCTILE IRON GEARS: BIODEGRADABLE ESTER VS. MINERAL OIL

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ABSTRACT

High strength austempered ductile iron (ADI) gears are widely used in mechanical transmissions having as main advantages the low production cost, the eventual noise and vibration reduction and the self lubricant properties of graphite nodules. Environmental awareness is leading to a growing interest in biodegradable non-toxic lubricants. However, the key aspect for any industrial application is technical performance and technical advantages proved in dedicated tests. The aim of this work is to evaluate and compare the protection against micropitting provided by a biodegradable non-toxic ester and a reference mineral industrial gear oil in gears manufactured in ADI. Gear micropitting tests were performed in the FZG test rig using type C gears according to the DGMK gear micropitting short test procedure. Lubricant samples were collected during the tests. Extensive post testing analysis was performed in order to compare the performance of the two industrial gear oils: pinion and wheel weight loss, evolution of the micropitted area on the teeth flanks, ferrometric analysis of lubricant samples and teeth flank surface roughness.

1 INTRODUCTION

One of the most important factors in gear micropitting development is the lubricant and its chemistry, and this influence must be determined and validated in dedicated tests.

High strength and high surface hardness materials, material cleanness and thermal treatments used in gear production allow very high contact pressures and improve substantially the contact fatigue behavior of gears. Therefore, the power limitation of gears is not determined by tooth root fatigue or pitting but by micropitting.

The progression of micropitting may eventually result in pitting or spalling. Cases have been reported where the micropitting progresses up to a point and stops, sometimes described as a form of running-in or stress relief. Although it may appear innocuous, such loss of metal from the gear surface causes loss of gear accuracy, increases vibration, noise and other related problems. The metal particles released into the oil may be too small to be picked up by filters, but large enough to damage tooth and bearing surfaces.

This work presents micropitting tests realized with AID gears and two industrial gear lubricants. The lubricants, material, test rig, test procedure and results are presented and analyzed in the next paragraphs.

2 LUBRICANTS

Environmental compatibility is usually viewed in respect to biodegradability and toxicity. While the first issue is reached by using a suitable bio-degradable base fluid, low toxicity requires additives that are environmentally friendly, too. However, lubricant performance (friction, wear, lifetime, load bearing, efficiency etc.) has a major impact on its overall environmental compatibility. Premature wear, high energy needs are as well harmful to the environment.

Two industrial gear lubricants are tested and compared: a reference ISO VG 150 mineral oil, containing an additive package to improve micropitting resistance, and an ISO VG 100 biodegradable fully saturated ester lubricant with a low toxicity additivation. Both oils are specified as CLP gear oils according to DIN 51517.

The reference gear oil is based on a paraffinnic mineral oil with significant residual sulphur content. It contains an ashless antiwear additive package based on phosphorous and sulphur chemistry and metal-organic corrosion preventives.

In contrast, the biodegradable product uses a fully saturated ester based on harvestable materials. The absence of unsaturated bonds in this base fluid leads to excellent thermal and oxidative stability. To combine the desired low toxicity with superior gear performance, environmentally compatible, highly efficient additives have been selected. Metal-organic compounds have been completely avoided.

The main properties of the two lubricants are shown in Table **1** . The two oils were chosen so that their kinematic viscosities will be almost the same at 90 ºC.

The additive content of the reference oil is considerably higher than that of the ester fluid, mainly in what concerns the sulphur compounds.

Standardized, internationally recognized test methods are available for determining the biodegradability and environmental toxicity of lubricants and their components.

The “ultimate” biodegradability of lubricants is best assessed using a “ready” biodegradability test as published by the OECD and adopted by European Union.

The mineral oil didn’t match the minimum requirements of 60% biodegradability in 28 days, as shown in Table 1. Thus, no toxicity tests were performed for this lubricant.

The ester based oil exceeded the minimum requirements of 60% biodegradability in 28 days and pass both toxicity tests, OECD 201 “Alga growth inhibition test” and OECD 202 “Daphnia Magna acute immobilization” as show in Table 1.

Table 1 – Physical and chemical properties of the considered lubricants.

Parameter	Method	Desig.	Units	Lubricating Oils	
Base oil	DIN 51451	/	/	paraffinic mineral oil	fully saturated ester
Physical properties					
Density @ 15ºC	DIN 51757	ρ_{15}	g/cm^3	0.897	0.925
Kinematic Viscosity @ 40 ºC	DIN 51562	ν_{40}	cSt	146	99.4
Kinematic Viscosity @ 100 ºC	DIN 51562	ν_{100}	cSt	14.0	14.6
Viscosity Index	DIN ISO 2909	VI	/	92	152
Pour point	DIN ISO 3106		ºC	-21	-42
Wear properties					
KVA weld load	DIN 51350-2	/	N	2200	2200
KVA wear scar (1h/300N)	DIN 51350-3	/	mm	0.32	0.35
Brugger crossed cylinder test	DIN 51347-2	/	N/mm^2	68	37
FZG rating	DIN 513540	K_{FZG}	/	>13	>12
Chemical Content					
Zinc	ASTM D-4927	Zn	ppm	-	-
Calcium	ASTM D-4927	Ca	ppm	40	-
Phosphor	ASTM D-4927	P	ppm	175	146
Sulphur	ASTM D-4927	S	ppm	15040	180
Biodegradability and toxicity properties					
Ready biodegradability	OECD, 301 B		%	<60	≥60
Aquatic toxicity with Daphnia	OECD, 202	EL_{50}	ppm	-	>100
Aquatic toxicity with Alga	OECD, 201	EL_{50}	Ppm	-	>100

3 AUSTEMPERED DUCTILE IRON

Austempered Ductile Iron (ADI) has been used since the late 1970s, as a result of the strong research effort made by manufacturers like General Motors (USA) and Kymmene (Finland), among others. Since then a lot of progress has been made and it is now possible to produce high-resistance ADIs, materials that are almost impaired in terms of mechanical properties among the Fe-C alloy products. Actually, ADIs are only surpassed by high-resistance alloyed steels when tensile strength is considered [1].

Replacing conventional steel parts by ADIs results in several advantages which strongly promoted the acceptance and use of these materials, namely in the automotive industry. The first economical reason to use ADIs is that the base material (nodular iron) is cheaper than steel, the second is that ADIs are casting materials, thus products can be molded, allowing significant cost reduction of the manufacturing process when compared to conventional steel machining [2]. ADIs are also very interesting for the automotive industry as they allow considerable weight reduction (10% lighter than steel), high vibration absorption (more than 6 dB attenuation can be achieved in a gearbox, per instance [3]) and a very high wear and scuffing resistance, avoiding malfunctions under unpredicted unfavorable working conditions (a momentaneous failure of a lubrication system, per instance) [4].

ADIs present several important tribological characteristics, most of them dependent on the matrix structure and on the presence of the graphite nodules. These self-lubricating materials also provide strong fatigue resistance due to the TRIP phenomena (a mechanically induced phase transformation that can delay the growth of fatigue cracks) [5]. ADIs' tribological performance is not dependent of the presence of AW and EP additives in the lubricants, allowing the use of non-additivated oils, a major ecological benefit. The heat-treatments are also low-energy consumers (austempering is done at about 300ºC), avoiding the use of special equipments and allowing cost-savings when compared to steel quenching or other conventional heat-treatments [2].

The use of ADIs is limited when extreme tensile strength is required (most of the power-transmission gears are still made of steel) but some ADIs can now reach more than 1600 MPa u.t.s., according to ASTM normalization, thus being able to support the efforts imposed by the majority of the mechanical applications [4].

The ADI used has the following nominal chemical composition (weight % ± 10%): 3.52 C, 2.39 Si, 0.89 Cu, 0.51 Mn, 0.042 Mo, 0.038 Cr, 0.012 P and 0.012 S. The ADI gears heat treatment consists of austenitization at 875ºC and austempering at 300ºC.

Table 2 displays the main mechanical properties of ADI material used in this work in comparison to those of 16 MnCr 5 carburized steel, a typical gear material.

Table 2 - Technical properties of ADI material and of 16 MnCr 5 carburized steel.

Properties	Unit	Austempered Ductile Iron	16 MnCr 5 carburized steel
Modulus of elasticity	10^3 N/mm^2	170	206
Poisson's ratio		0.25	0.3
Density	g/cm^3	7.06	7.85
Surface hardness	HRC	42	60
Tensile strength	N/mm^2	1208	1300
Yield strength 0.2%	N/mm^2	1070	550
Elongation	%	6	8

4 GEAR MICROPITTING TESTS

4.1 Introduction

Micropitting is a contact fatigue wear phenomenon that is observed in combined rolling and sliding contacts operating under elastohydrodinamic lubrication (EHL) or mixed EHL/Boundary lubrication conditions. Micropitting can be regarded as fatigue failure with a net of cracks close to the surface which typically starts during the first 10^5 to 10^6 stress cycles. The cracks propagate at a shallow angle to the surface forming micro-pits with characteristic depth in the range of 5-10μm. The micro-pits coalesce to produce a continuous fractured surface with a dull mate appearance. In case the surface cracks propagate deeper into the material, pitting and spalling can be initiated [6, 7].

Micropitting is known to be influenced by operating conditions such as temperature, load, speed, sliding, specific film thickness, lubricant additives and surface material as well.

Not considering lubricant chemistry, the key factors to produce micropitting are mixed lubrication and combined rolling and sliding. By a thick EHL film and smooth surfaces micropitting can be eluded [8].

For gears with parallel axis, pure rolling exists only at the pitch point. Above and below this point there is a combination of rolling and sliding, and sliding speed increases when the contact point moves away from the pitch line. Figure 1 shows two teeth at the beginning and at the end of the engagement, showing the directions of the rolling speed (R) and sliding speed (S). The most critical contact condition that leads to micropitting occurrence is when sliding and rolling directions are opposite. This contact condition always occurs below the pitch diameter both for the driving and the driven gears.

4.2 FZG test rig

The micropitting tests were performed on the FZG gear test rig, shown in Figure 2. It's well known back-to-back spur gear test rig with "power circulation".

The test pinion (1) and the test wheel (2) are connected by two shafts to the driving gears (3). The front shaft is divided in two parts with the load clutch between (4). One half of the load clutch can be fixed to the foundation by a locking pin (5) while the other part can be twisted using a load lever and weights (6). After bolting the clutch together the load can be removed and the shaft unlocked. Now a static torque is applied to the system that can be measured by the torque measuring clutch (7).

The maximum speed of the AC-motor is 3000 rpm. The test gears can be dip lubricated or jet lubricated. When dip lubrication is used, the oil may be heated using the electrical heaters mounted in the test gearbox. The heater and cooling coil allows the settling of a constant oil temperature measured by the temperature sensor (8).

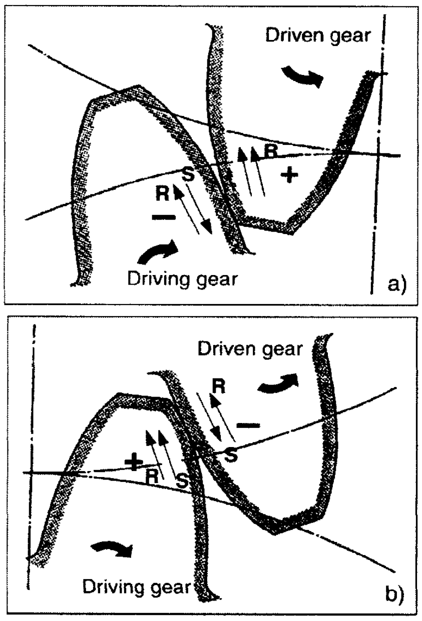


Fig 1 - Rolling and sliding directions. a) Beginning of engagement. b) End of engagement.[9].

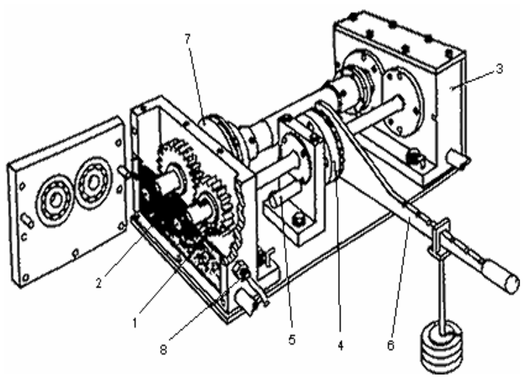


Fig 2 - FZG Gear Test Rig: Schematic view.

Table 3 - Geometry of the test gears.

Parameter [Units]	Pinion	Wheel
Number of teeth	16	24
Module [mm]	4.5	
Center distance [mm]	91.5	
Addendum diameter [mm]	82.45	118.35
Pressure angle [°]	20	
Addendum modification [/]	+0.182	+0.171
Face width [mm]	14	

The test gears used in these micropitting tests are similar to standard FZG type C gears. The geometric characteristics are presented in Table 3.

Table 4 shows the gear quality grade of tested steel and ADI gears according to ISO1328 standard in comparison with the standard FZG type C gear for micropitting. The tested gears have a quality grade considered "current" while the standard gear has a "fine" quality grade. This difference is expressed in the average flank roughness.

4.3 Test definition

The definition of the test conditions was based on the FVA research project Nr. 54/I-IV [10] and the DGMK-FZG micropitting short test (abbreviated as GFKT-C/8.3/90) [11].

The GFKT-C/8.3/90 is a short term test that is able to classify candidate lubricants analogous to the FVA-FZG micropitting test. Being the later a well established standard test but having high costs and being quite time consuming.

The standard GFKT micropitting test is performed on load stages K3 (running-in), K7 and K9, which are excessively severe for ADI material, since ADI contact fatigue resistance is lower than that of case hardened steel.

The set of tests followed the test conditions proposed by GFKT-C/8.3/90, but with some differences: the gear quality, the surface roughness of test gears and the load stages used with ADI gears (see Table 5).

The test procedure for micropitting resistance evaluation can be resumed as follows:

1. Load stage K3 (running-in),
2. Collect a lubricant sample for analysis,
3. Load stage K5,
4. Collect a lubricant sample for analysis,
5. Dismount gears, weight and roughness measurement and surface photography,
6. Mount gears with fresh lubricant,
7. Load stage K7,
8. Repeat step 4 and step 5.

4.4 Gear test results

The results of micropitting tests are presented in a comparative way, i.e. each considered property is analyzed for all the test combinations in order to allow a better understanding of relative behaviours.

Table 4 – Gear quality grade and average surface roughness (pinion and wheel).

	Gear reference	Lubricant type	Gear quality grade (ISO 1328)	Mean roughness Ra of tooth flanks
Standard gear	-		5	0.5 μm
ADI austempered at 300ºC	ADI-Mineral	Mineral	9	0.70 μm
	ADI-Ester	Ester	9	0.73 μm

Table 5 – Test procedure and operating conditions for micropitting tests with ADI gears.

	K_{FZG}=3, running in		K_{FZG}=5		K_{FZG}=7	
	pinion	wheel	pinion	wheel	pinion	wheel
Temperature [ºC]	80		90			
Torque [Nm]	28.8	43.2	70	104.9	132.5	198.8
Rot speed [rpm]	2250	1500	2250	1500	2250	1500
Vt [m/s]	8.3					
Hertzian Stress [MPa]	487		760		1046	
Power [kW]	6.8		16.5		31.2	
Duration [h]	1		16		16	
N cycles [x10^3]	135	90	2160	1440	2160	1440

The micropitting failure normally occurs on the pinion teeth, since it performs 33% more cycles than the wheel. So, the results concerned with micro-pitted area (pictures and surface roughness) are referred to the pinion, while the lubricant analysis results report to both pinion and wheel.

4.4.1 Gear mass loss

The mass loss results for ADI gears during micropitting tests are represented in Fig 3. Fig 4 shows the sum of mass losses at the end of test.

The mass loss comparison shows that the ester oil promotes a smaller mass loss than mineral oil, although after running-in and load stage K5 it displays a larger mass loss.

4.4.2 Lubricant samples ferrometry

The analysis of the wear particles contained in the lubricant gives quite good indication about the wear of lubricated parts, since those particles in a closed box have origin in the contacting parts.

The direct reading ferrometry counts the particles contained in a lubricant sample and separates them by size. After each load stage, including running-in FZG load stage 3, a lubricant sample has been collected to evaluate lubricant condition.

Those samples are analyzed by Direct Reading Ferrometry in order to measure the ferrometric parameters ***Dl*** (large wear particles index) and ***Ds*** (small wear particles index).

The values of ***Dl*** and ***Ds*** are used to evaluate the concentration of wear particles

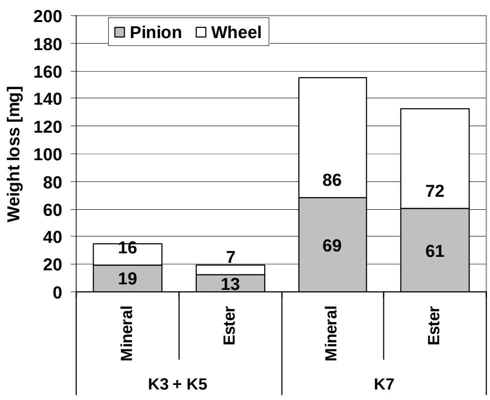


Fig 3 – Pinion and wheel mass loss s after the different load stages for ester and mineral lubricants.

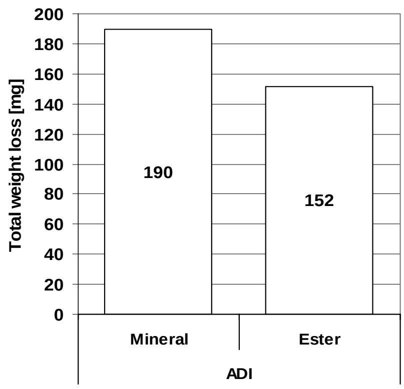


Fig 4 – Cumulative mass loss of ADI gears.

index - CPUC and the severity of wear particles index - ISUC, defined as

$$CPUC = \frac{Dl + Ds}{d} \text{ and } ISUC = \frac{Dl^2 - Ds^2}{d^2},$$

where d stands for the oil sample dilution.

The CPUC index grows when the sum of the small and the large particles increase, while the ISUC index grows when the number of particles with a size greater then 5μm are present in major number than the smaller than 5μm.

It's important to remember that after each load stage the lubricant is replaced, thus the wear indexes presented refer to the test period, not to all test duration.

Fig 5 shows the CPUC index (wear particles concentration) and Fig 6 shows the evolution of the ISUC index (severity of wear particles) measured for the mineral and ester oils during the gear micropitting tests. The general behavior is similar for both lubricants: The sizes and numbers of wear particles almost don't increase from running-in to load stage 5, but increase very significantly from load stage 5 to load stage 7, indicating a severe increase in the number of wear particles, for both lubricants.

However the ester oil generates less wear particles then the mineral oil in the highest load stage.

4.4.3 Analytical ferrography

The lubricants samples collected during the gear micropitting tests were also analyzed using analytical ferrography. The corresponding ferrograms are shown in Fig 7.

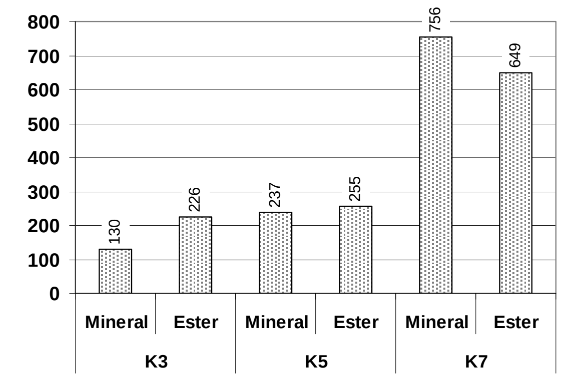


Fig 5 - Evolution of ferrometric index CPUC during the gear micropitting tests.

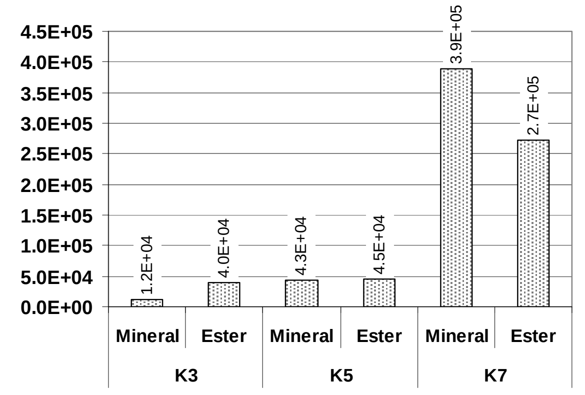


Fig 6 - Evolution of ferrometric index ISUC during the gear micropitting tests.

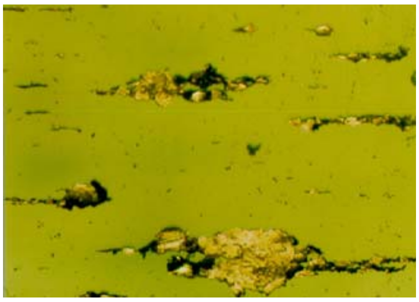
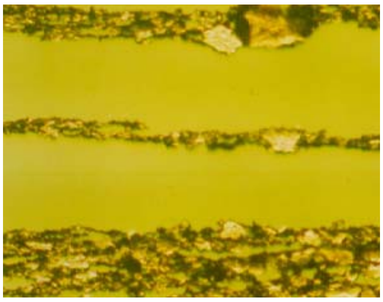
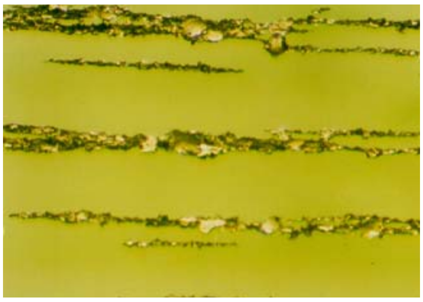
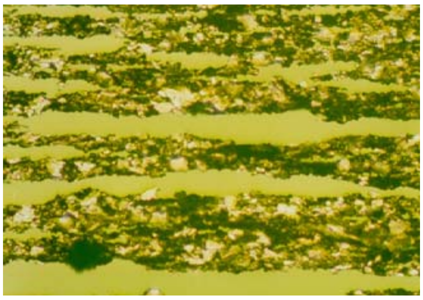
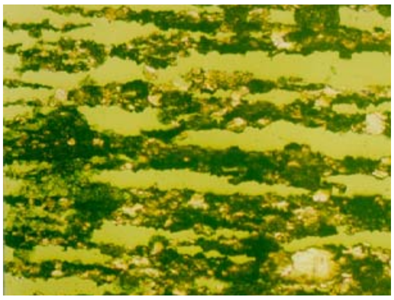
	ADI - Mineral oil	ADI – Ester oil
Running in, load stage K3	 **d = 0.1; Dl = 11.3; Ds = 1.7;** **CPUC = 130; ISUC = 1.3E4;**	 **d = 0.1; Dl = 20.1; Ds = 2.5;** **CPUC = 226; ISUC = 4E4**
Load stage K5	 **d = 0.1; Dl = 21; Ds = 2.78;** **CPUC = 237; ISUC = 4.3E4**	 **d = 0.1; Dl = 21.6; Ds = 3.9;** **CPUC = 255; ISUC = 4.5E4**
Load stage K7	 **d = 0.1; Dl = 63.5; Ds = 12.1;** **CPUC = 756; ISUC = 3.9E5**	 **d = 0.1; Dl =53.4; Ds = 11.5;** **CPUC = 649; ISUC = 2.7E5**

Fig 7- Ferrogram pictures after each load stage for micropitting tests ADI-Mineral and ADI-Ester. Magnification = 200 x.

ADI - Mineral	ADI - Ester

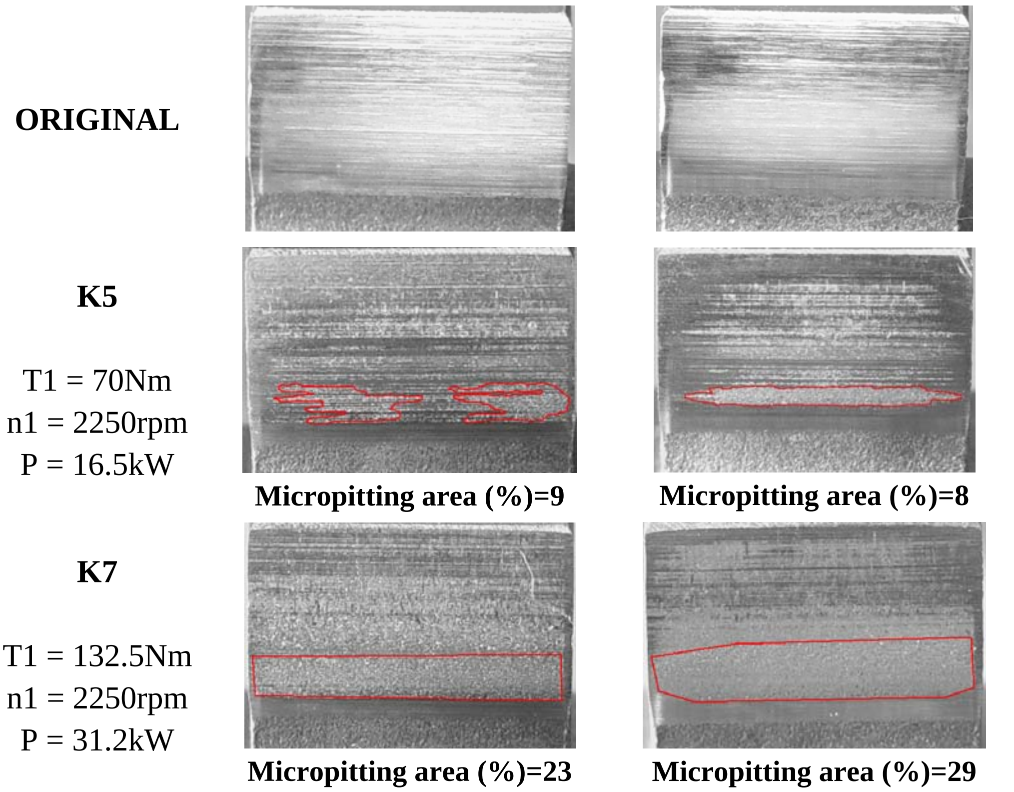


Fig 8 - Pictures of pinion teeth before and after each load stage (ADI lubricated with mineral and ester oils).

Large size wear particles are generated during the running-in period, decreasing its number during load stage K5 and reappearing in load stage K7.

Typical contact fatigue wear particles are generated in all load stages and their number increase with increasing load stages for both lubricants. After load stage K7, the number of wear particles generated by the ester oil is, in general, smaller then that corresponding to the mineral oil.

4.4.4 Micropitting area

Assessment of micropitting failure is a difficult task to perform by visual inspection. It is often reported that with the gears mounted on the shafts, it is almost impossible to detect micropitting. Light of high intensity is needed to distinguish the grey stained area that micropitting resembles. In these tests, that same difficulty was experienced. The visual inspection of gear teeth was done with recourse to a camera to photograph the teeth allowing the observation of micropitting evolution along tests. After dismounting and cleaning the teeth surface, significant pictures were recorded, shown in Figure 8. On these pictures the micro-pitted area is surrounded by a red line for easier reading.

After load stage K5, the micropitted area is very small. On the test with mineral oil (ADI-Mineral) the micropitting band has a larger width but has a shorter height than with ester oil (ADI-Ester). After load stage K7 the micropitted area increased significantly, presenting on both tests a micropitting band along the total width of the tooth and a significant increase in micropitted area, as can be observed in Figure 9. The micropitted area after load stage K7 is two times the area measured after load stage K5.

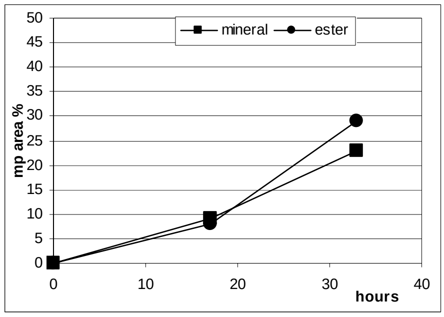


Fig 9 - Micropitted area on ADI gear tests with Mineral and Ester based oils.

5 DISCUSSION

5.1 Mass loss

The ADI gear lubricated with ester lubricant (ADI - Ester) shows 20% less weight loss than the ADI gear lubricated with mineral oil (ADI - Mineral).

With DIN 20MnCr5 case carburised gears the opposite behaviour occurs and the mineral oil generates less mass loss than the ester fluid [12].

5.2 Ferrometry measurements

The ferrometric indexes evolution for ADI gears from running-in to load stage K5 displays a small growth of ferrometric indexes, but for load stage K7 the concentration of wear particles (CPUC) gets twice greater and the severity of wear (ISUC) growth even more indicating a very severe wear during load stage K7 and that the size of wear particles is getting bigger.

These results happen within both lubricants although the test ADI-Mineral presented the highest values on both indexes after load stage K7.

A comparison between the two lubricants is presented in Table 6, where the percentage difference on ferrometric index is represented for each load stage.

The results of direct reading ferrometry, in particular the CPUC wear index, correlate very well with mass loss measurements, as shown in Figure 10. This good agreement between mass loss and CPUC index was also observed with case hardened gears [12].

5.3 Analytical ferrography

The micropitting tests with ADI gears displays large wear particles after running-in, decreasing substantially after load stage K5 and increasing again after load stage K7. In both tests (ADI - Mineral and ADI – Ester) after load stage K5 the ferrograms show some large size contact fatigue particles, that also appear in load stage K7, although the particles are larger in test ADI - Mineral (both in load stage K5 and load stage K7) being these results in agreement with mass loss and ferrometry results.

The presence of large wear particles is due to the high initial roughness and low manufacturing quality in relation to GFKT test method. This also justifies the increased presence of large wear particles on load stage K9 were the specific film thickness decreases and the contact between surfaces became more frequent.

The type of wear particles generated inside the contact between the gear teeth are similar to those observed in case carburised gears [12].

5.4 Micropitting area

The evolution of the micropitting area, assessed by visual inspection, shows a very similar behaviour between the two lubricants on the ADI gears (mineral and ester). The difference between the two lubricants is presented in Table 7.

Table 6 – Difference in ferrometric indexes between ester and mineral oil.

FZG load stage	K3	K5	K7
$\frac{CPUC_{ester} - CPUC_{mineral}}{CPUC_{mineral}}$ [%]	74	8	-14
$\frac{ISUC_{ester} - ISUC_{mineral}}{ISUC_{mineral}}$ [%]	219	4	-30

Table 7 – Difference in micropitting area ($\mu_{Pitt\ Area}$) between the ester and mineral oil.

FZG load stage	K5	K7
$\frac{(\mu_{Pitt\ Area})_{ester} - (\mu_{Pitt\ Area})_{mineral}}{(\mu_{Pitt\ Area})_{mineral}}$ [%]	-11	26

In general the micropitting area on the teeth flanks of ADI gears is 2 to 3 times larger than that observed with case carburized gears, meaning that the FVA failure criteria developed for carburized gears can’t be applied to ADI gears.

The micropitting behaviour of ADI gears is very good, however not comparable to that of case carburized gears for the same operating conditions and teeth flank surface finishing.

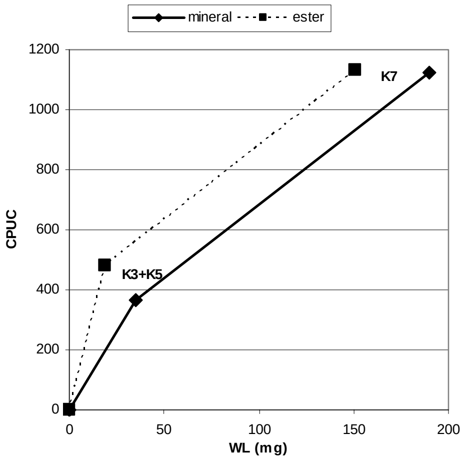


Fig 10 – Correlation of accumulated values of weight loss v.s. CPUC index.

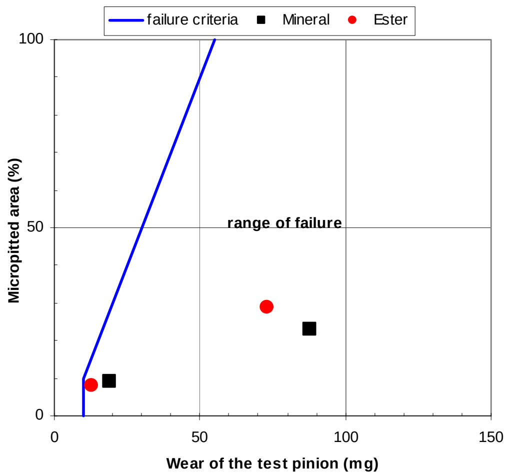


Fig 11 – Comparison of test results with FVA micropitting failure criteria for case carburized gears.

5.5 Modified test procedure

The GFKT short test procedure for the investigation of gear micropitting was adapted with success for testing ADI gears, using FZG load stages K5 and K7 instead of load stages K7 and K9.

ADI is a very interesting gear material, offering reduced manufacturing costs, noise and vibration reduction, slightly lower weight, higher scuffing load carrying capacity, not requiring lubricants with high additive contents, when compared to case carburized gears [13].

The ADI gears are not prone to replace case hardened gears but to be used in applications specifically designed for ADI material.

6 CONCLUSIONS

1. The GFKT short test procedure was adapted with success for testing micropitting in ADI gears
2. The ester oil compared with the mineral oil conferred several advantages:
   - 20% lower cumulative mass loss,
   - 14% lower concentration of wear particles (CPUC)
   - 31% lower severity of wear particles (ISUC)
3. The ester oil generated a 6% larger micropitting area than the mineral oil.
4. The wear above the pitch line is slightly larger on the tests lubricated with ester oil.
5. The type of wear particles found as result of micropitting gear tests is similar for ADI and carburizing gears.
6. The ADI micropitting behaviour is good but incomparable and considerably lower to that of carburizing gears.

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