An Experimental Investigation of Aerospace-Quality Gears Operating in Loss-of-Lubrication Condition

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This work establishes a baseline for aerospace spur gear behavior under oil-off conditions. The collected test results document a different oil-off time, dictated by material used.

Introduction

The ability of gearboxes to perform in a loss-of-lubrication condition is an important parameter in design criteria—particularly in aerospace applications. The heat generated by a lost lubricant is extremely high and can lead to loss of gear backlash, which in turn leads to thermal expansion, reduced hardness, plastic deformation and high frictional wear—all of which contribute to a total failure of the transmission system (Ref. 1).

The certification of large rotorcraft drive systems requires survival of a loss-of-lubrication test. The test must certify that—for at least 30 minutes after the lubrication system failure (Ref. 2)—any performance issues resulting in loss of lubricant will not prevent continued safe operation, and will maintain the torque and rotational speed prescribed by the applicant for continued flight.

Whereas calculation methods and standard criteria for predicting gear damage, e.g.—wear, scuffing, pitting and bending—are available, an analytical standard criterion for determining the capability of a transmission to achieve the required 30 minutes running in oil-off condition is not. Thus an experimental approach is required. A need for establishing a baseline for gear behavior in oil-off condition—exacerbated by the dearth of published data on prior work in this area of study—justifies the experimental work described herein.

Experimental Approach

The experimental work was carried out in two ways:

1. Four tests were conducted with gears of different geometry and materials to gain preliminary indication of the heating of the running gears and to check the capability of the test facilities to perform the test.
2. Thirty-six tests were planned using the "design of experiment" (DoE) technique to evaluate the influence of three parameters: 1) material (variable on two levels); 2) sliding speed (variable on three levels); and 3) contact pressure (variable on three levels). Each combination of these parameters was investigated twice and, indeed, 36 tests were conducted.

The tests involved (Fig. 1):

- Warm-up of the test rig and steady-state operation of the test spur gears under normal lubricating conditions; in this phase the gears were jet- lubricated with an in-mesh spray bar (Fig. 2).

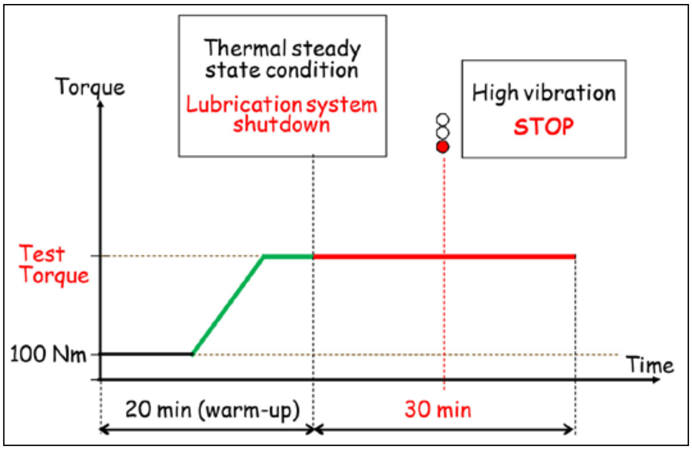

Figure 1 Test procedure.

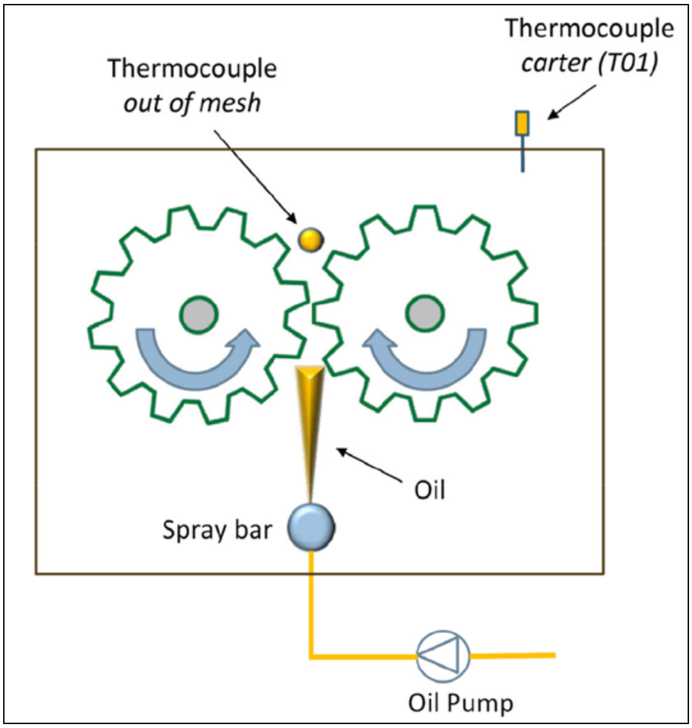

Figure 2 Gear lubrication.

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- Lubrication system shutdown.
- Continued operation at constant speed and constant torque on the driven gear in loss-of-lubrication condition for 30 minutes.

(Were the safety threshold of the test rig (high vibration) endangered, the test was to be stopped immediately.)

Throughout the test, the temperature—at a point very near the mesh, referred to as "temperature out of mesh"—was measured (Fig. 2.) to gain an indication of the heating of the gears. In some tests the bulk temperature of the running gear was measured. At conclusion, the gears were visually inspected and, in some cases, a metallographic observation of the teeth and a hardness measure were made. These results are reported in this paper.

Description of Test Facility

Gear rig. The experiments were carried out using a back-to-back test rig specifically designed for aerospace gear testing (Refs. 3 and 4), shown in Figure 3.

The test rig is capable of high performance; maximum rotational speed is 18,000 rpm and maximum circulating power about 1 MW.

Torque in the system is provided by an electromechanical servo-actuator that varies the axial position of a load shaft on which two helical gears are mounted. The aggregate motion of the load shaft controls the magnitude of torque in the closed-loop system (Fig. 4).

The bench is equipped with two torque meters—one on each test gear shaft—of 20 thermocouples installed on the bearing outside ring and at several points of the test and slave gearbox. An online vibration monitoring system based on four high-frequency accelerometers is used to control damage to the sample gears as well as other test rig components.

The lubrication system provides thermo-regulated, independent lubrication of the slave gearbox and test gearbox.

During initial operational mode—but before loss-of-lubrication testing—a single lubricating jet impinged on the gear teeth just prior to mesh. Oil temperature was the same in all tests. To avoid dripping of the lubricant during the oil-off phase, the spray bar was positioned under the gears (Fig.2).

Test gears. Two identical gears were used for all tests. Owing to the 1:1 gear ratio, the same tooth pairs are in mesh throughout the test. The test gears were made from two steels typical for aerospace application, and referred to here as Material A and Material B.

In order to measure the tooth bulk temperature, one of the two sample gears was equipped with a K-type thermocouple buried in the end-face (Fig. 5). The temperature signal, conditioned on-board by a purposely developed electronic amplifier, was transmitted to the acquisition units through a slip-ring (Ref. 5).

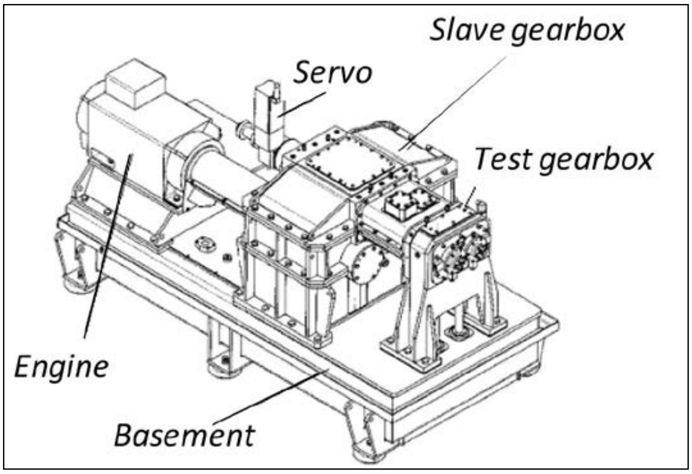

Figure 3 Test rig.

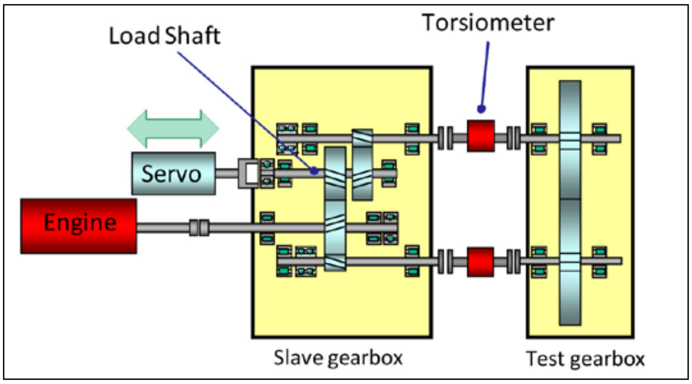

Figure 4 Test rig layout.

Figure 5 Gear equipped with thermocouple for bulk temperature measurement.

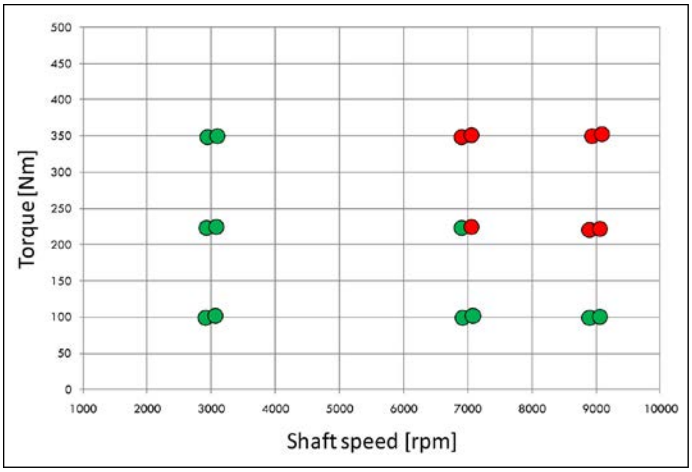

Figure 6 Test results: Material A.

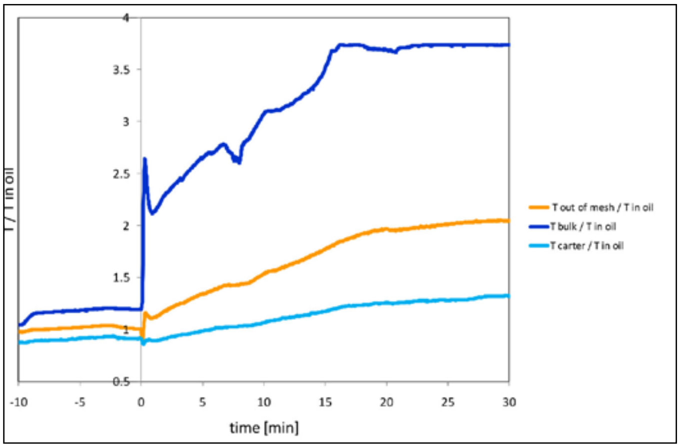

Figure 8 Loss-of-lubrication effect on bulk temperature at 350 N-m and 3,000 rpm.

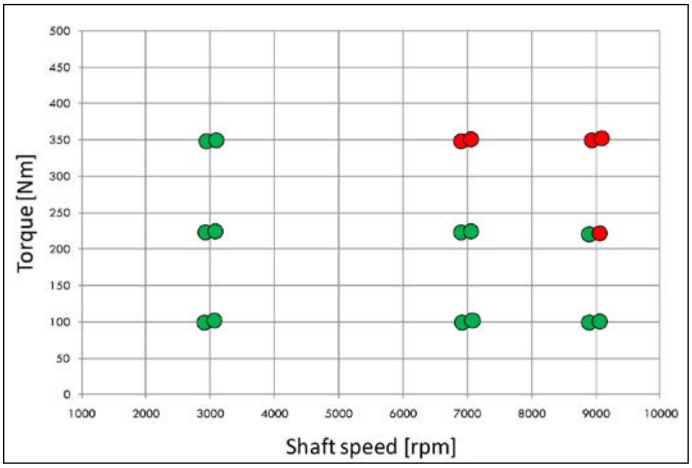

Figure 7 Test results: Material B.

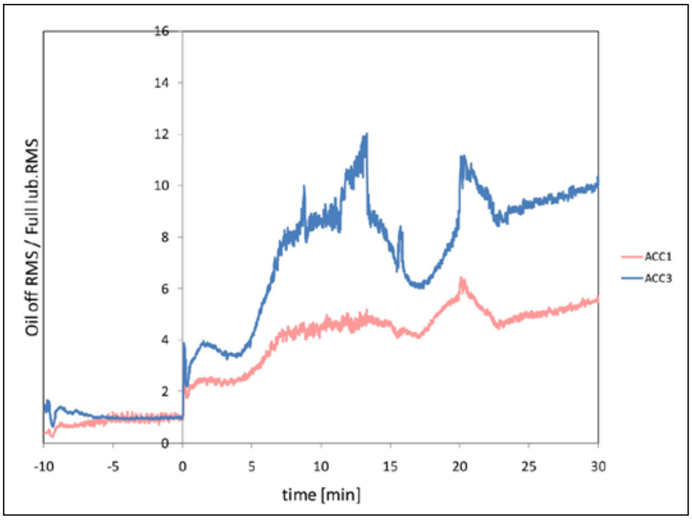

Figure 9 Loss-of-lubrication effect on RMS at 350 N-m and 3,000 rpm.

Test Results

Figures 6 and 7 show the torque and shaft speed values for the tested operating conditions. Since the gear geometry was the same in all tests, the observed torque and shaft speed levels correspond to a like number of contact pressure and sliding-speed levels.

Test conditions with an oil-off time of 30 minutes are indicated in green; conditions with the shorter oil off-time are indicated in red.

Of the 36 tests conducted, 24 met the 30 minute requirement despite the loss of lubrication; 12 tests were stopped prematurely.

All tests with an oil-off time less than 30 minutes were stopped before the required time due to a breaching of the safety threshold of the test rig (high vibration). However, in all tests the transmission was able to transfer the required power.

In Figures 8 and 9 we see the trend of the main parameters monitored during a test carried out at 350 N-m and 3,000 rpm in which bulk temperature was measured. Immediately after the lubrication shut-down, a rapid, attendant increase in bulk temperature and vibration level (RMS of the accelerometer signal) was observed.

Whereas the RMS spiked up and down several times during the test, the bulk temperature showed an initial, progressive increase; but after about 15 minutes it stabilized and remained so until the end of the test.

The out-of-mesh temperature showed a trend similar to that of the bulk temperature.

During the loss-of-lubrication phase a progressive increase in the motor current—due to the increase in the mesh power losses—was observed.

In most of the tests a variation of the load shaft position was required to keep the running torque constant to compensate for a loss of torque—due probably to the progressive and severe wear on the running gears' active surface (Ref. 6).

The data shown (Figs. 10–12) demonstrates the effect of load and speed on out-of-mesh temperature. As can be seen in comparing the reported data, the out-of-mesh temperature increased slightly with the shaft speed, but was affected more by the load. This data was collected from tests carried out with gears made from Material A, but similar results were found in tests carried out with Material B.

The out-of-mesh temperature at the end is, as expected, higher than at the beginning of the oil-off phase in all tests except the one carried out at 3,000 rpm and 100 N-m; it was conducted under less-severe operating conditions than among all those tested. In this case the temperature decreased; the same result was found for Material B.

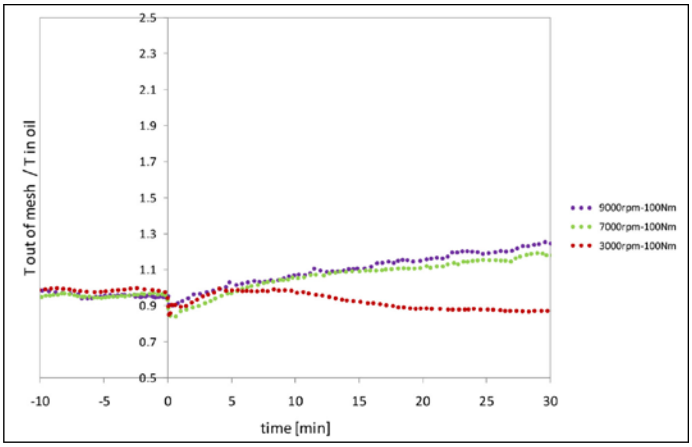

Figure 10 **Loss-of-lubrication effect on temperature out of mesh at 100 N-m at various speeds.**

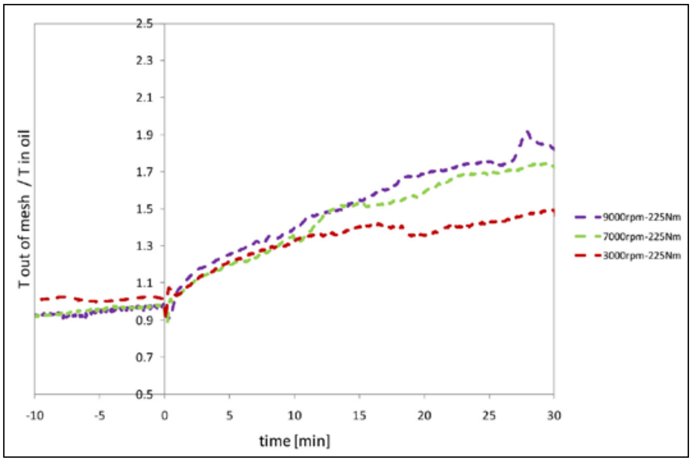

Figure 11 **Loss-of-lubrication effect on temperature out of mesh at 225 N-m at various speeds.**

The heat generated by meshing gears is principally due to friction power losses (Ref. 7). If the relative sliding is not altered, and if the load remains constant, the possible mechanism to explain the temperature decrease is a decreasing of the friction coefficient. As has been described by others (Ref. 8), the reduction of the friction coefficient could be explained in that perhaps the interacting surfaces, with the combination of pressure and temperature, caused the formation of a carbonaceous layer.

Thus if the operating condition, particularly the load, determines a severe wear ratio, it follows that the formation of the carbonaceous layer is insufficient to cause a reduction of the friction coefficient, and a loss of temperature out of mesh cannot be observed.

A statistical analysis of data (*ANOVA*) was carried out to establish which parameter—material, torque or speed—most affected the heating of the gear. The temperature out of mesh, indicative of gear heating, was considered in performing this analysis. The results showed that torque is the most influential parameter, followed by speed and material.

Gear Post-Test Analysis

At the end of all tests, the gears were visually inspected to determine damage on the tooth surfaces. Post-test photographs of the gear teeth and of the gear body were taken.

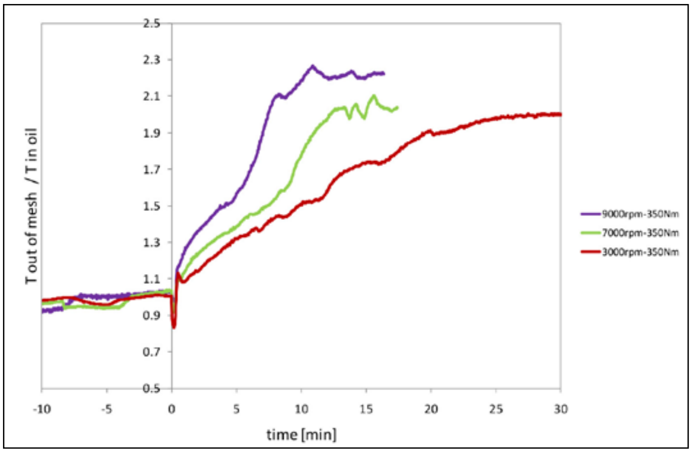

Figure 12 **Loss-of-lubrication effect on temperature out of mesh at 350 N-m at various speeds.**

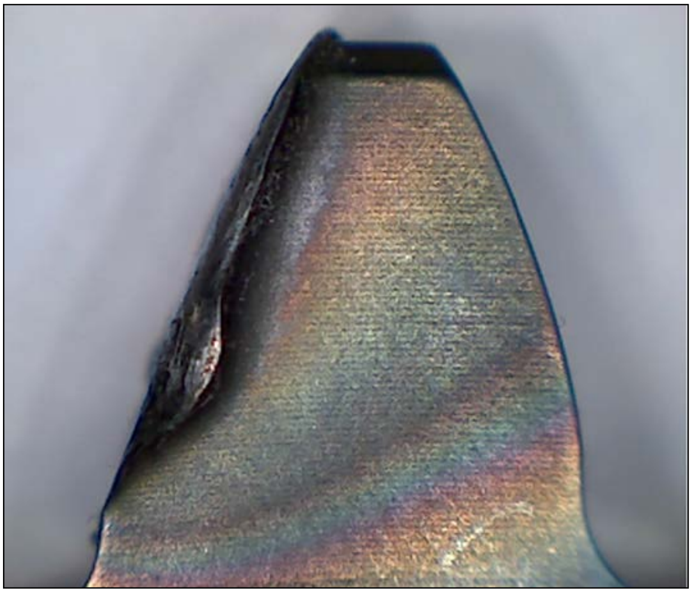

Figure 13 **Severe alteration of tooth surface geometry.**

In some cases, one tooth was removed from the gear to perform metallographic analysis and hardness measurement. The entire gear appeared to have a great deal of scuffing and metal removal.

Gears employed in the severest test conditions showed a dramatic alteration of surface geometry (Fig. 13).

At the end of one test, both the flank of the tooth, even the flank that carried no load, appeared coated with a dark deposit; such a deposit was even found within the **carter** gearbox (Fig. 14).

Another test revealed a different amount of wear, depending on the material and operating conditions. When employed at high loads, the gear made from Material A showed a more relevant wear than gears made from Material B when employed at high speed.

In Figure 15, post-test photographs of gear teeth made from Material A, and subjected to various test conditions, are shown; after running less than 30 minutes the working time in lubrication loss is indicated.

Teeth operating at minimum torque and an increasing level of speed display a very similar amount of wear. Yet the teeth oper-

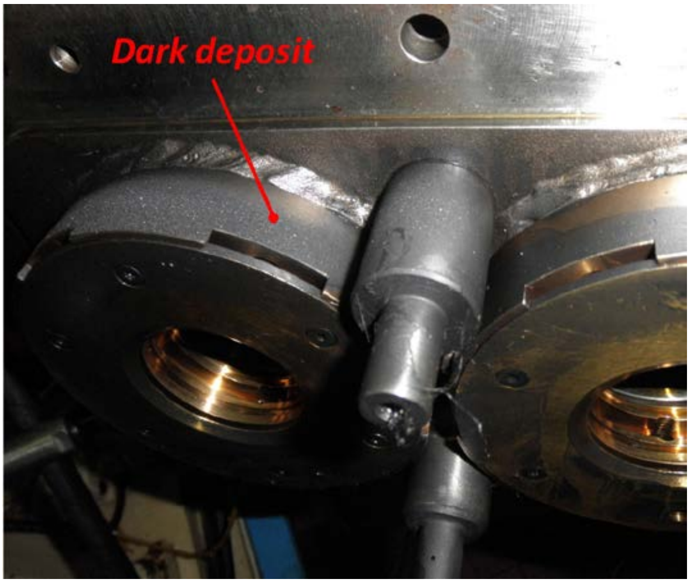

Figure 14 Dark deposit on test gearbox.

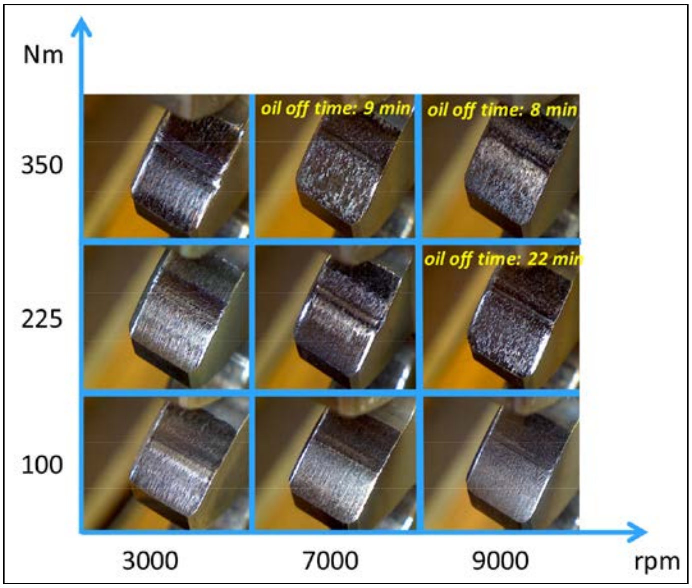

Figure 15 Post-test: effect of the operating condition on teeth wear (Material A).

ating at minimum speed and increasing torque show an amount of wear significantly increased with the increasing torque.

Similarly, Figure 16 shows the effect of the operating condition on gear heating. Gear heating can be qualitatively deduced from the color change of the gear; a dark color indicates higher warming. As operating conditions become more severe, the color change affects not only the teeth but the gear body as well.

In comparing the gear's aspect at minimum torque/increasing speed with the gear's aspect at minimum speed/increasing torque, it can be seen that gear heating was influenced more from load variation than speed variation. This supports the results reported earlier for the temperature out of mesh.

Figure 17 shows the metallographic analysis of a tooth that at the visual inspection showed strong alteration of the active surface; layers of dark material alternating with layers of lighter material are evident. SEM (scanning electron microscopy) analysis showed that the dark areas represent layers of oxidized material due to the progressive plastic deformation of the running surfaces.

Conclusions

An experimental study to establish a baseline for gear behavior running in loss-of- lubrication condition has been conducted. Aerospace-quality spur gears made from two materials and operating at different levels of sliding speed and contact pressure were tested.

Thirty-six tests under 18 different operating conditions were planned using the design of experiment (DoE) technique. Conclusions drawn from the experiments in this study are the following:

- Among the 36 tests carried out, 24 tests ran the required 30 minutes in oil-off condition; 12 were stopped short.
- In all tests the transmission was able to transfer the required power.
- The tests stopped earlier than required were stopped because of test rig safety issues (high vibration).
- In all tests the vibration signal of the gear mesh for Material A was higher than for Material B; moreover, a more relevant increase of the vibration level was observed with the increase of the contact pressure, rather than with an increase of sliding speed.
- As expected, the gears made from Material B were able to run in a loss-of-lubrication condition longer than gears made from Material A.
- The capability of the gears to run in a loss-of-lubrication state differed, depending on the operating condition; a more relevant influence on the oil-off time of the contact pressure, rather than of the sliding speed, was observed.
- The statistical treatment of the results (*ANOVA*) showed that gear heating and wear are influenced more from the variation of the contact pressure than from variation of the sliding speed; this evidence was confirmed with the gears' post-test evaluation.
- A post-test evaluation of the gears showed the presence of plasticized areas in teeth in which severe wear was observed; measure-of-hardness in these areas showed hardening; no relevant difference of the metallographic structure between the two tested materials was observed.

Future Work

The collected data will be used to develop a test model that will serve to demonstrate thermal behavior of the test gearbox in a loss-of-lubrication state.

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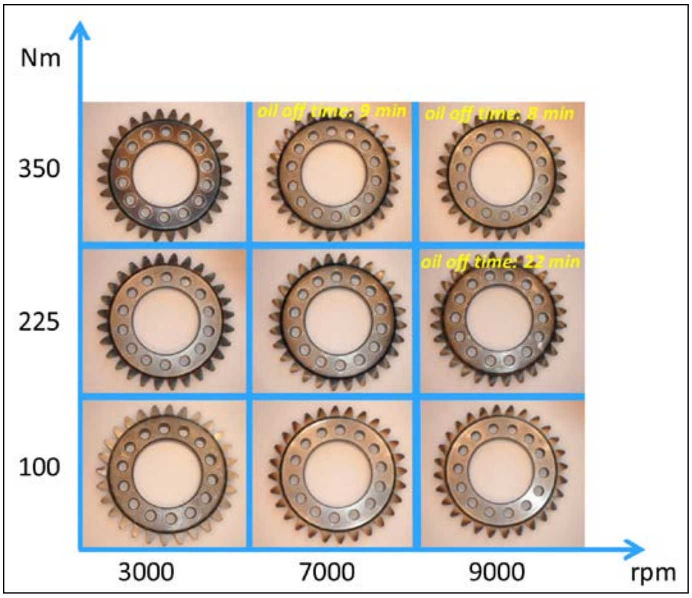

Figure 16 Post-test: effect of the operating condition on gear heating (Material A).

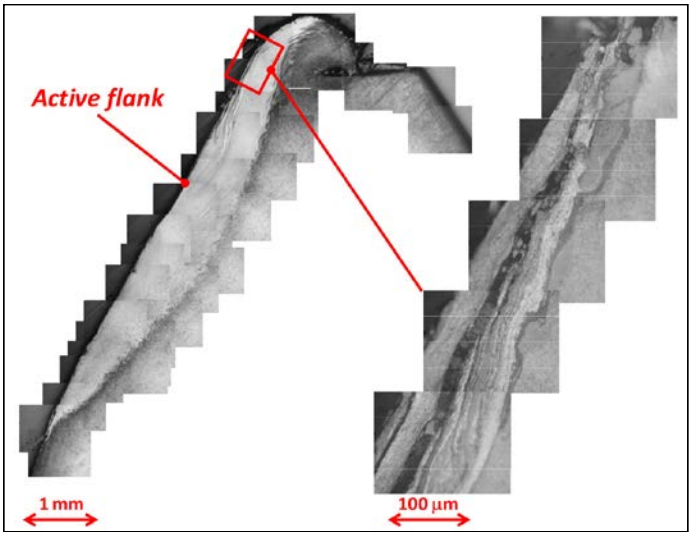

Figure 17 Metallographic analysis.

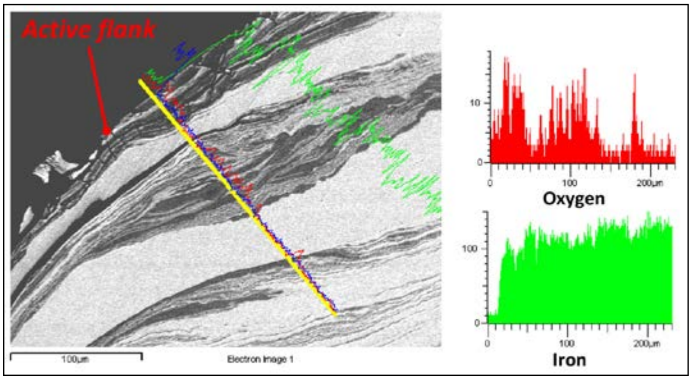

Figure 18 SEM analysis.