Detection of gear pitting failure progression with on-line particle monitoring

J. Kattelus[1*], J. Miettinen[1], A. Lehtovaara[1]

[1] *Group of Tribology and Machine Elements, Materials Science: Tampere University of Technology P.O Box 589 33101 Tampere, Finland.*

Abstract

Macroscopic pitting is a common gear flank failure mode. The determination of pitting life is done experimentally and the formation of macropit is typically followed by regular visual inspections and photographing of tooth flanks, which is time consuming and gives limited information about progression of failure. In this study, the progression of gear macropitting was detected with on-line particle monitoring from lubricating oil together with vibration monitoring and visual inspections. The tests were carried out with case-hardened gears under heavy loading condition. The results show that the concentration of metallic particles in oil correlate well with the severity of macropitting obtained from the visual inspection. Vibration acceleration descriptors indicating peaked signal correlate also with the wear of gear contact.

Keywords: gears, pitting, on-line particle monitoring, vibration monitoring.

*Corresponding author: Juho Kattelus (juho.kattelus@tut.fi).

1. INTRODUCTION

Macroscopic pitting is one of the most common gear flank failure modes mainly caused by repetitive Hertzian contact stresses of the mating surfaces. This may cause fatigue cracks initiating from the surface or nearby subsurface leading to the detachment of a macropit. Macropits usually appear at dedentum tooth flank, where both stress and sliding velocity are high. [1] The determination of gear pitting life is done experimentally and the formation of macropit is typically followed by regular visual inspections and photographing of tooth flanks. Visual inspection is pretty time consuming and gives information only from one single time moment. In addition, it is often very challenging to estimate proper inspection intervals especially at the end of the test, when pitting process starts to be progressive. Fundamental knowledge of pitting as well as practical testing procedure would be improved if continuous information related to the progression of pitting failure is available.

Wear of gear pair is challenging to measure directly without disturbing the running contact state and lubrication condition. Indirect methods based on, for example, temperature, acoustic, vibration and oil particle contamination has been used to detect the symptoms of failure caused by wear. Ferrography and spectrometric methods [2; 3; 4] are known to be powerful tools for identifying wear degree and mechanism, but as off-line methods based on analysis of oil samples, they are considered to be too time consuming, laborious and hence providing too delayed information. In on-line and in-line particle monitoring, the detached pits or other solid contaminants in lubricating oil is detected continuously with specific sensors at gearbox outlet proving real time information. The on-line particle monitoring methods can typically detect the amount of particles and classify them to different size classes, but are missing of the ability to detect the shape of the particles. Salgueiro et al. [5] applied an electromagnetic metallic particle sensor, that counts ferrous particles of size ranges from 40 to 300 µm, to monitor the pitting test in single-stage gear box and concluded that the amount of wear particles followed the trend of load level. Feng et al. [6] predicted wear of a spur gearbox and observed early-warning signs of abnormal wear behavior related to pitting and scuffing by employing an on-line visual ferrograph with an index of particle coverage area to characterize wear debris concentration. Martin [7] studied oil contaminants usually found from machines and engines by using digital imaging and digital shape recognition and concluded that it was possible to separate reliably real wear particles from other contaminants like bubbles and drops. This gives also the possibility to make form and particle size analysis for wear particles. Iwai et al. [8] determined wear quantity of against each other rubbing components with on-line particle monitoring based on number of particles and their sizes. The used method correlated well with the measured values of mass loss of the specimen. However, lubricating oil can contain some other contaminants which decrease the accuracy of real wear particle counting. Sugimura et al. [9] used wear image analysis in wear debris analysis to characterize different progress of wear in gears.

Most suitable methods for observing continuously the wearing of gears are particle and vibration monitoring. Vibration monitoring can be used to indicate the gear flank geometry changes due to the wear, for example, in the form of detached pits. In gear operation monitoring typically the amplitude of meshing frequency, number and amplitudes of meshing frequency sidebands, amplitude and multiples of rotational frequencies of shafts and resonance frequencies are measured. [10] The amplitude of meshing frequency is mainly proportional to the loading but not to the fault severity of the gear contact. The sideband frequencies above and below of the meshing frequency tell that there are some problems in running of the gears. Sidebands are generated by amplitude modulation, where the modulating frequency is typically the rotational frequency of one or both shafts and carrier frequency is the meshing frequency. The number and amplitudes of sidebands correlate with the severity of the fault in gear wheel. Normally some low amplitude sidebands can exist also in gear transmission which is in good condition. Typically, the trend of sidebands is monitored. The advantages of vibration monitoring compared to oil particle monitoring are simple sensor installations and simple usage even if the prices of the equipment are very close to each other. Difficulties come up in symptom extraction i.e. to determine suitable descriptors for computing from vibration signal to describe right phenomena. Local wear in gear wheel surface causes local starved lubrication situations. These kinds of phenomena and wear particles in lubrication oil generate in addition to cyclic vibration also random vibration. Random vibration signal can be analysed with several statistical descriptors, which indicate the level of the signal and if the signal is peaked. [11]

It has been shown by many research studies that gear damage can be predicted more reliably by combining on-line particle and vibration monitoring methods [12; 13; 14]. Shah et al. [15] used on-line and off-line oil analysis connected to vibration measurement in condition monitoring of spur gears. Oil analysis consists of on-line particle counting and oil condition and moisture measurement. On-line oil analysis results were verified with off-line methods like analytical ferrography and SEM methods. Vibration analyses contained time synchronous averaging and spectrum methods combined to amplitude modulation phenomenon. Main result was that combining oil particle analysis and vibration analysis techniques gives more reliable condition monitoring, even if vibration analysis needs deep understanding of the frequency responses of gear transmission components. Dempsey [16; 17] combined oil debris monitoring and vibration analysis in machine health monitoring. They found that oil debris monitoring cannot discriminate between gear and bearing failure. Loutas et al. [13] combined acoustic emission monitoring with oil debris and vibration monitoring.

The main objectives of this study are to detect the progression of gear macropitting failure with on-line particle monitoring from lubricating oil and its correlation to the corresponding results obtained with vibration monitoring from the test gearbox and with visual inspection documented by photographs. The tests were carried out with modified FZG gear test rig with real gears and operating condition.

2. EXPERIMENTS

2.1 Test device

Gear tests were carried out using a modified FZG test device, which is shown in (Fig. 1). The loading of the test gears can be adjusted by applying appropriate torque to shaft 1 through the load clutch using weights and a rod. The applied torque is measured on-line from shaft 1 with strain gages and telemetry device. The required power is fed with an electric motor, of which adjustable rotating speed is controlled by frequency converter. The rotational speed is measured from shaft 2 with a pulse sensor. The system friction torque is measured with torque transducer from shaft 2.

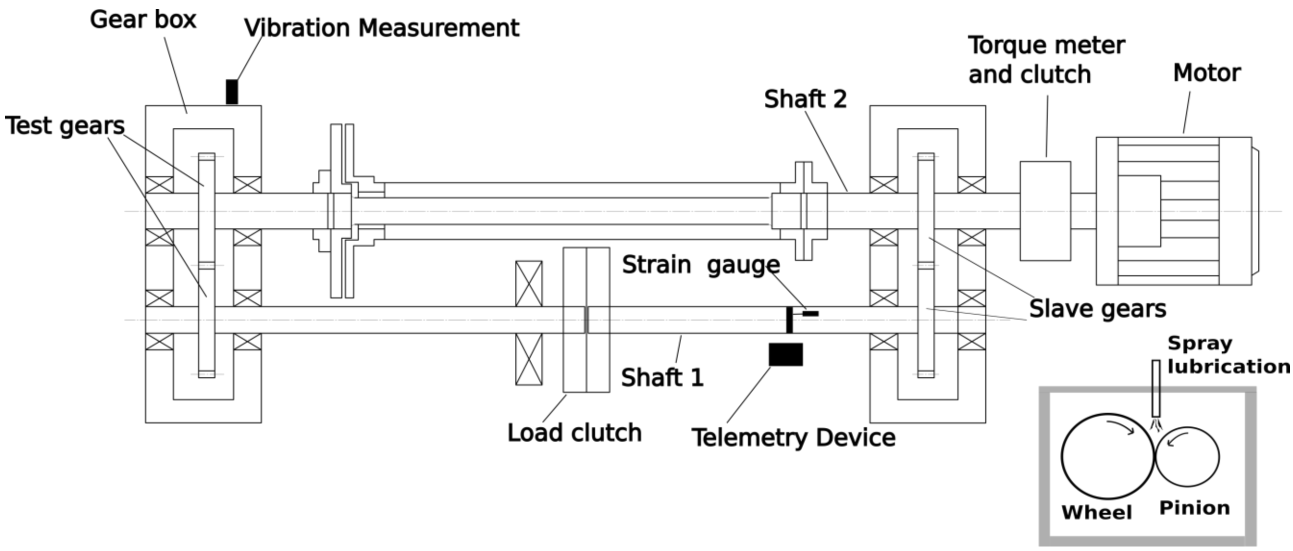

Figure 1. *Principle of the test rig.*

2.2 Test gears and lubricants

The material of the test gears is case hardened steel 18CrNiMo7-6. The gears are case hardened to a depth of 1.0 – 1.3 mm, with specific surface hardness of 60 – 62 HRC. After hardening the gears were ground resulting in the flank Ra surface roughness in the range of 0.46 – 0.52 µm. The main features of the test gears are shown in Table 1. The test gears have modifications in the axial and profile directions.

Table 1. *Gear tooth geometry.*

Parameter	Pinion	Wheel
Number of teeth	16	24
Profile shift	0.182	0.171
Pitch diameter (mm)	73.2	109.8
Tip diameter (mm)	82.45	118.35
Centre distance (mm)	91.5	
Normal module (mm)	4.5	
Face width (mm)	14	
Pressure angle (º)	20	
Working pressure angle (º)	22.439	

The test lubricant was synthetic gear oil ISO VG 320 with kinematic viscosity at 40 and 100 °C of 335 and 38.3 mm^2/s, respectively. The density of the lubricant at 15.6 °C was 860 kg/m^3. The tests were carried out with oil inlet temperature of 60 °C and lubricant flow rate of 2.0 l/min.

2.3 Particle monitoring

The gears and bearings are lubricated using pressurized circulating (spray) lubrication so that the spray is directed with the direction of rotation of gears as shown in Fig. 1. The test and slave gears have their own lubricating systems. The flow chart of the lubrication system of the test gearbox is shown in Fig. 2. Oil fed into the test gearbox is filtrated with 6 µm filter. Cleanliness of the inlet oil is measured from a side flow using an optical particle counter. Particles larger than effective diameter of 4 µm are detected and the results are classified to three different size classes according to ISO 4406 standard. Particles in outlet oil are observed on-line with an inductive metallic contaminant sensor. Ferrous particles larger than the effective diameter of 70 µm and non-ferromagnetic metallic particles larger than the effective diameter of 200 µm are detected. The sampling intervals of the particle monitoring in both cases are one minute.

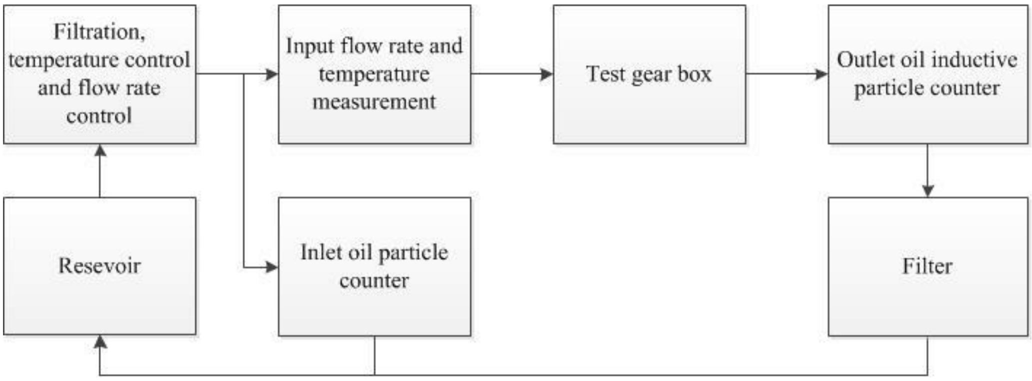

Figure 2. *Basic principle of the lubrication system used in test gear box.*

2.4 Vibration monitoring

The primary target of vibration monitoring was to find out if the progression of pitting is detected with vibration measurements. The other target of vibration measurements was to monitor possible phenomena which are not connected to the gear wheel pitting. These kinds of phenomena are gear wheel misalignment, different kind of looseness and rolling bearing failures. Combining vibration and oil particle monitoring and other running parameter monitoring and photographing may offer more reliable view about the progression of pitting.

The measured parameter was vibration acceleration. Sensor was a piezoelectric accelerometer model B&K 4382. It was installed on the test gear box and fixed with magnet fixing. The + 10 % frequency range of the sensor is 8.4 kHz, but magnet fixing may a little bit reduce the useful frequency band of the sensor.–The meshing frequency of the gear transmission was 600 Hz. Standards e.g. PSK 5719 [10] recommend that the upper frequency limit should be minimum 3.25 times meshing frequency, which in this case means frequency of 1.95 kHz. The sampling rate in measurements was 10 kHz and results were analysed in area of of 5 Hz … 5 kHz in different frequency bands. The descriptors computed from measurement results are presented in Table 2.

Table 2. *Descriptors extracted from vibration acceleration measurement results. N is number of samples,* y_i *is sample value,* y_{max} *and* y_{min} *are max and min values of samples,* $\bar{y}$ *is average and* σ *is standard deviation.*

Descriptor	Definition	Frequency bands
rpm amplitude	rpm	25 Hz and 37.5 Hz
RMS	$RMS = \sqrt{\frac{1}{N}(\sum_{i=1}^{N} y_i^2)}$	20 Hz ... 40 Hz (freq. band of rpm)
Crest Factor	$CF = \frac{\max\lvert y_{max} ; y_{min}\rvert}{\sigma}$	5 Hz … 10 kHz (measurement band) 0.4 kHz ... 0.8 kHz (freq. band of mesh) 1 kHz ... 3 kHz (freq. band of multiple mesh)
Kurtosis	$K = \frac{1}{N\sigma^4}\sum_{i=1}^{N}(y_i - \bar{y})^4$	
Form Factor	$F = \frac{RMS}{\bar{y}}$	

Kurtosis and Crest Factor indicate if the signal is peaked or flat. RMS value indicates vibration acceleration overall level and Form Factor indicates the relationship of RMS and average value. In addition to these values the spectra in the area of meshing frequency was analysed.

2.5 Test procedure

At first the lubricant was circulated through the test device and warmed up to the test temperature in time of minimum of two hours. Running-in was started by setting the rotating speed of 1500 rpm to the shaft 2 and increasing the load stages with 8 steps ranging from 3 to 239 Nm, each step having a time interval of 10 minutes. After running-in the steady-state operating conditions was maintained with the load level of 405 Nm and wheel speed of 1500 rpm. The test rig was stopped at least after every 2,5 million load cycles to detect the possible flank damages. Inspection was documented by photographing all loaded teeth flanks from pinion and if needed also from wheel. The obtained photographs were analysed and the initiation of the damage and the damaged area of the flank were determined. After the inspection the test was continued without running in stages i.e. with the load of 405 Nm. Test was stopped when macropitting damage of at least 4% of the active gear flank was detected or when the cut-off limit of 50 million load cycles was completed. The test rig operation was monitored continuously with the measured signals such as oil temperature, oil flow rate, number of particles, vibration acceleration and torque. An automatic shutdown is followed if the given set limits of these signals were achieved. Before the actual tests the shape of the contact pattern was pretested successfully with first gear of the test series by using contact colour.

Before the experiments the test gearbox was cleaned carefully with solvent. The main parameters and measured signals are loading torque, oil inlet temperature and flow rate, particle counting and vibration acceleration. Loading torque measurement was calibrated with simple weight and torque arm principle. The loading torque was also monitored continuously during the experiments giving the mean value of 404 Nm with standard deviation of 0.04 Nm. Oil inlet temperature was controlled with PID controller resulting in the mean temperature of 60 °C with standard deviation of 0.6 °C. The oil flow was 2.0 l/min and it was measured with oval wheel flow meter having accuracy of ± 5% of reading, which corresponds to error of ± 0.1 l/min in the flow. The operation of vibration sensor was checked with accelerometer calibrator. All measurements except particle counting were carried out with data acquisition device with valid calibration certificate. The particle counter was inductive sensor operating with its factory settings and under valid factory calibration.

3. RESULTS AND DISCUSSION

The progression of gear macropitting was detected using traditional visual inspection documented by photographs, on-line particle monitoring from lubricating oil and vibration monitoring of the test gearbox. The tests were carried out with the modified FZG gear test rig with real gears using pinion rotating speed of 2250 rpm and loading of 405 Nm. The particles in inlet oil flow to the test gearbox were monitored continuously resulting in an average cleanliness class of 8/1/0 according to ISO 4406. This result confirms that the cleanliness of inlet oil was in good level and that there was no recirculation of particles (> 70 µm) already once detected from the outlet oil. The major damages were detected at the pinion gear which rotates 1.5 times compared to wheel gear. All cycle counts and damages mentioned in this work will apply to the test pinion.

3.1 Visual inspection

The visual inspections and photographs were taken after 2.50, 5.00, 7.50, 10.00, 10.76 and 10.84 million cycles on test load of which four is shown in Fig. 3. Fig. 3a shows that after 2.5 million load cycles only very minor scars can be observed in the middle of the flank. The orientations of these scars are in the direction of flank rolling and sliding indicating that they are caused by wear occurring most probably during the start-up, which was done in loaded condition. In any case, running-in of the gears can be considered to be successful. The first signs of micropitting were observed in the root of the pinion in the visual inspection made after 5 million load cycles (not shown in figure). Early signs of macropitting were observed in 10.0 million load cycles as shown in Fig. 3b. Most part of the appeared scar can still be classified as micropitting (grey areas), but the deeper and brighter small areas are already the first symptoms of macropitting even they damaged area compared to the total active flank area is still close to zero. This figure also indicates that the initiation of macropitting is promoted by micropitting as it originates in the same region where micropitting had already occurred. After initiation, the damaged area related to macropitting increases rapidly being 3.3 % in 10.76 million load cycles and 5.7 % in 10.84 million load cycles as shown in Figs. 3c and 3d, respectively. In this stage, the damaged area caused by macropitting had reached over 4 % of the single active tooth flank and the test run was stopped. Macropitting occurred mainly in two adjacent flanks in pinion. The flank presented (Fig. 3) was dominant in size of the macropitting damage. Damages in pinion caused some visible damages to the corresponding wheel teeth. Further on, damages in wheel also caused some minor damages to other two pinion teeth mating with damaged wheel teeth.

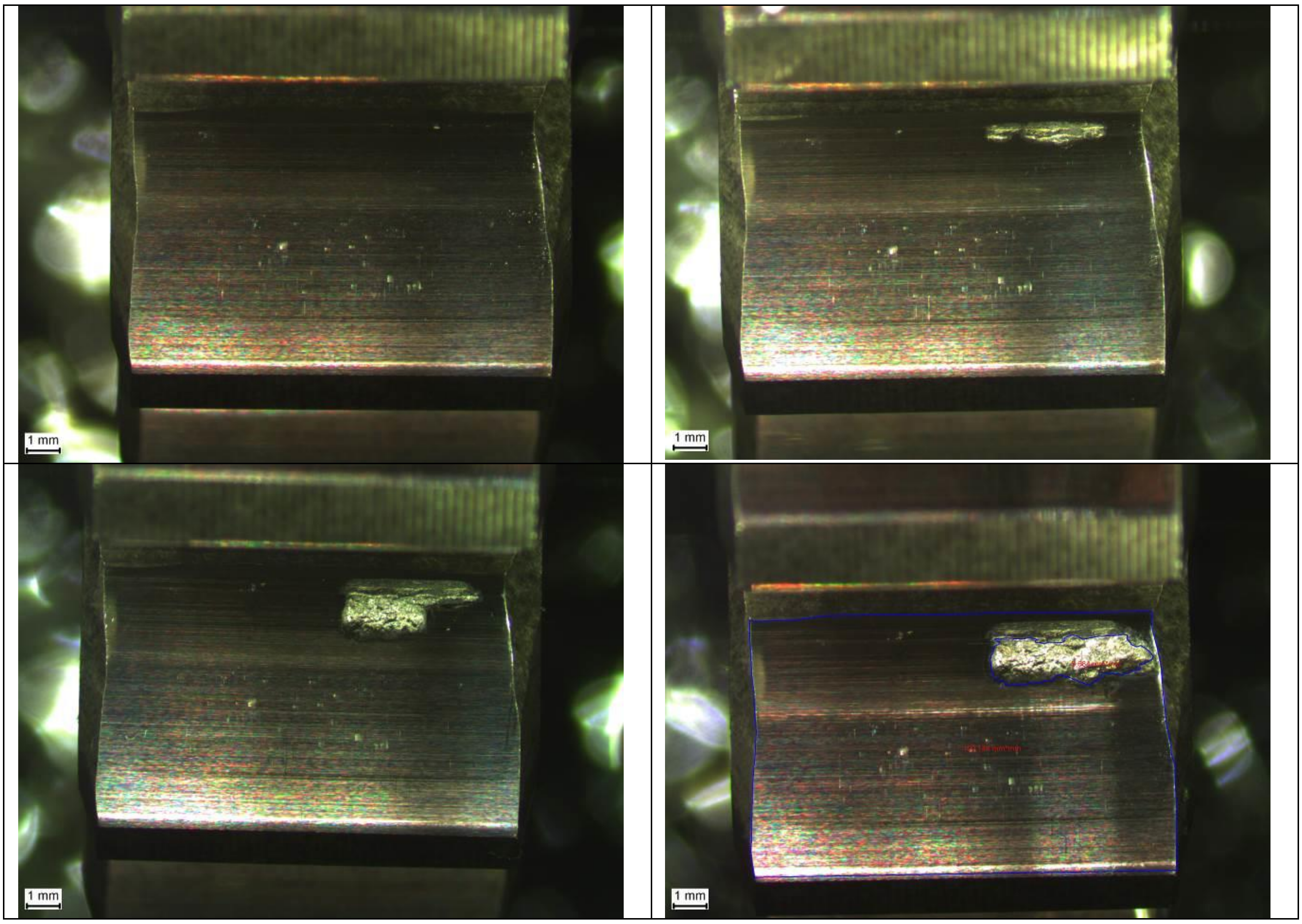

Figure 3. *Progression of macropitting. Pinion teeth after 2.5 (stage 0) (up left), 10.0 (stage 1) (up right), 10.76 (stage 2) (lower left) and 10.84 (stage 3) (lower right) million load cycles.*

3.2 On-line particle monitoring

The results of continuous on-line particle monitoring from oil outlet in the range of 0 - 10.84 million load cycles is shown in Fig.4. The ferrous particles larger than 70 µm in outlet oil were measured and classified to the three different size classes as shown in Fig. 4a. Three particles have bypassed the counter during the first running-in stage, but no further particles were obtained until 6 million cycles and micropitting had already appeared. In this stage some particles were detected, even the size of micropitting particles can be considered to be less than 70 µm. However, Fig. 4b shows that particles observed during last 2 hours, i.e. 270 000 load cycles, produce only occasional single occurrences until after 9 million load cycles they become more regular, but still being mainly single particles. After load cycles of 10.4 million progressive particle production appeared and nearly stepwise increase occurred in 10.7 million load cycles. About 55 % from the total number of particles were obtained during the last 300 000 cycles. Fig. 4a shows that main share of the particles belongs to the smallest size class (70-100 µm), but in later part of the run, where the progressive macropitting occurred particles of size larger than 150 µm already appeared.

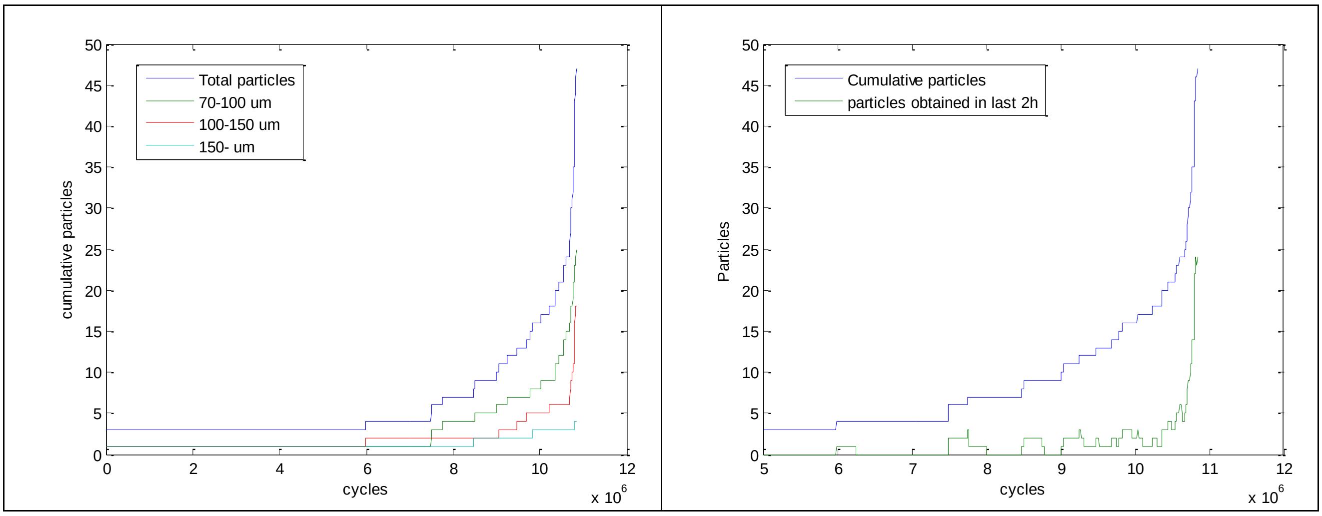

Figure 4. *Ferrous particle accumulation measured from outlet oil (left). Accumulated particles and particles observed in last two hours (right).*

The comparison of the results obtained from the visual inspection and particle on-line monitoring are shown in Fig. 5. The overall trend view is that the results correspond well. After 2.5 million load cycles the gear flank is practically undamaged (Fig. 3a) and the corresponding on-line monitoring showed no particles during loaded run before that time. During the time of micropitting, 5-10 million load cycles, first symptoms of macropitting arose (Fig 3b), but the damage area related to macropitting remained still very small. Correspondingly occasional single particles can already be observed from on-line monitoring. At the end of the run, the number of particles is increasing progressively, which can also be seen in the visual inspection as rapidly increasing damaged area in active gear flank.

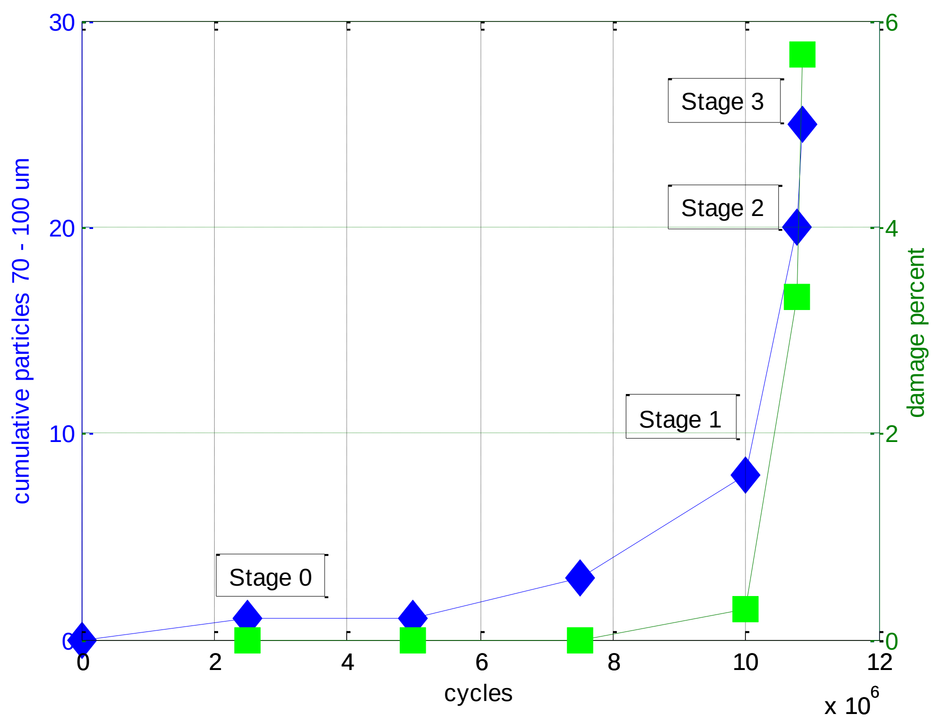

Figure 5. *The comparison of the gear flank damaged area and the measured particles in oil outlet as a function of load cycles. Visual inspection points are dotted. Stages 0 … 3 represent vibration analysis points.*

It is obvious that the particle on-line monitoring provides a promising way to follow the progression of pitting damage in parallel with visual inspection. It gives continuous on-line information about particle accumulation and time for occurrence of single particles as well as the size classification to the appeared particles providing more specific and fundamental view to the formation and evolution of macropitting. In testing point of view, the on-line particle monitoring is able to indicate the initiation of macropitting resulting in that the "extra" visual inspections with the undamaged gears may be avoided and the time for the visual inspection can be triggered from the on-line particle monitoring causing automatic shutdown of the test rig as the given set limit for the number of particles is achieved. It should be noted that the visual inspection is pretty time consuming and it is often very challenging to estimate proper inspection intervals. However, the linking of the absolute number of particles with the absolute damaged flank area is somewhat case dependent. If the progression of pitting is dominant in one gear flank instead of having many flanks pitting at the same speed causes that the first scenario provides larger single flank damaged area vs. the number of particles than the second one. The on-line particle monitoring also counts particles from possible bearing damages in gearbox.

3.3 Vibration monitoring

In Fig. 6 the results of vibration acceleration signal descriptor values in four different running stages are presented. The number of loading cycles of each running state is presented in Fig. 5. Analysis frequency bands are 5 Hz ... 5 kHz which is whole analysis area, 1 kHz … 3 kHz describing the area of multiple meshing frequency, 0.4 kHz … 0.8 kHz which is the area of meshing frequency and sideband frequencies and their multiples, rotational frequency area 20 Hz … 40 Hz and amplitudes in rotational frequencies of the shafts. The results show that the trend of all descriptors is rising. The strongest correlation between descriptors and gear wheel wear stage is in vibration meshing frequency band 0.4 kHz … 0.8 kHz. Most sensitive descriptors were Kurtosis and Crest Factor values. These results tell that the fault in gear wheel generates impact pulses in the vibration acceleration. Form Factor indicated very weakly. The vibration amplitudes at rotational frequency 25 Hz and 37 Hz rose also very clearly along the wear progress. The wear in gear wheels may influence on the roundness of the pitch cone which generates stronger vibration at rotational frequency.

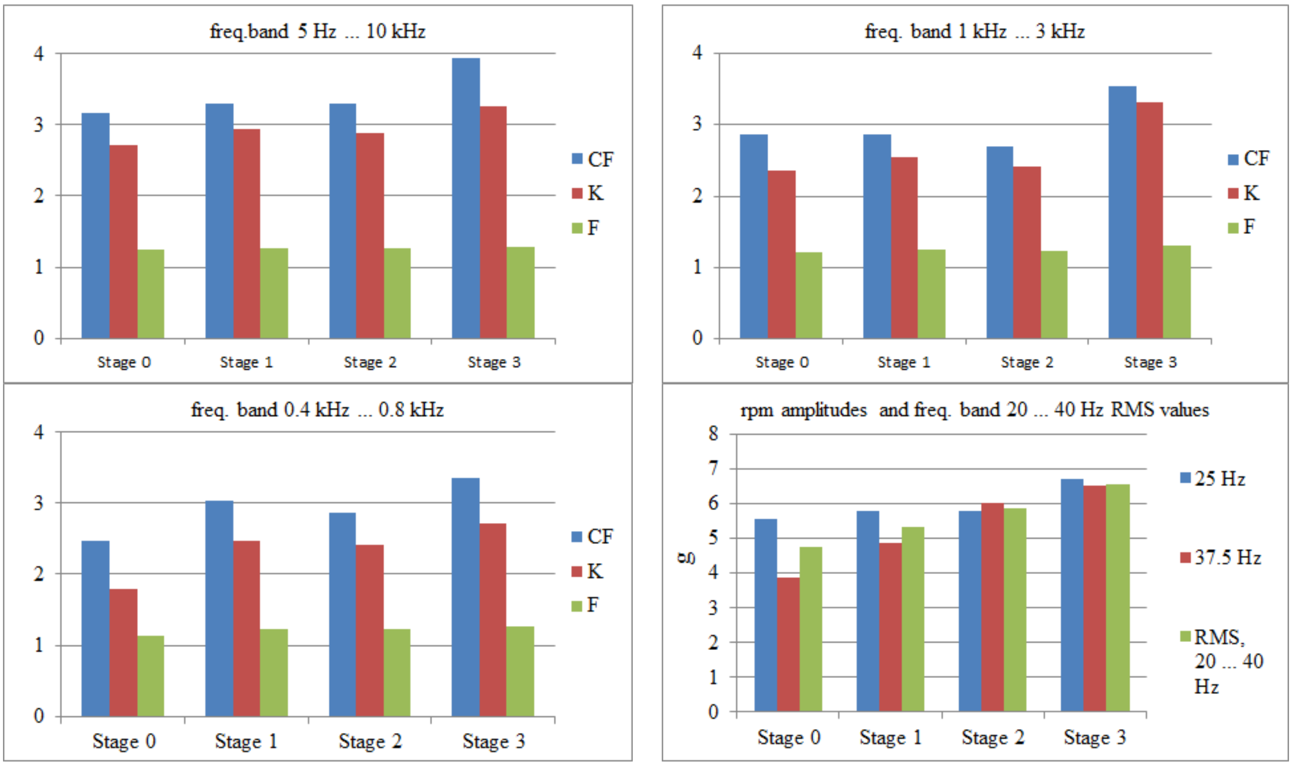

Figure 6. *Values of descriptors extracted from vibration acceleration in different fault stages.*

In Fig. 7 the spectra in frequency band of 500 Hz ... 700 Hz, which is the area covering meshing frequency, sidebands and their multiples are shown. The spectra are scaled relative so that meshing frequency amplitude has value of 1. This has been done, because the interesting thing is relative amplitudes between meshing frequency and sideband frequencies and number of sidebands. Some sidebands are visible in spectrum of stage 0. However, there is a very clear difference in sidebands already between stage 0 and wear stage 1. In stage 2 and 3 the amplitudes of sideband have still a little bit risen.

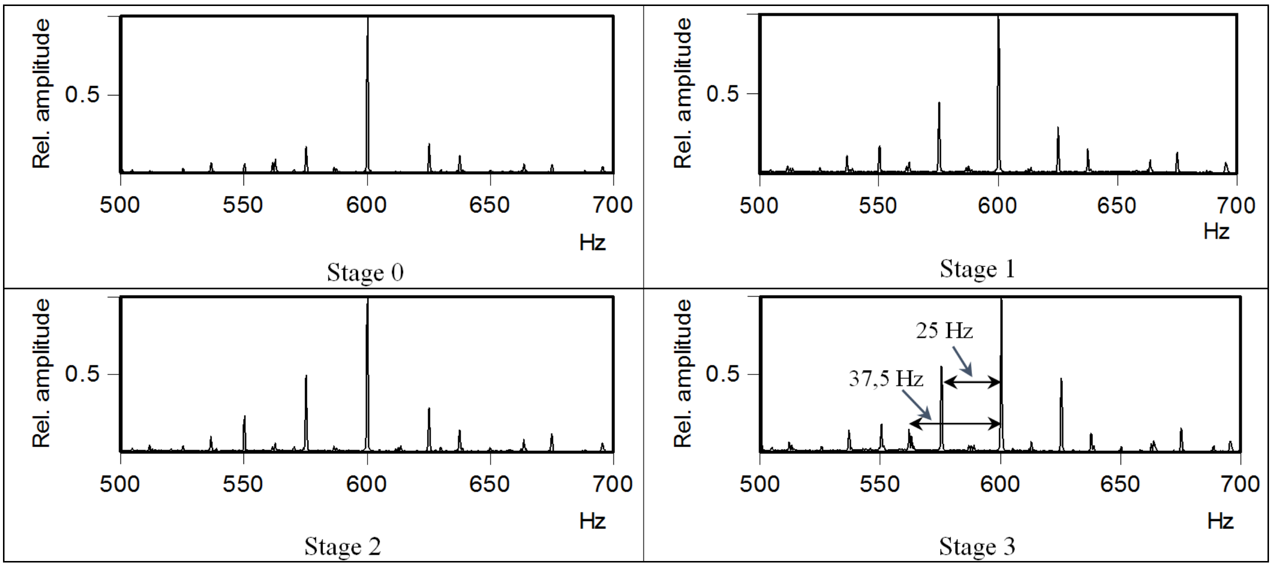

Figure 7. *Spectra in frequency band of 0.5 kHz ... 0.7 kHz in different fault stages. Meshing frequency is 0.6 kHz and sidebands ±25 Hz and ±37.5 Hz and their multiples.*

This study comprises the methodology of applying on-line analysis methods for failure detection and progression in the connection of gear pitting fatigue life testing, where the formation of macropits is traditionally monitored by regular visual inspections. The pitting progression was analyzed in parallel with three different monitoring methods giving new insight to pitting process as well as pointing out characteristic features of each monitoring method and their combination in the studied application. The total view of the results show that on-line particle monitoring from oil as well as vibration monitoring from gearbox offer efficient ways to detect the symptoms of gear fault in early stage of damage. In addition, on-line oil monitoring is also able to follow the progression of gear damage by providing information about the time for occurrence of single particles and particle accumulation and as well as the size classification to the appeared particles. However, the final damage mode of gear flank as well as the absolute damaged flank area need to be verified with visual inspection. The challenge in gear transmissions is that different damage modes can generate very similar kinds of on-line measurement results. The reliability of the right diagnosis increases significantly by combining wear particle and vibration monitoring methods. Taking into account gear transmission design and running stage, gear flank, bearing and several other fault modes can be distinguished using vibration diagnostics. Both methods are also suitable for remote on-line monitoring of gear contact and implementation of automatic diagnosing is possible. The use of visual inspection by photographing may take place mainly to confirm damage mode and its severity if wear particle and vibration monitoring diagnosis shows that wear of gear tooth is probable. Itself digital photographing and picture data transfer for analysis is quick via e-mail or cloud services. The outcome of this study shows that on-line wear particle and vibration monitoring boost the pitting life testing in research environment and provides insight view to the pitting progression. It also supports the view of many other studies [12-17] that both on-line methods have their own specific advantages and especially their combination offers an effective way for modern gear transmission monitoring.

4. CONCLUSIONS

The progression of gear macropitting was detected using traditional visual inspection documented by photographs, on-line particle monitoring from lubricating oil and vibration monitoring of the test gearbox. The tests were carried out with the modified FZG gear test rig with real gears using pinion rotating speed of 2250 rpm and loading of 405 Nm. The following main conclusions were drawn:

- The progression of macropitting failure indicated by the number of metallic particles in oil obtained with on-line particle monitoring correlates well with the damaged gear flank area given by the visual inspection.
- Initiation of macropitting is promoted by micropitting.

- Time intervals for visual inspections can be minimized based on on-line particle monitoring
- On-line particle monitoring provides insight view to the formation of macropitting as it gives information about particle accumulation and time for occurrence of single particles as well as the size classification to the appeared particles.
- On-line particle monitoring is a promising way to follow the progression of pitting damage in parallel with visual inspection.
- The statistical vibration acceleration descriptors indicating random peaks in vibration signal are more suitable indicating tooth wear than spectrum methods.
- Meshing frequency sideband analysis method is very powerful to indicate gear fault in very early stage. The method also correlates with the severity of the fault, but to identify the fault as wear is challenging.
- Vibration acceleration descriptors indicating peaked signal correlate with the wear of gear contact, but the correlation is not as strong as in wear particle on-line monitoring.

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