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Wear Behavior of Polymeric Compound Measured on a New Test Rig for Plastic Gears

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1 Abstract

The objective of this work was to validate a methodology to assess the performance of a polymer compound in gear application with a particular focus on the characterization of the wear behavior of the polymer compound during the gear test.

This paper describes how the wear variation of gears made of Ixef® PARA material was determined and demonstrates how the test bench is necessary to characterize the plastic gears.

A case study proposed by the Solvay company for a specific test is described and how the testing activity was carried out to validate the product.

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2 Introduction

The adoption of plastic materials in various engineering applications is increasing more and more [1]. In particular, the use of plastic gears is increasing. These gears are being used in new applications, especially in the automotive sector, where they are chosen for their important properties:

- Low mass and inertia
- No lubrication required
- Corrosion resistance
- Sound and vibration damping (NVH behaviour)
- Lower cost for serial production
- Short production time per part
- Flexible, complex & highly integrated parts
- Lower waste and CO_2 production

We must remember that these types of gears could have also some disavantages:

- Inferior mechanical properties
- Inferior thermal properties
- Lower manufacturing tolerances
- Lower operating temperature
- Moisture absorption

Every year, new types of materials are produced and, in addition, new fillers such as PTFE for self-lubrication, glass and carbon fibers are added to the compound to improve its mechanical performance [2] . The general problem is that there is a lack of knowledge about the behavior of such materials in terms of tooth-root failure and wear, which makes it difficult to select the correct type of material to match several different requirements at the same time: for example the constraint at a given temperature, the difference between dry running and lubricant meshing, the performance of plastic on plastic or plastic on steel.

This case study is an interesting example of how a plastics company (Solvay) creates a new gear compound to be tested under the conditions required by the end customer (torque, speed, temperature) and with grease lubrication.

The specific test case described in this paper can be generalised by showing that the test bench built by Longato Srls is certainly necessary not only to perform specific tests requested by the customer but also in general to characterize the new material through the realisation of fatigue curves, the determination of wear coefficients to describe the main phenomena studied.

To summarize, this paper would like to address the following:

- Develop and validate a new test rig for gear characterization at high temperature in greased environment.
- Generate gear wear data on a new material for which literature data are not available.
- Demonstrate the range of use and applicability of the tested material by integrating chemical resistance tests and post-mortem analysis.

3 Test rig description

The test rig is a non-mechanically closed loop rig and it was designed using the layout proposed in VDI 2736-4 [3].

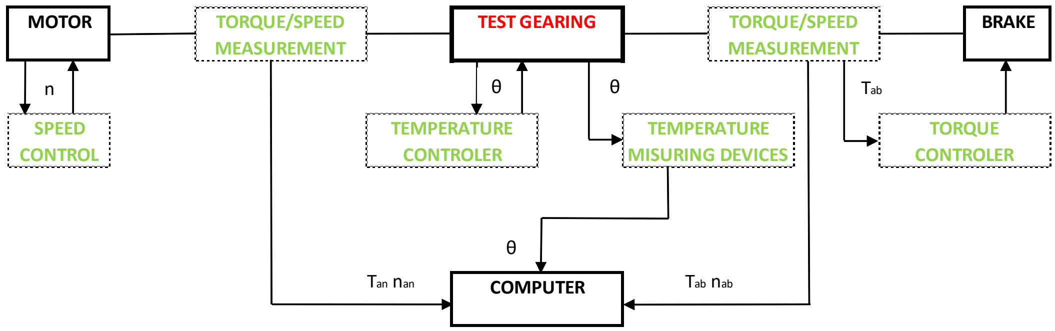


Figure 1 – Closed-loop test rig

The drive motor of the driver gear (steel) is controlled by an encoder to monitor the rotation speed and by a torque meter to check the torque. The same checks are applied to the motor used for the driven gear (plastic, subject to testing), which acts as a brake with re-circulation of electric power to minimize electrical consumption while performing testing.

Checking of rotation and torque allows the rig to stop almost immediately in the event of breakage of a tooth.

The gears are placed inside a climatic chamber to perform testing at a controlled temperature.
The temperature of the plastic wheel can be handled in two different ways: the first involves keeping a constant temperature inside the chamber while the second involves a check of the temperature of the flank or root of the tooth. The testing described below was performed by checking the temperature on the flank of the tooth.

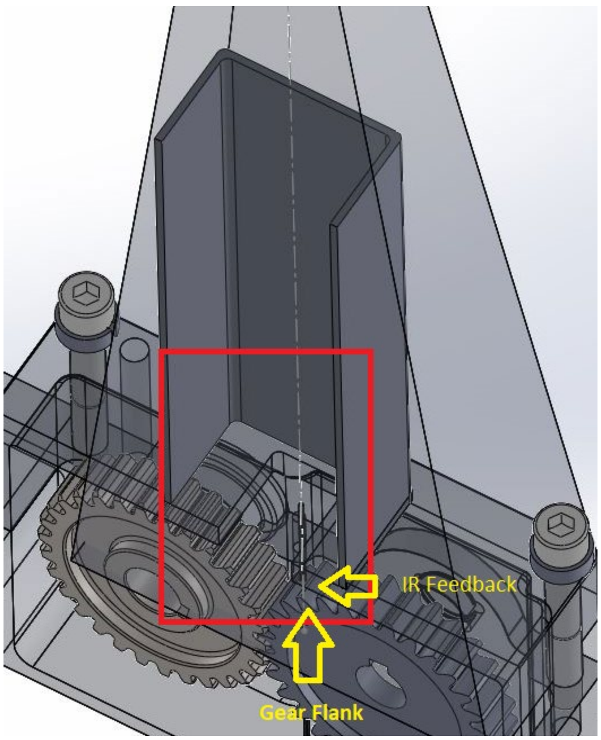


Figure 2 – Flank measurement with IR camera

The climatic chamber is kept at a constant temperature in counteraction by checking the thermal signals sent by the Optris thermographic IR camera or by the PT100 temperature sensor placed inside the chamber itself.

Figure 3 – PT 100 sensor inserted for grease temperature control

The test rig properties are summarized in:

Table 1 – Test rig data sheet

	Range	Catalogue data		Scale		Theoretical resolution	
Center distance	20 ÷ 150 mm			200	mm	± 0.01	mm
Position/speed	500 ÷ 4000 rpm	20	bit/rev	360	°	0.000343323	°
Torque	0 ÷ 10 Nm	24	bit	50	Nm	2.98E-06	Nm
Thermocouple PT100	-15°C ÷ +150°C	16	bit		°C	0.01	°C
Thermographic camera	-15°C ÷ +150°C	16	bit			Dipending on the range of measure	

4 Description of Solvay products

Solvay has a broad portfolio of high performance polymers suitable for gear applications. The ultrapolymer compounds of Torlon® PAI and Ketaspire® PEEK can meet very demanding requirements thanks to their excellent thermal, mechanical and F&W properties. The use of the semicrystalline polymer compounds of Amodel® PPA, Ixef® PARA, Ryton® PPS are recommended for less demanding and more cost-effective gear applications. These materials show superior chemical, thermal and mechanical properties and have low water adsorption over more widely used POM or PA46.

5 Case study

In this paper, we present the analysis of the tribological behavior of an Ixef® PARA gear. This material is a 30% glass-fiber reinforced polyarylamide compound. It exhibits high strength and rigidity, outstanding surface finish and excellent creep resistance.

Table 2 – Ixef®PARA properties

Properties	Typical value	Test method
Tensile modulus	11500 MPa	ISO 527-2/1A
Tensile stress (break)	190 MPa	ISO 527-2/1A
Tensile strain (break)	2%	ISO 527-2/1A
Flexural modulus	11500 MPa	ISO 178
Flexural stress	285 MPa	ISO 178
Deflection temperature under load 1.8 MPa, unannealed	230°C	ISO 75-2/A
Water adsorption (24h, 23°C)	0.2%	ISO 62

The chemical resistance test performed on IXEF® PARA against the lubricating grease Multemp SC-U at 140°C shows the excellent polymer stability in temperature and in presence of the lubricant. The mechanical properties of the IXEF® PARA measured at RT are similar when the aging at 140°C is performed with or without grease contact. The chemical stability of the polymer compound in presence of the lubricating grease in temperature is important to ensure continued high mechanical and fatigue properties over the gear lifetime. The chemical degradation can lead to early failure.

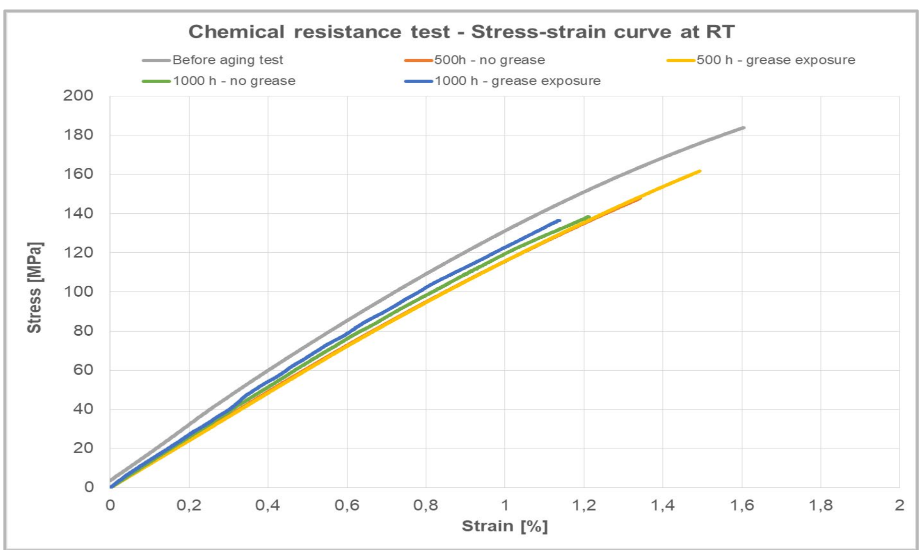


Figure 4 – Chemical resistance test

The gear test is carried out in a climatic cell at a temperature of 100°C, an input torque of 10 Nm and a rotational speed of 1000 rpm. The whole system is lubricated by the MULTEMP SC-U grease made by Kyodo Yushi Co, Ltd. In the test we utilize a steel gear as driving gear and the Ixef® PARA gear (Mn=2) as driven gear. The gear ratio is 1:1. The test is carried out on gears with the same geometric characteristics (normal module, number of teeth, etc.). To get a statistical point of view, we carry out two tests under the same conditions [torque, speed, temperature].

6 Wear check

We check the wear behavior in two different ways, we compared the wear measured by the 3D optical scanner and by component weighing. Also every $3x10^6$ (3 million) cycles, we stop the test, do a visual check and Wildhaber measurement of the teeth on board the machine, then we restart the test. The gears are mounted again on the test bench with the same tooth in contact as before.

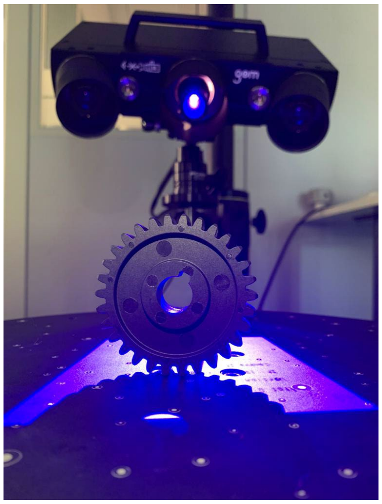


Figure 5 – 3D optical scanner

Figure 6 – Component weighing

7 Basic gear measurement

In order to check the plastic gears, we analyze the gears as manufactured utilizing two methodologies. In this paper, we use these symbols following the ISO/TR 10064 [4]

Table 3 – Gear geometry symbols

Symbol	Designation	Unit
W_{ks}	Base tangent length steel gear	mm
W_{kp}	Base tangent length plastic gear	mm
z	Number of teeth	-
x	Profile shift coefficient	-
a_w	Center distance of a cylindrical gear pair	mm
b	Facewidth	mm
B_W	Common face width	mm
d	Reference diameter	mm
F_α	Total profile deviation	µm
F_β	Total helix deviation	µm
F_r	Concentricity deviation	mm
H_v	Degree of tooth loss	-
k_W	Wear coefficient	10^{-6} $mm^3/(N*m)$
l_{Fl}	Profile line length of the active tooth flank	mm
N_L	Number of load cycles	-
T_d	Nominal torque	N*m

Contact machine: Using a machine Zeiss 3D PRISMO 7 with rotary table and Gear software we investigate the gearing parameters, geometric analysis of the flank, the profile and the pitch with standard reports. We utilize the accuracy grade following ISO/DIS 1328-1 [5]. This standard establishes a tolerance classification system relevant to manufacturing and conformity assessment of tooth flanks of individual cylindrical involute gears. This is an extract of Zeiss report that indicate the quality of gear 11 because the gears are molded with a prototype mold.

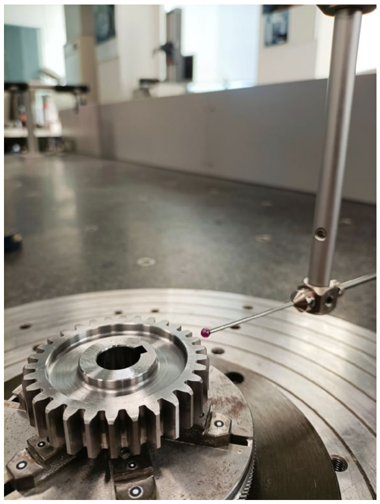


Figure 7 – Zeiss contact machine

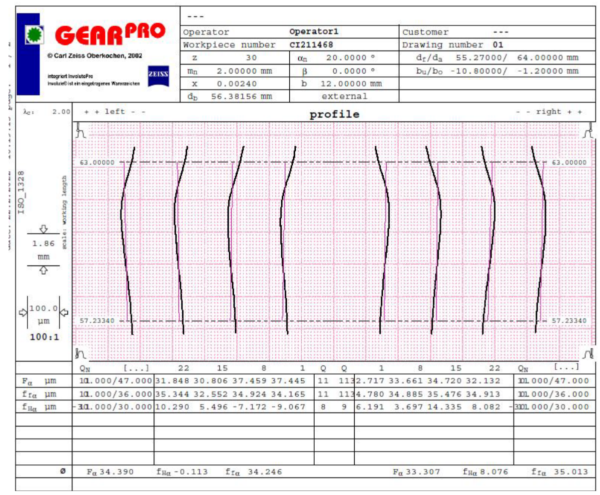


Figure 8 – Report of Zeiss machine

Non-contact machine : with an optical scanning machine ATOS Q, we acquire of the 3D surface of the gear in "stl” format for subsequent comparison with the mathematical 3D CAD “step” model by means of a chromatic map of deviations and subsequent digitization of the first 3D reference surface corresponding to the newly gear.

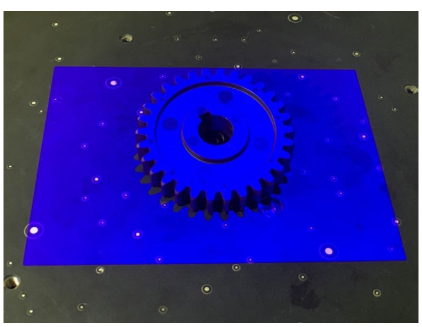


Figure 9 – Optical scanning machine

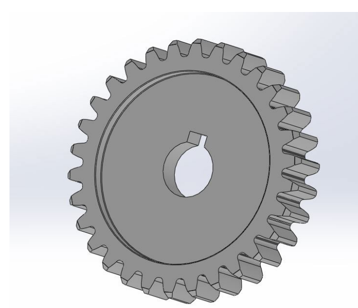


Figure 10 – Result of optical scanning (“.step” file)

We build a model for calculations of the real gear following these steps :

1) Acquire the gear before the test (teeth surface without wear effect). The output of the scanning is a file “.stl” format of the entirely surface of the gears. By the cad software SolidWorks we import the "stl" file and we manage it to draw section of a single theet in "dxf" file.

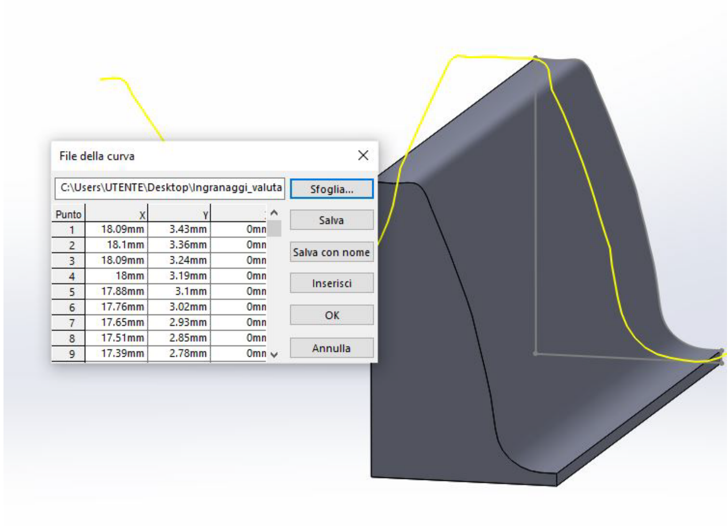


Figure 11 – SolidWorks tooth form

2) By The software KISSsoft we insert the data of macro geometry as for the standard report of a control machine (ZEISS). We import the "dxf" section of a single tooth in KissSoft to create a "ideal" gear made from the "real teeth section". After we export the "real gear" in ".step" format.

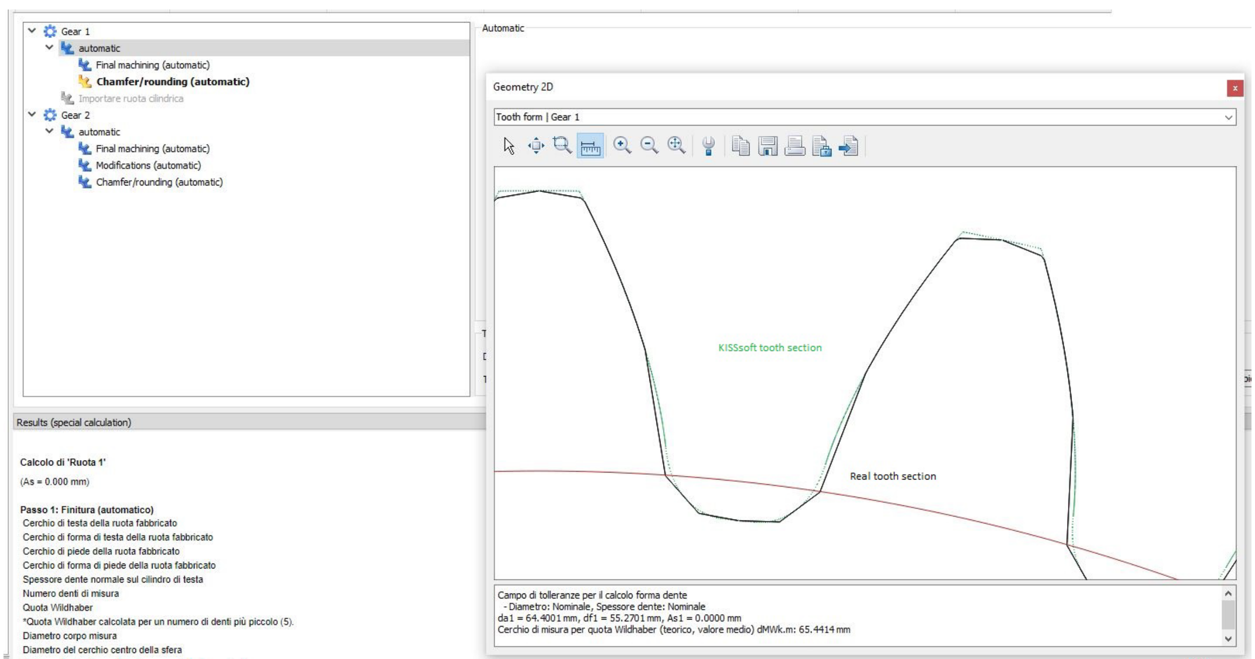


Figure 12 – KISSsoft tooth form

3) We compare with the “GOM Inspect” software the "real " image 3D of the gear with the "ideal" 3D model of the gear to do the best fit.

This is a chromatic map of superimposition from 3D optical scanning and 3D KISSsoft model built with “tooth form” tab. Finally, we have the 3D model with the "best fit geometry" to utilize for the FEM analysis.

The actual gear profiles differs a maximum 0,05-0,06mm more the ideal calculate involute.

It would be interesting to use the same procedure to evaluate the tooth profile of steel gears but this is not the subject of this research.

These real profiles will be compared during the test to analyze the wear advancement.

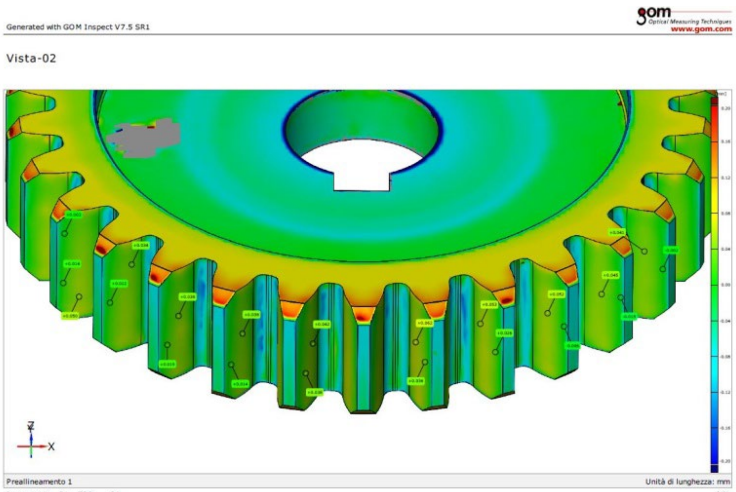


Figure 13 – 3D Chromatic map

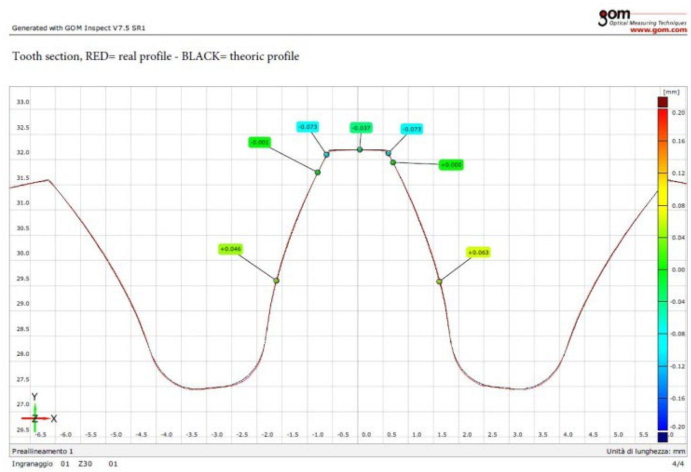


Figure 14 – 2D section of chromatic map

4) Component weighing, with resolution 0.01 mg The gear was blown with compressed air and then conditioned in an oven at 40°C for 30 min, finally stabilized in a desiccator for 15 min and weighed.

The following table shows the average weight of the two gears before the test (0 cycles).

The formula of average is:

$$Average\ [g] = \sum_{n=1}^{3} g_n / n$$

where

$Average\ [g]$ is the average weight of the gear

g_n is the weight of the n-weighing

Table 4 – Component weighing before the test

Component	GEAR #1 before the test	Component	GEAR #2 before the test
First weighing [g]	31.46409	First weighing [g]	31.47275
Second weighing [g]	31.46400	Second weighing [g]	31.47273
Third weighing [g]	31.46410	Third weighing [g]	31.47272
Average [g]	**31.46406**	**Average [g]**	**31.47273**

8 Data acquisition

Our kind of test is a long-life test, we want to check the behavior of the gear until it fails. In order to perform it, we utilize a steel gear as driving gear and the plastic gear ad driven gear in grease lubrication conditions [6].

The input conditions that the test rig must be maintains constant are:

- ✓ Input torque: 10Nm
- ✓ Input speed: 1000 rpm
- ✓ Teeth temperature of plastic gear: 100°C

The data that we want to collect are:

- ✓ Grease temperature [°C]
- ✓ Number of cycles [-]
- ✓ Wildhaber measurement of the gears every $3x10^6$ million cycles [mm]
- ✓ 3D optical scanner analysis and gear weighing [gr]

We perform a test on two gears (GEAR#1 and GEAR#2) in order to have a statistical point of view.

9 Test rig setup

To reproduce this application, we built an aluminium housing. In this housing we inserted the gears and then the entire system was placed inside a climate chamber.

In the aluminium box we have installed a PT100 in order to check the grease temperature during the test.

A thermal IR camera is used to maintain the gear temperature and signal temperature retrofitting. This signal is sent to the climate control software to maintain the temperature value on the tooth surface of 100°C by heating or cooling the atmosphere inside the climate chamber in a close loop.

The electric motors are equipped with encoders for speed monitoring and two torque transducers are installed on the input and output shafts.

The test starts with the warm-up phase, in which the gears rotate at 60 rpm with a torque of 0,5 Nm. Once the teeth temperature of 80°C is reached, the test phase begins in which the gears accelerate to 1000 rpm and a torque of 10Nm with an acceleration ramp defined by the author. In this way, we do not thermally stress the gears and do not introduce mechanical factors that could compromise the test.
A sensitive system for measuring torque and gear speed stops the test when the fault occurs.

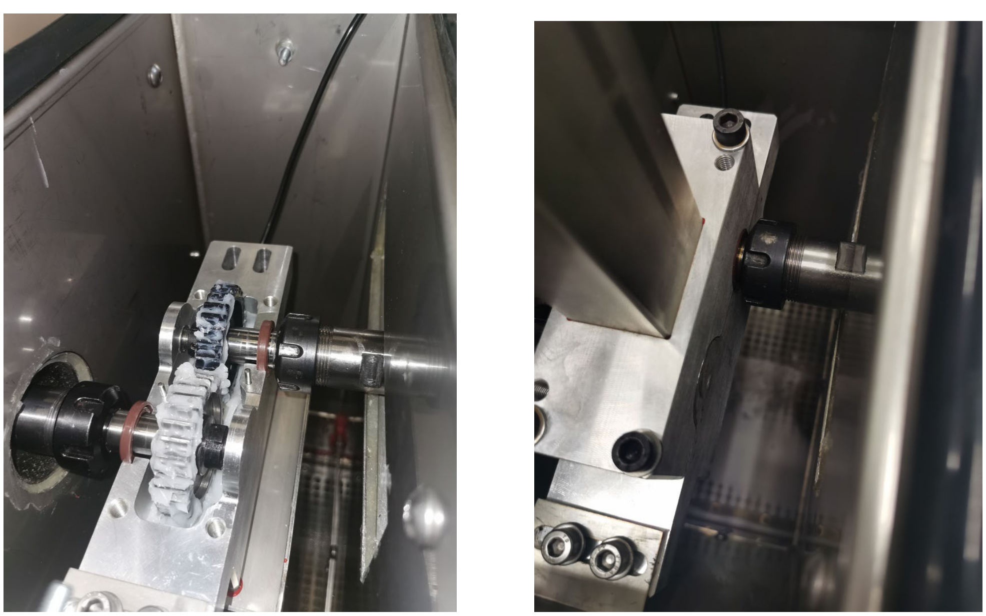


Figure 15 – Test rig setup

10 Test post processing results

In the following table on see the failure cycles on gears test: the failure was a tooth root breakage.

Table 5 – Test results

	Cycles [-]	Failure	Gear Temperature [°C]	Std. Dev.
GEAR#1	**10.059.222**	Tooth root breakage	**100.33**	1.51
GEAR#2	**9.272.959**	Tooth root breakage	**100.32**	1.31
	Grease Temperature [°C]	**Std. Dev.**	**Torque on gear 2 [Nm]**	**Std. Dev.**
GEAR#1	**99.29**	2.95	**10**	0.03
GEAR#2	99.14	2.78	**10**	0.03

Table Note: "Std. Dev" is the "standard deviation" of the gear temperature measurement. We collect temperature data from the IR camera every 27Hz during the test. Finally, the average and standard deviation of the collected data are calculated.

The picture shows the grease and gear temperatures. We observe the transition phase in which the temperature rises up to 110°C and then the temperatures reaches thermal equilibrium in 2 hours.

During the phase test, the grease temperature followed the thermal behavior of the gear temperature. At the end of the test, the average grease temperature was 99°C and the average gear temperature 100°C, demonstrating the good quality of the grease.

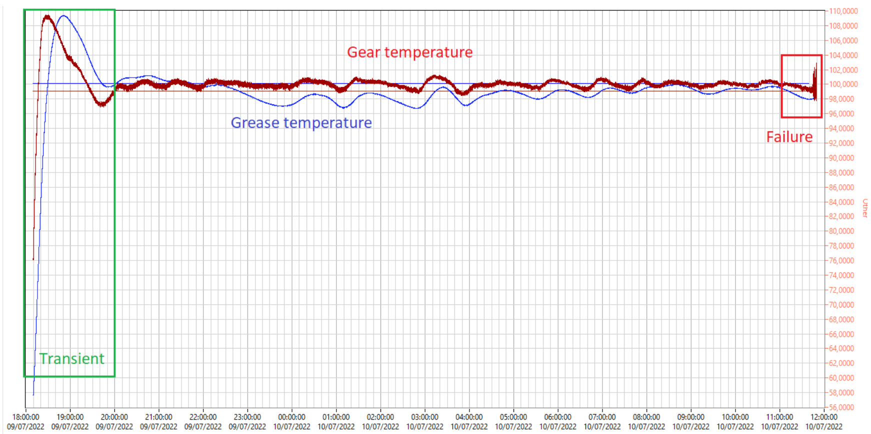


Figure 16 – Temperatures graph

The next image shows the temperature behavior when the fault occurs.

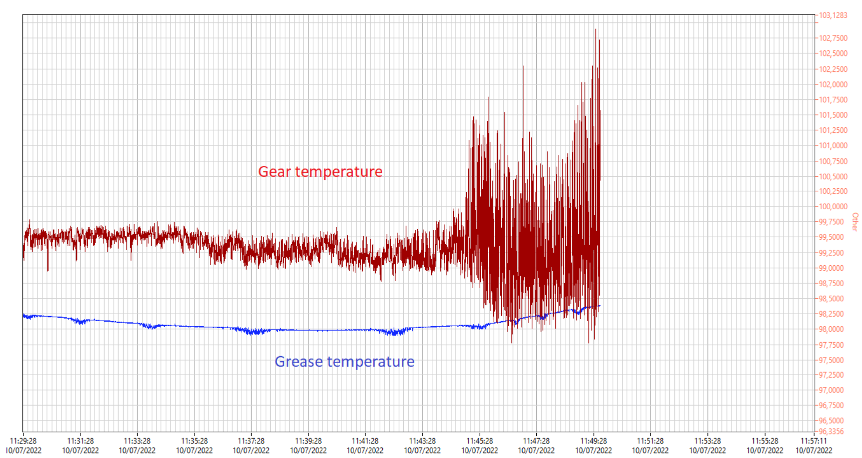


Figure 17 – Temperature at the fail

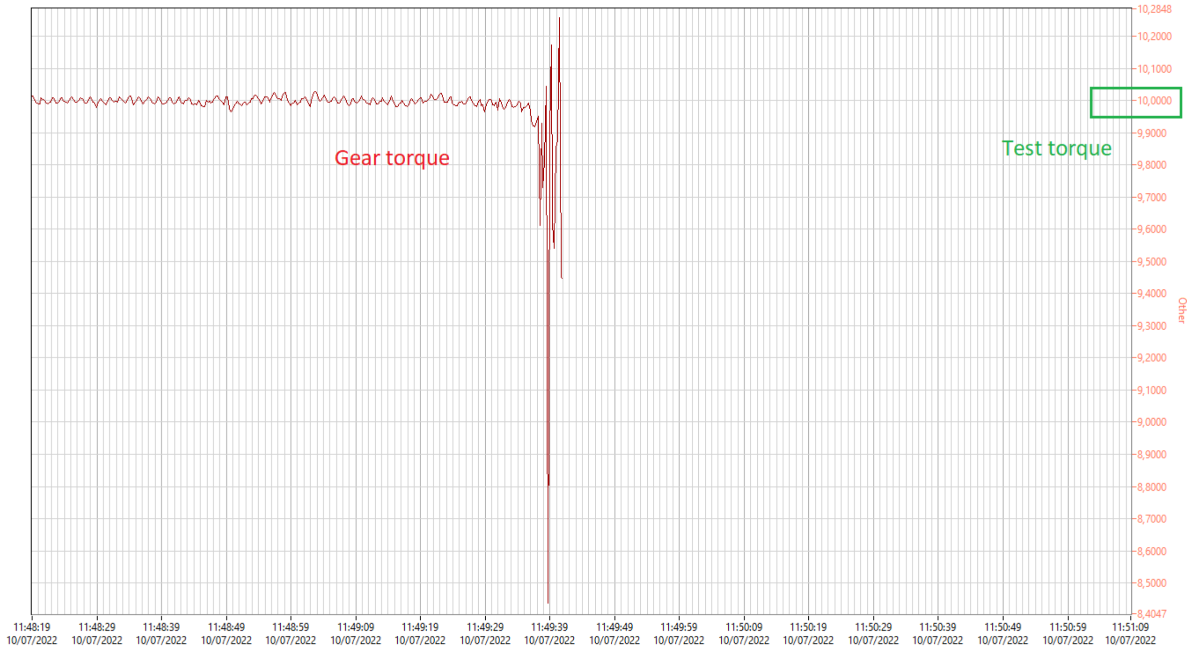


Figure 18 – Torque graph at the failure

Then we have checked gear 1 and gear 2 every $3x10^6$ (3 million) cycles. During this phase we carry out a visual control and a Wildhaber measurement of the tooth on the test rig. The gears are mounted again on the test bench with the same tooth in contact as before.

Every $3x10^6$ cycles We measured the same teeth 3 times and calculated the average Wildhaber measurement.

Table 6 – Wildhaber measurements

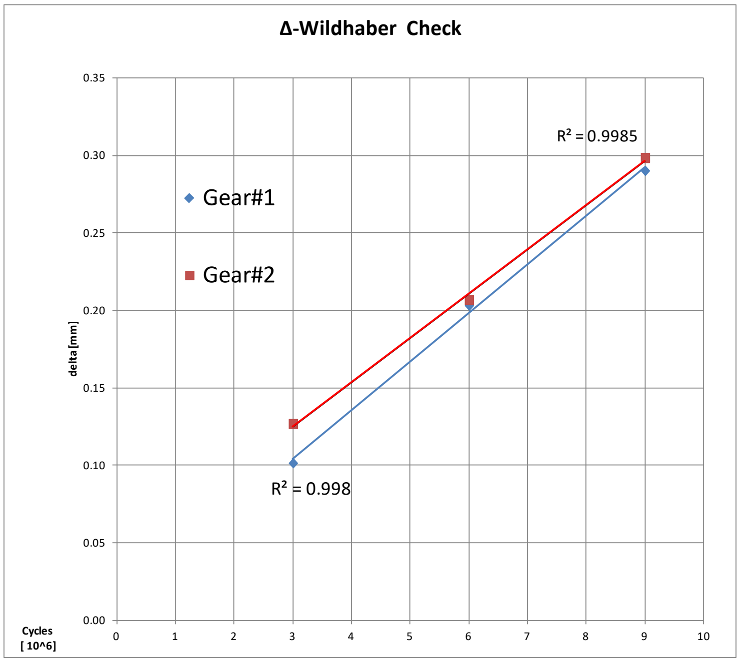
	Before the test				3 millions cycles				6 millions cycles			
	1	2	3	Average	1	2	3	Average	1	2	3	Average
N° Gear	W on z=5 teeth [mm]				W on z=5 teeth [mm]				W on z=5 teeth [mm]			
1	27.37	27.36	27.35	**27.36**	27.259	27.259	27.258	**27.26**	27.156	27.158	27.157	**27.16**
2	27.35	27.35	27.32	**27.34**	27.28	27.18	27.18	**27.21**	27	27.3	27.1	**27.13**

	9 millions cycles				10 millions cycles			
	1	2	3	Average	1	2	3	Average
N° Gear	W on z=5 teeth [mm]				W on z=5 teeth [mm]			
1	27.03	27.08	27.1	**27.07**	27.07	27.08	27.07	**27.07**
2	27.05	27.04	27.04	**27.04**				

If we plot the difference between the Wildhaber measurement of the test and the Wildhaber measurement of the previous gear test (GEAR#1 and GEAR#2) against load cycles, we obtain a straight line with a linear correlation of approximately R^2=0.99.

The graph show a linear relationship of the wear rate with the number of cycles.

Table 7 – Plot of delta Wildhaber measurements



We also measured the weight of the gears, after thorough washing to remove all contamination. The loss weight is done by the wear process that remove the plastic gear material.

The GEAR#1 has reduced in weight of 1.25861 gr, the GEAR# 2 shrunk in weight of 1.33560 gr.

Table 8 – Gear weight measurements

Component	GEAR #1 before the test	GEAR #1 after 6 million cycles	GEAR #1 failure
First weighing [g]	31.46409	31.17290	30.20547
Second weighing [g]	31.46400	31.17281	30.20545
Third weighing [g]	31.46410	31.17283	30.20544
Average [g]	**31.46406**	**31.17285**	**30.20545**

Component	GEAR #2 before the test	GEAR #2 failure
First weighing [g]	31.47275	30.13715
Second weighing [g]	31.47273	30.13711
Third weighing [g]	31.47272	30.13714
Average [g]	**31.47273**	**30.13713**

From the formula (19) of the standard VDI 2736 part 2, we try to check the wear coefficient from the geometry and the degree of tooth loss.

$$k_W = \frac{W_m \cdot b_W \cdot z \cdot l_{Fl}}{T_d \cdot 2 \cdot \pi \cdot N_L \cdot H_v} \quad (1)$$

where

W_m is the averaged linear wear;

b_W is the common face width;

z is the number of teeth;

l_{Fl} is the profile line length of the active tooth flank;

T_d is the nominal torque;

N_L is the number of load cycles;

H_v is the degree of tooth loss;

We obtained k_w= 4.81 [10^{-6} $mm^3/(Nm)$] ±0.12, this is an indicative value of the wear coefficient because it was very difficult to check the Wildhaber measurement on the gear affected from the wear.

With an optical scanning machine, we acquire the 3D surface of GEAR#1 at $6x10^6$ cycles and we compare this gear geometry with the original geometry before the test.

It appears that the material is transported from the top (tip diameter) of the gear to the root area.

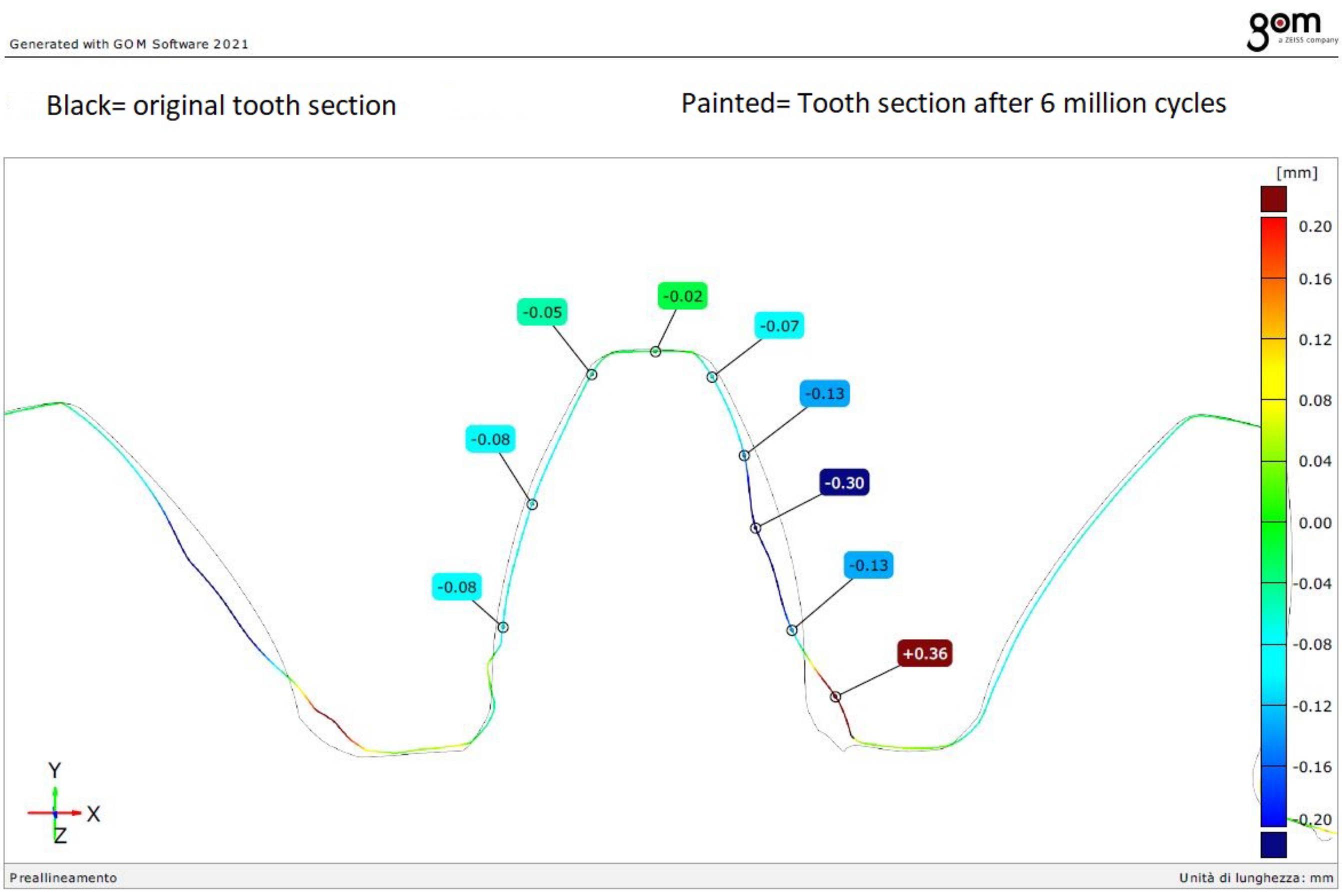


Figure 19 – Behavior of the GEAR#1

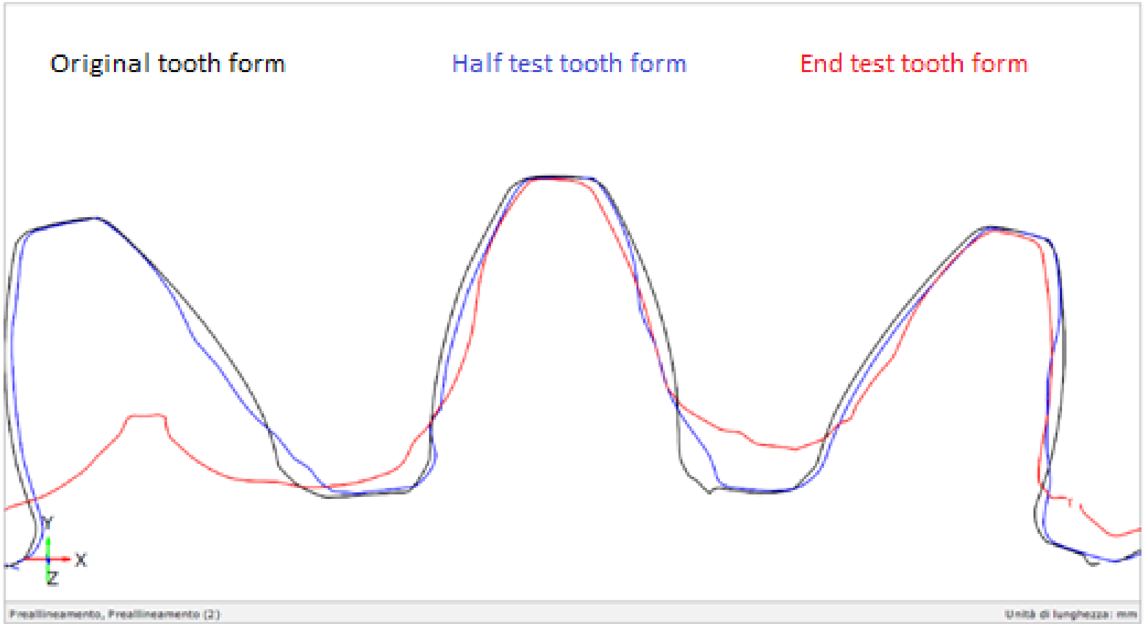


Figure 20 – Behavior of the GEAR#1 final

This image shows an example of an acquired chromatic map.

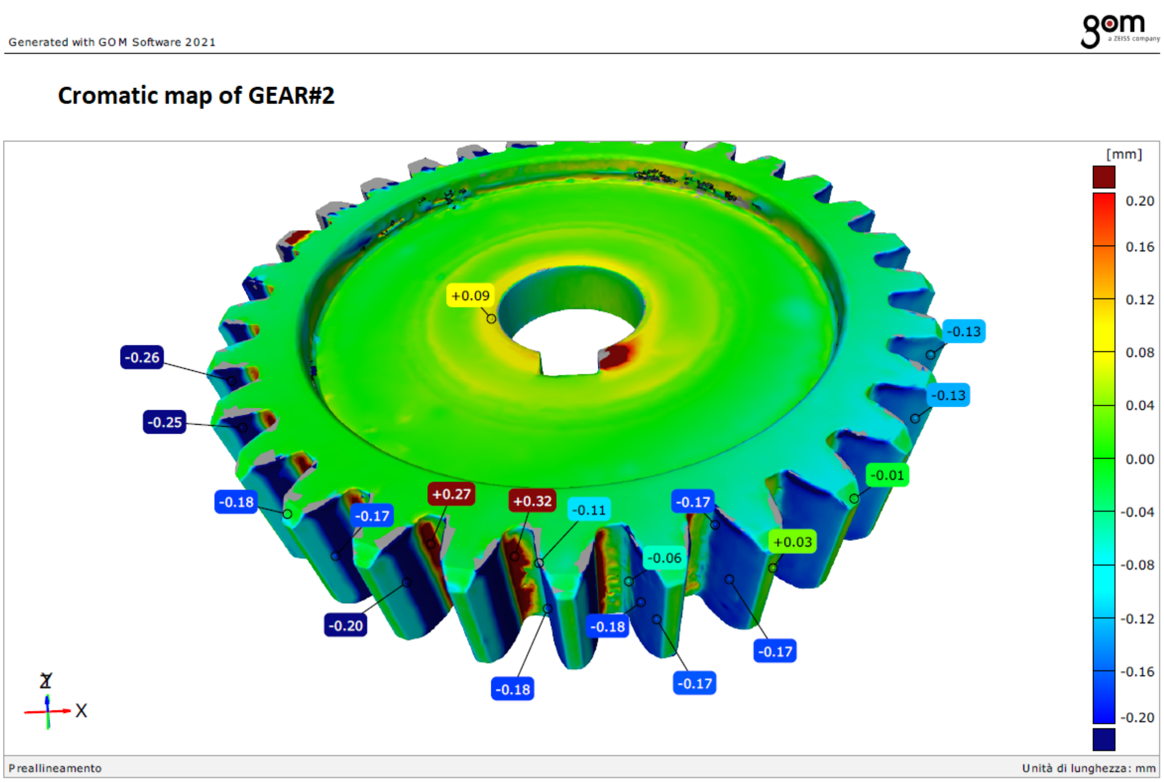


Figure 21 – Chromatic map of GEAR#2

The post-mortem optical analysis of the IXEF® PARA gear shows that each tooth is worn out on their curved side. All teeth present transversal micro fractures at the bottom of the flank. It indicates that the strain was homogeneously distributed.

Figure 22 – Optical analysis

The SEM analysis shows that the glass fibers in the worn gear maintain a residual layer of polymer on their surface, indicating a remaining good adhesion between the glass fibers and the polymer matrix. This is crucial to avoid early crack initiation and propagation in the polymer compound that can lead to early failure in gear application. The good properties of the IXEF® PARA compound allowed reaching long lifespan of 10 million cycles.

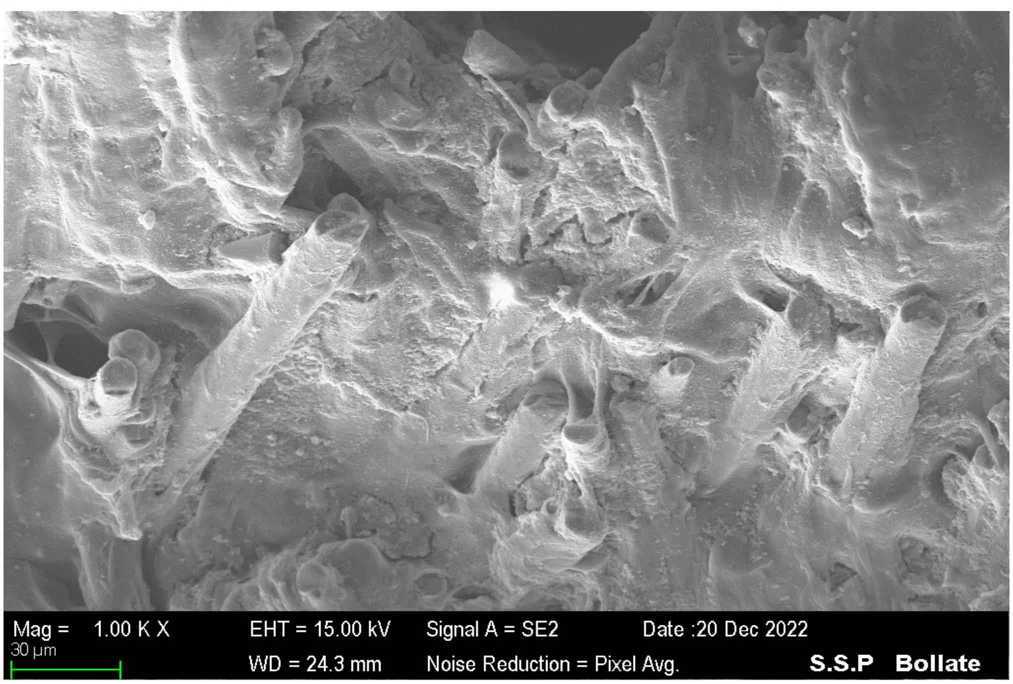


Figure 23 – SEM analysis

11 Conclusions

The methodology used to characterize the performance and wear behavior of a polymer compound gave an interesting outcome. The wear coefficient of the polymer compound in gear test was determined by weight and Wildhaber measurements. In addition, the optical scans combined with the optical microscopy analysis at the end of the test gave a good indication of the way the teeth were worn and deformed during the test.

The IXEF® PARA compound showed good gear performance at 100°C under the testing conditions, reaching 10 million cycles. No major wear on the tooth flank was observed in this test that was conducted in presence of a lubricating grease. Finally, since the impact of the grease on material performance is negligible, we could correlate any wear measured to the progressive fatigue deterioration coming from the gear rotation.

The tests confirmed the superior performance of Ixef® PARA when tested in contact with grease at high temperature. Such an achievement is opening the way to a new set of applications, for which temperature requirements become more challenging day after day.

12 Acknowledgements

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