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Bending Fatigue Tests of Helicopter Case Carburized Gears: Influence of Material, Design and Manufacturing Parameters

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Abstract

A single tooth bending (STB) test procedure has been developed to optimally map the AgustaWestland gear design parameters and a test program on case carburized, aerospace standard gears, has been conceived and performed in order to appreciate the influence of various technological parameters on fatigue resistance, and to draw the curve shape up to the gigacycle region.

In a first phase, tests up to 10 million cycles have been performed on four test groups differing by material (VAR and VIM-VAR 9310, and VIM-VAR EX-53) and by manufacturing process (ground fillet versus unground fillet); in the second phase, VIM-VAR 9310 ground fillet specimen have been tested up to 100 million cycles. All the gear types were shotpeened.

FEM analysis, strain gauge measurements and rating formula of AGMA standard are used to express test loads in terms of tooth root stresses.

The program has been completed by failure analysis, based on SEM, on failed specimens and by ultimate load tests.

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Introduction

The safety, performance and reliability required to helicopter gearboxes are constantly increasing and gears are therefore subjected to increasing bending fatigue loads at the tooth root while at the same time longer lives are demanded.[1]

Many aspects of gear design and manufacturing must be controlled in order to obtain such results, like material cleanliness, case depth and hardness, tooth root shape and roughness, compressive residual stresses. Gear design and manufacturing processes, developed and optimized during many years, are therefore the key of the increasing performances of helicopter transmissions and a deep knowledge of the influence of each single design and manufacturing parameter on the fatigue strength is also required. Moreover, helicopter gears are designed to withstand loads in the very high cycle field (> 10^8 cycles) but are also subjected to short duration overloads and therefore a precise knowledge of the shape of the S-N curve is of great importance for precisely assessing their in service life.

Rating Standards, like AGMA 2101-D04 [2] and ISO 6336 [3], provide methods to assess gears bending fatigue performances, based on the comparison between the stress induced at the tooth root and the material allowable stress. Both terms are calculated in detail, taking into account with appropriate factors many influencing aspects, like tooth geometry, gear mounting conditions, contact ratio, overloads, velocity, number of cycles, roughness, dimensions, etc., but some limitations can be pointed out, and in particular:

1. Material data provided are lower limits, which can be granted if the conditions specified by the Standard are respected, but cannot take into account the actual performances which can be achieved through appropriate design, development and manufacturing.

2. The stress cycle factor/life factor, which represents the shape of the S-N curve, is not specified in the highest number of cycle region, that is represented as a range by a shaded area. In that area the actual value of the factor depends on such items as material cleanliness, ductility, fracture toughness and pitch line velocity (Figure 1). Therefore the responsibility of selecting a value is left to the designer, based on his specific knowledge. The range between the lower and the upper limit of the factor, at 10^{10} cycles, varies from 0.8 to 0.9 according to AGMA and from 0.85 to 1.0 according to ISO.

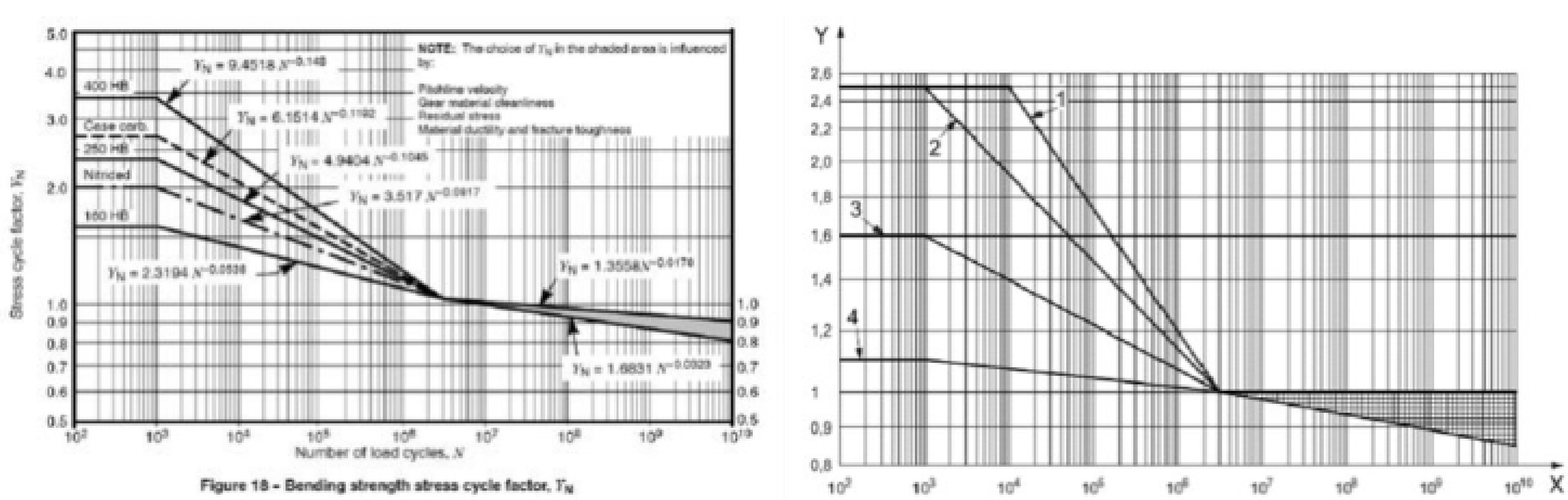

Figure 1. AGMA stress cycle factor (left) and ISO life factor (right)

For these reasons, in applications which require an accurate evaluation of gear performances, like helicopter transmissions, manufacturers must perform a systematic testing program in order to determine material fatigue limits, which must take into account specific design and manufacturing conditions, and the shape of the S–N curve in the range of interest.

Initial bending fatigue tests are generally performed using a STF (single tooth fatigue) scheme, instead reproducing gear meshing. The data for actual running conditions can then be determined by means of an appropriate factor, which can be explained as a consequence of a different load ratio R and of statistical considerations depending on the teeth number loaded during the tests [9]. The load ratio R, which is defined as the minimum test load versus the maximum test load in a load cycle, is $R = 0$ in running gears and typically $R = 0.1$ in STF tests.

Test setup

STF tests are usually performed by means of hydraulic machines or resonance machines. Two basic load application schemes, with several variations, are known:

1. In a "true" STF scheme, like in SAE J1619 [4] test rig for instance (Figure 2), the gear is supported by a pin, one tooth is tested while a second one, which is loaded at a lower position along the profile, acts as a reaction tooth. Such scheme is more common in the United States. With this scheme, some problems can arise if the tests are performed on mechanical resonance machines and the test are not stopped before reaching the final breakage
2. A second test scheme, more common in Europe [12][11], in which actually two teeth are loaded at the same time, is a consequence of the involute profile properties, and of the span measurement (the so called "Wildhaber span") in particular. In this case the gear blank can be left unsupported since the two equal and opposites applied forces are perfectly balanced (Figure 3).

The test fixture (Figure 4) designed specifically for the present research program can be used for both testing schemes. By changing the length of the anvil on the left side, the position of the load along the flanks of the tooth can be varied, thus changing the stresses on the two loaded teeth. With an appropriate length of the anvil the symmetric condition can be obtained and the pin, which in this case is used only for the positioning of the gear, can be removed: in this way no load can be absorbed by the pin and the load and stress on the two teeth are the same.

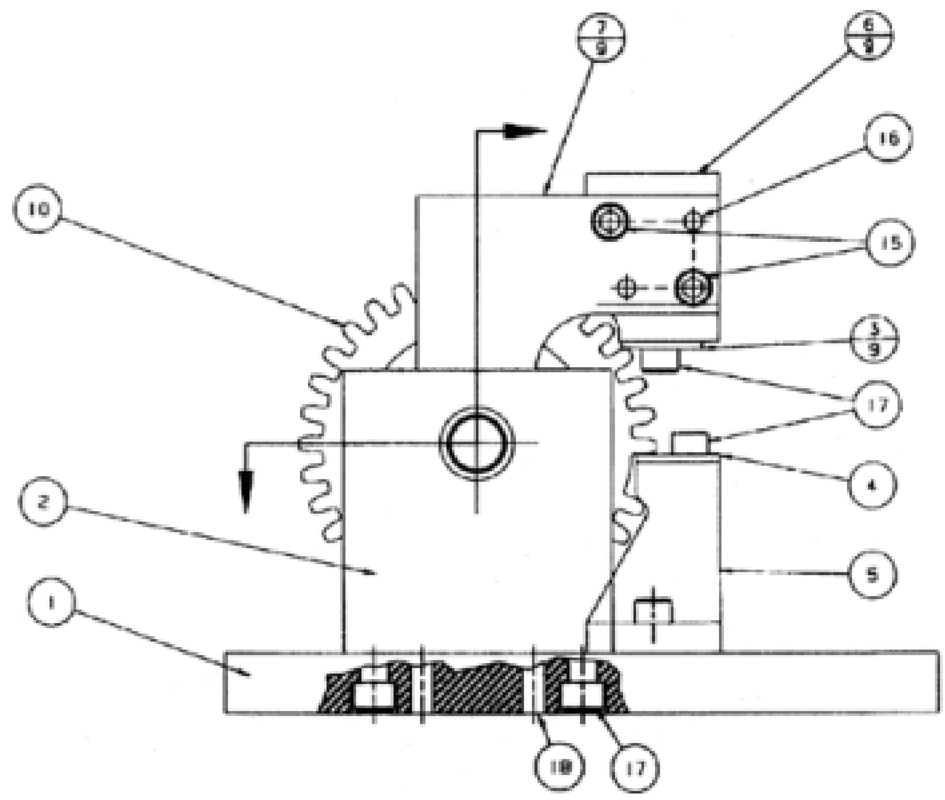

Figure 2. SAE J1619 test scheme

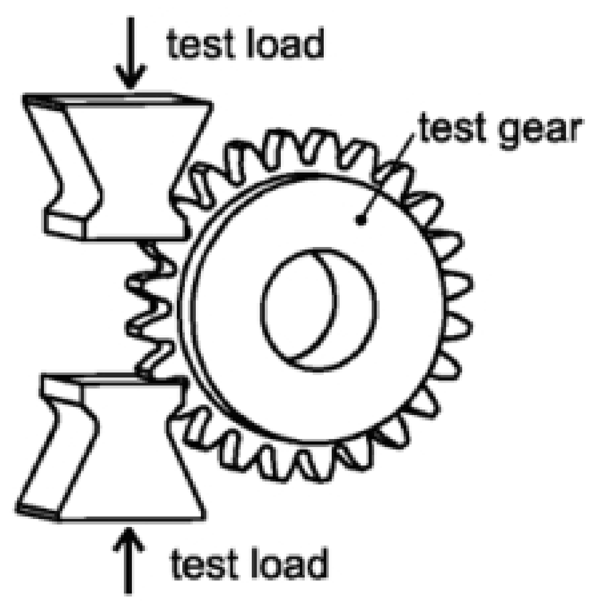

Figure 3. Testing scheme without supporting the gear blank (from [11])

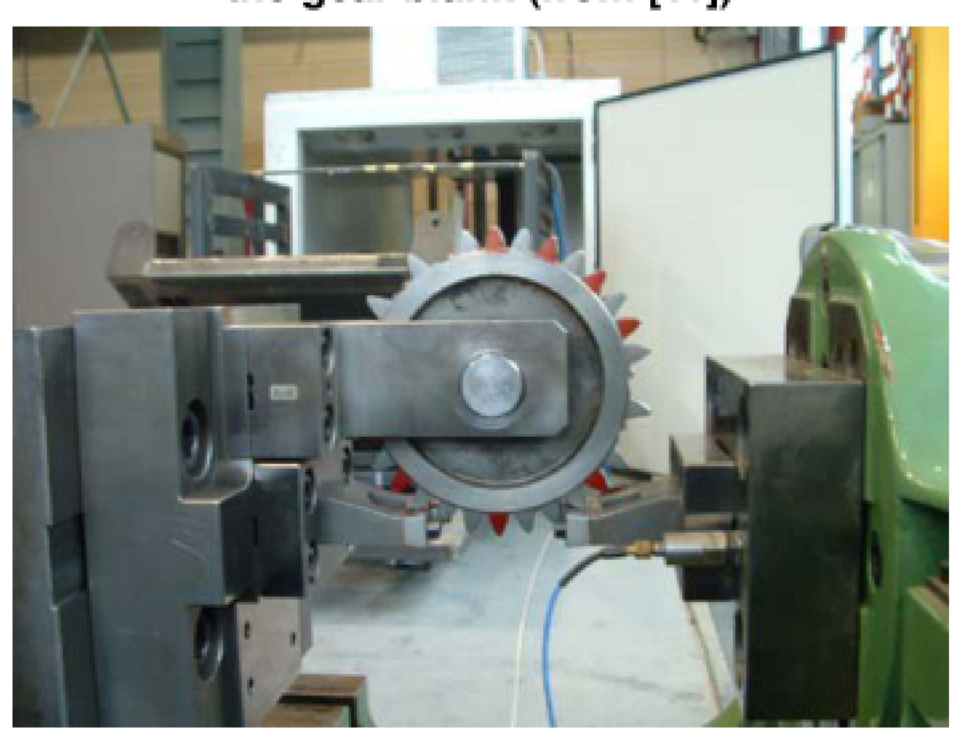

Figure 4. Fixture designed for AgustaWestland tests

The tests have been performed on a mechanical resonance 60 kN Schenck pulsator, without the pin (Figure 5).

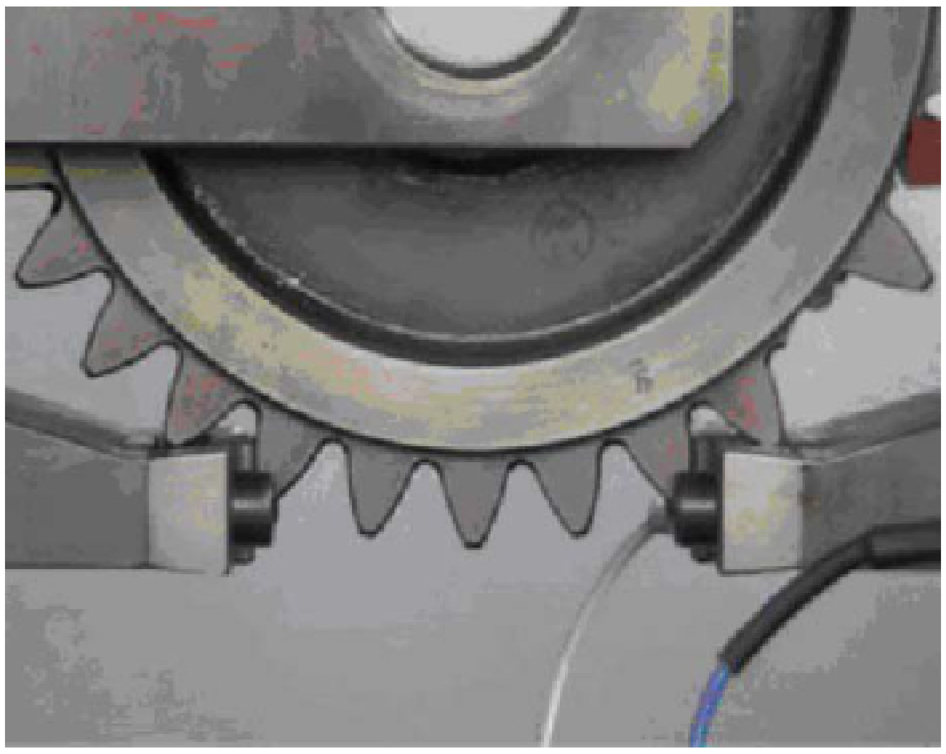

Figure 5. Gear specimen during test

Gear data and test groups

Table 1 summarizes the main gear data. For this test program a specifically designed test gear was defined and manufactured with different technological options. The gear proportions have been selected after several iterations optimizing test machine capabilities and representation of typical parameters of main power gears used on AgustaWestland helicopter transmissions. This test gear has now become the standard AgustaWestland specimen for gear technology evaluation and screening.

The test gear has 32 teeth and the anvils span five teeth for the STF test. Consequently, eight independent test can be performed on each gear specimen, because the teeth nearest those already been tested are not used for testing.

Table 1. Main gear data

Number of teeth	–	32
Normal module	mm	3.773
Helix angle	°	0.0
Normal pressure angle	°	22.5
Transversal pressure angle	°	22.5
Transversal module	mm	3.773
Working pitch diameter	mm	120.74
Base diameter	mm	111.55
Effective face width	mm	15.0
Tip diameter	mm	130.0

Four test groups have been manufactured in order to quantify the influence of design, manufacturing and material parameters (Table 2).

Table 2. Test groups

Test group number	Material	Manufacturing
451	VIM-VAR 9310	Ground fillet, shotpeened
551	VIM-VAR 9310	Unground fillet, shotpeened
651	VAR 9310	Ground fillet, shotpeened
751	VIM-VAR EX53	Ground fillet, shotpeened

Investigations, like roughness and micro-hardness measurements, have been performed to confirm the compliance of the specimens to the design specifications included in technical drawings.

In a first phase of the research, the four test groups have been tested and compared up to 10 million cycles. In a second phase, the test group 451 has been selected to extend the testing range up to 100 million cycles.

Two ultimate load tests have also been performed on two specimens for each group, by fitting the anvils to an hydraulic universal testing machine (Figure 6).

Figure 6. Ultimate load test

Test loads and tooth root stresses

The relation between the applied load and the tooth root stress has been investigated trough different approaches: AGMA Standard, finite elements analyses and strain gauge measurements.

The calculation according to AGMA Standard is based on the following basic equation:

$$\sigma_F = \frac{F_t}{b\, m_t} \frac{1}{Y_J}$$

in which the form factor has been calculated by considering a virtual gear pair having the HPSC (high point of single tooth contact) for the $z = 32$ gear under consideration coincident with the point of load application in the tests.

In the FEM calculation (performed with ABAQUS software), due to symmetry considerations, half gear and one anvil in contact have been modeled: the gear has been constrained on the symmetry plane and a displacement has been applied to the anvil (Figure 7).

The tooth root stresses have also been determined by means of Strain Gauges, which have also been used to verify the alignment of the test gear. For this reason 8 strain gauges corresponding to two teeth, two sides (compression and tension) and two ends of the face widths have been applied to two specimens, representing the two different fillet geometries (ground and unground). The details of the strain gauges application are given in Figure 8.

Table 3 summarizes the comparison between the applied load and the root stress, according to different methods.

Test results

As AgustaWestland rating procedures are based on the use of a continuous S–N shape curve, the test results have been analyzed by means of various curves, from both AgustaWestland experience and from other sources, that belong to the family:

$$\frac{S}{S_L} = H + A\,(N + C)^B$$

where S is the stress, N is the number of cycles, S_L is the fatigue limit, and H, A, B and C are constants which correspond to the different shapes.

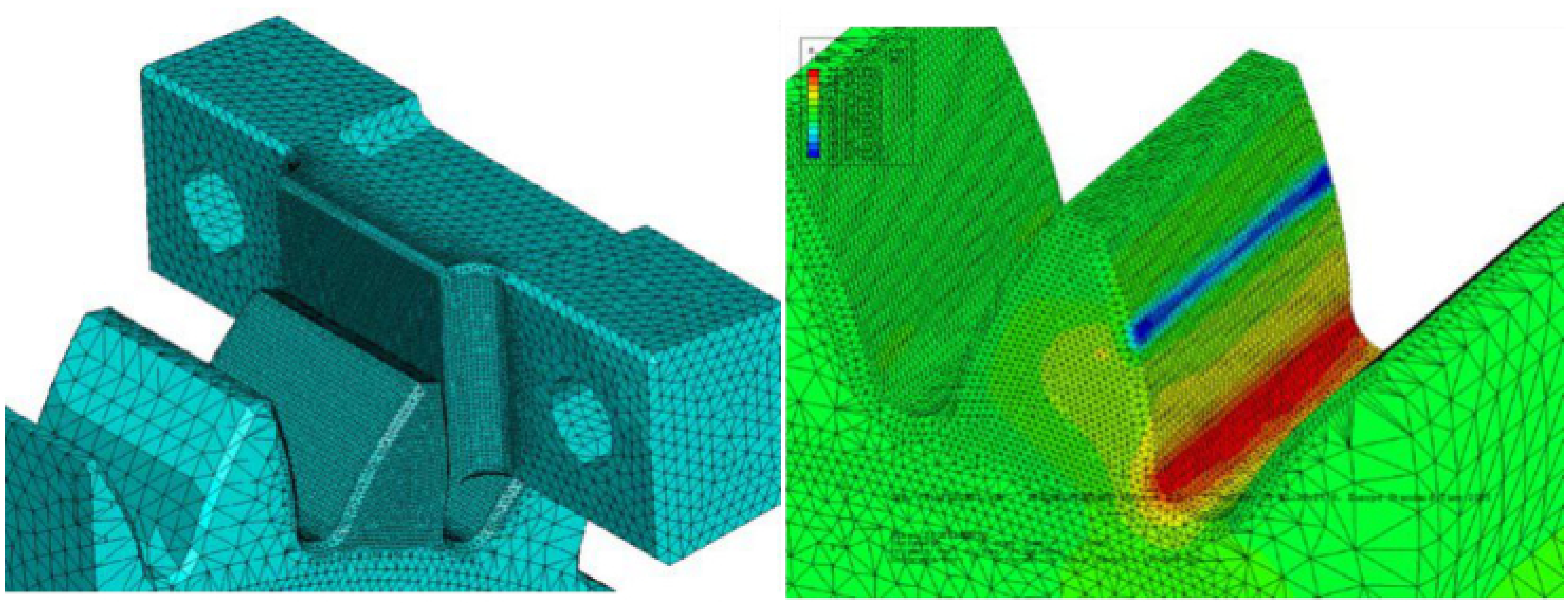

Figure 7. FEM model of the gear and the anvil, and example result of the FEM analysis

Table 3. Load vs. root stress according to different calculation methods

Test group	Fillet geometry	Load, kN	FEM stress, MPa	Strain gauge stress, MPa	ANSI/AGMA 2101–D04 bending stress, MPa
451, 651, 751	Ground	10	421.9	442.8	382.2
551	Unground	10	417.6	427.3	361.6

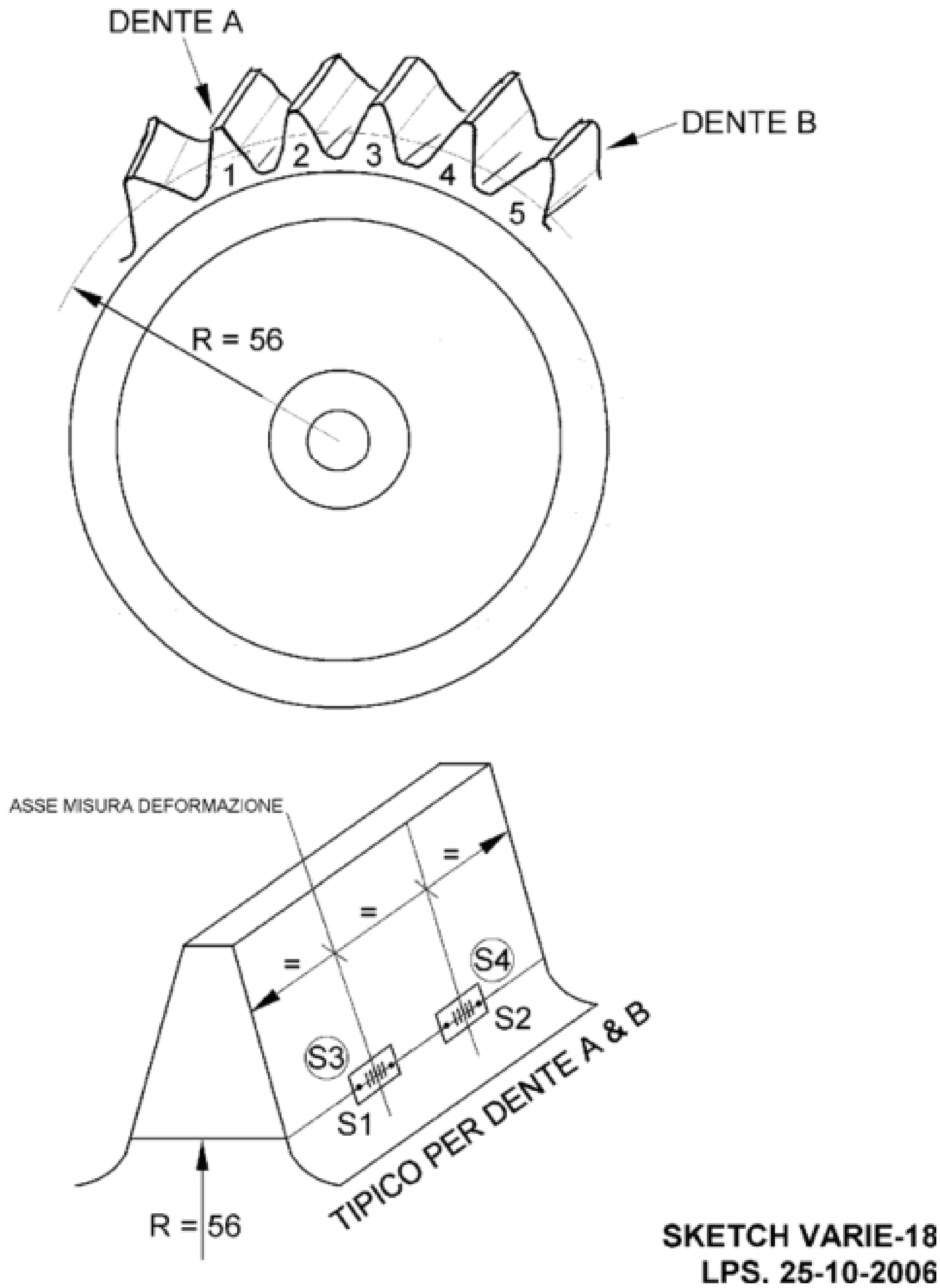

Figure 8. Strain gauges application sketch

Two curves, named GEAR05 and GEAR06, have proved to best fit the experimental data and therefore are plotted along with the test data (Figure 9 to Figure 12). In the curve GEAR05 the parameters *H*, *A*, *B* and *C* are fixed and correspond to a shape-curve previously used and accepted by AgustaWestland, while in the curve GEAR06 they have been optimized on the basis of the present test data.

Test results for test group 451 also include the data of the second phase of the research, up to 100 million cycles. Very high fatigue cycle test results have not been plotted separately because they are consistent with the estimations done on the basis of the shorter tests: the forecast of the fatigue limit based on the shorter duration tests is only slightly modified by the data obtained with gigacycle tests.

The comparison between the four test groups is made in terms of applied load in Figure 13, and in term of stress in Figure 14. The fatigue limit, that is the asymptotic value of the shape curve, appears similar for the test groups 451 and 751, with a slightly higher value for the 751. The values of the fatigue limits estimation according to curve GEAR05 are reported in Table 4.

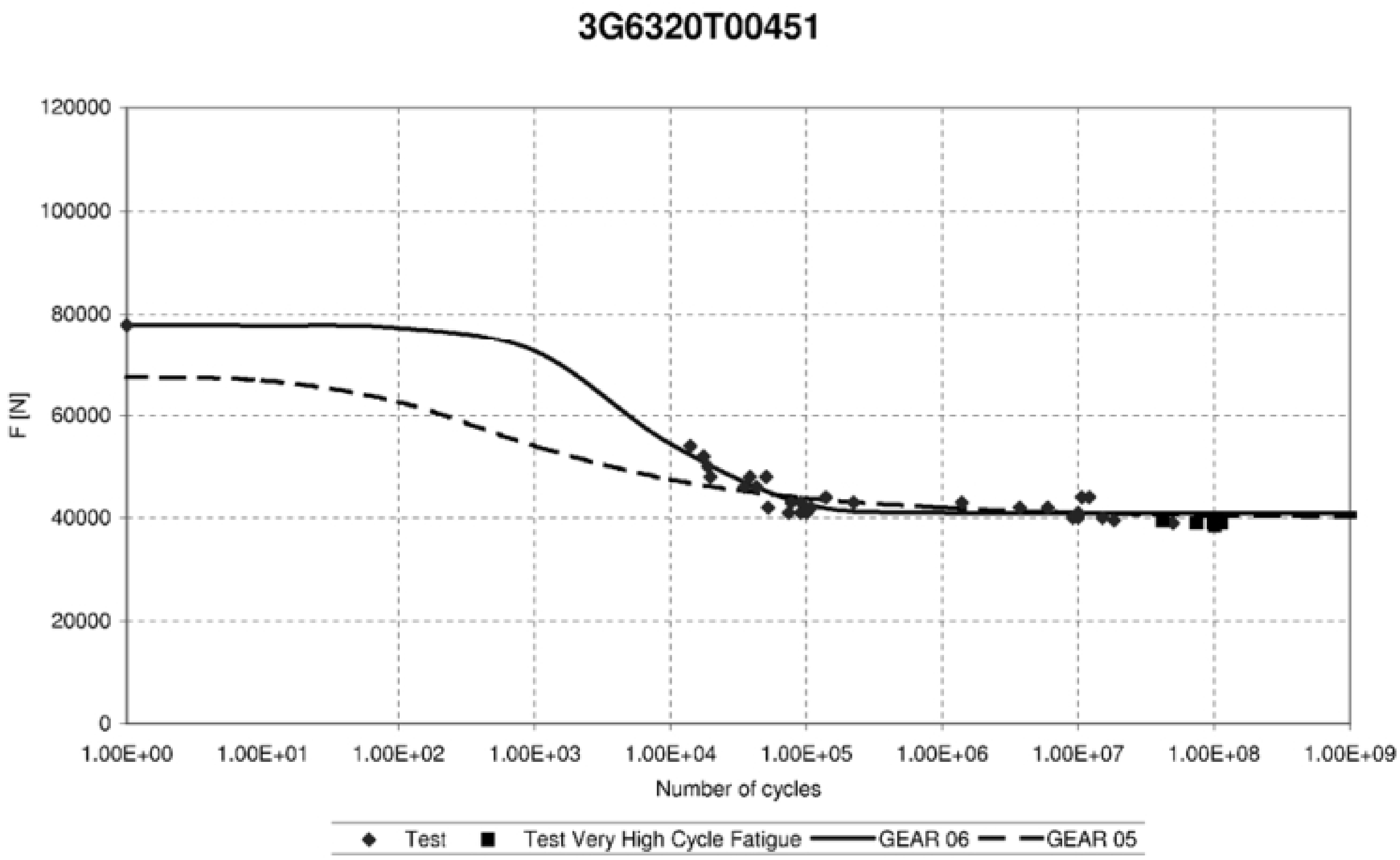

Figure 9. Test data, in terms of applied load, and curves GEAR05 and GEAR06 for test group 451

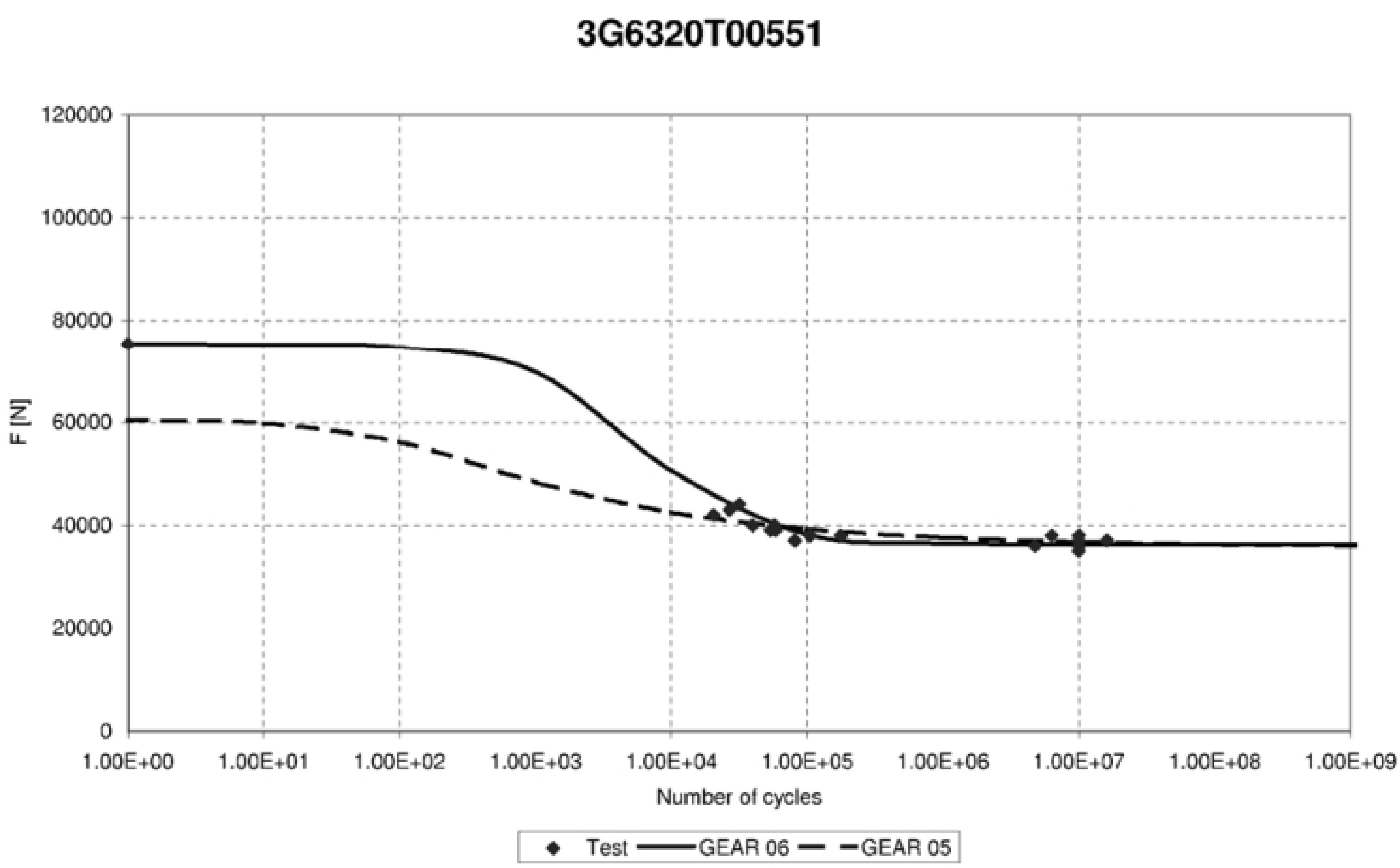

Figure 10. Test data, in terms of applied load, and curves GEAR05 and GEAR06 for test group 551

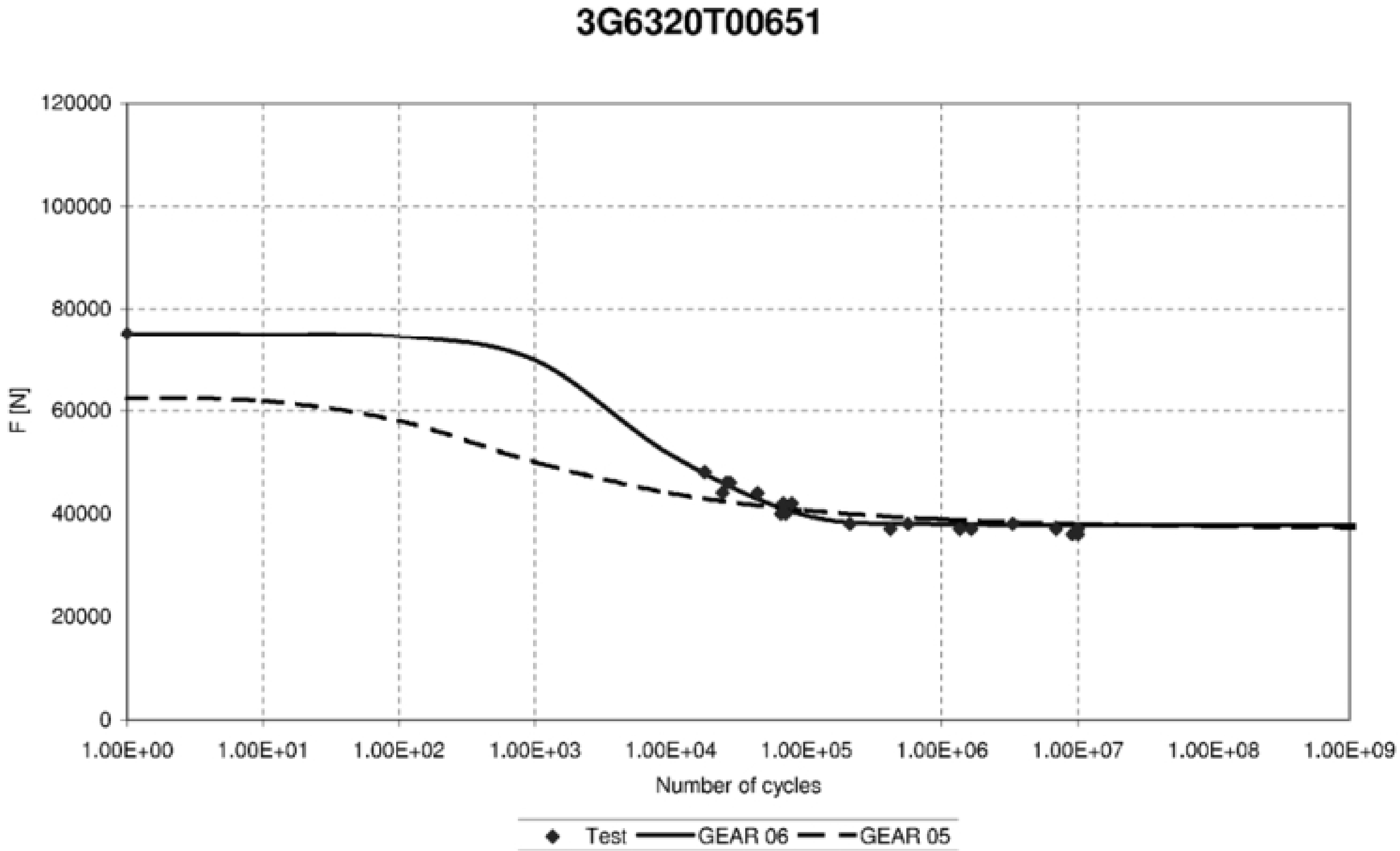

Figure 11. Test data, in terms of applied load, and curves GEAR05 and GEAR06 for test group 651

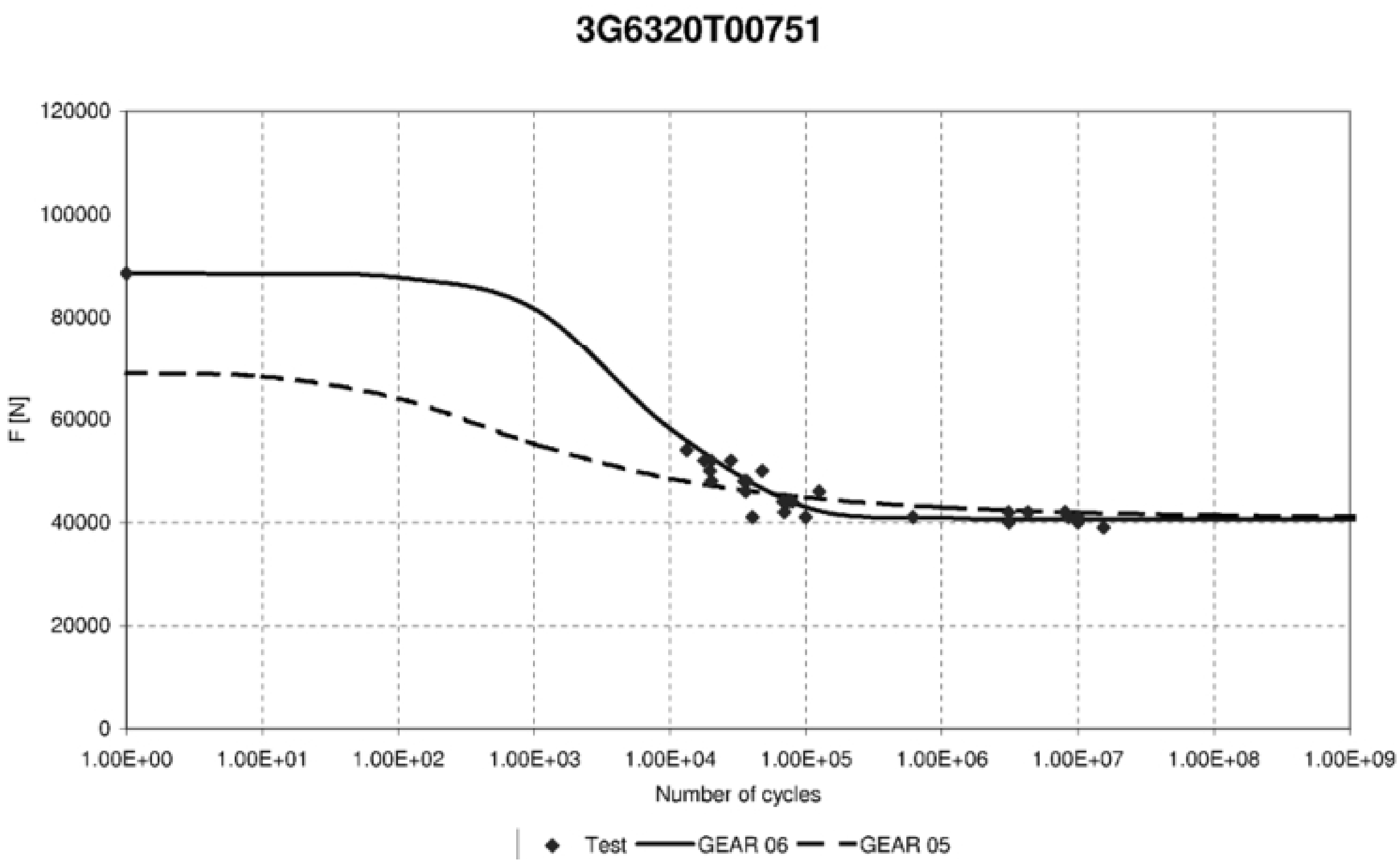

Figure 12. Test data, in terms of applied load, and curves GEAR05 and GEAR06 for test group 751

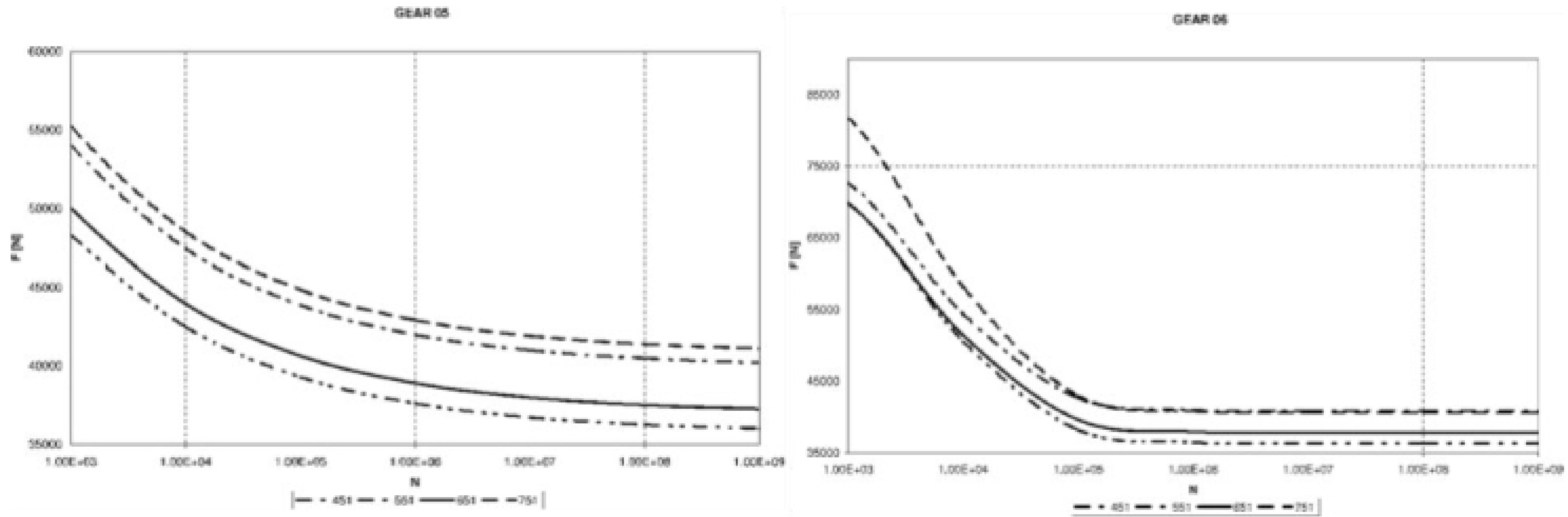

Figure 13. Comparison, in terms of load (N), among the four configurations by means of the curves GEAR05 (left) and GEAR06 (right)

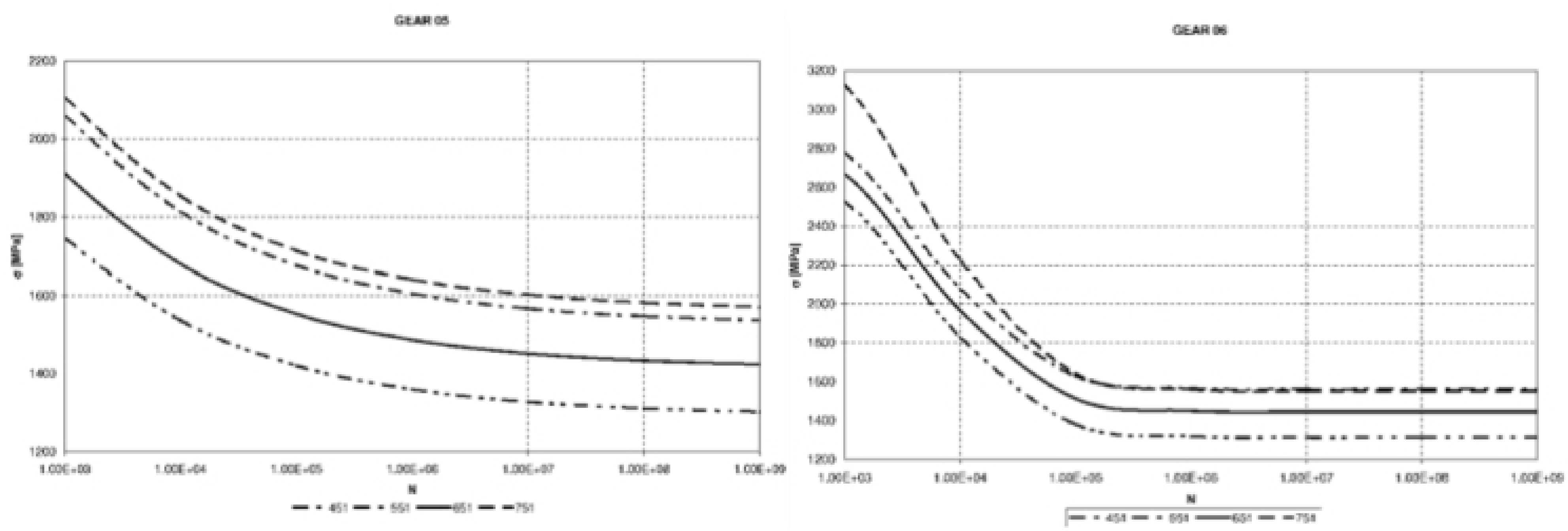

Figure 14. Comparison, in terms of stress (MPa), among the four configurations by means of the curves GEAR05 (left) and GEAR06 (right)

Table 4. Fatigue limit estimations with curve GEAR05 (the values in term of stress are derived according to ANSI/AGMA 2101-D04)

Test group	451 1st phase	451 1st + 2nd	551	651	751
Fatigue limit, N	40,281	39,928	35,758	36,989	40,819
Fatigue limit, MPa	1,540	1,526	1,293	1,414	1,560

In the first phase, VIM-VAR EX53 and 9310 (both according to AgustaWestland proprietary specifications) have shown the highest values of fatigue resistance with a slightly higher figure for EX53. The fatigue limit of 9310 VIM-VAR with unground fillet is about *8*% lower while the fatigue limit of 9310 VAR (according to AMS6265 [13]) and form grinding is about *11*% lower.

In the very high cycle fatigue tests on 9310 VIM-VAR, two failures occurred in the range between 10 and 100 million cycles. The results of the very high cycle tests confirm the curve determined with the ordinary tests and its asymptotic value.

The fatigue limits obtained in the present test program are much higher than those included in AGMA and ISO rating standards, but the opinion of the authors is that a direct comparison with those data is not meaningful, because they are not specific for the aerospace applications and do not consider the influence of such parameters like shotpeening or residual stresses. Besides the present data are obtained with a STF test, which have a different load ratio R and, also different statistical conditions, as explained in [9]. Literature data for a similar material and application can be found in [8] for the low cycles field and they are consistent with those of the present research in the same cycle range.

Furthermore, as already mentioned before, static tests to breakage has been performed on the gears to check the ratio between the static strength and the endurance limit and the results were in the range of 1.93 to 2.17 which are reasonably consistent with the ISO and AGMA standard curves for carburized gears (2.50 and 2.70 respectively, ref. Figure 1).

Crack nucleation and propagation

The tooth failure surface shows the typical shape of case hardened AISI 9310 gear teeth [6] [8], with a typical cone-cup final fracture. An example of fracture surface is shown in Figure 15.

From the SEM observation of the fracture surfaces it has been possible in some cases to identify the crack nucleation point, which sometimes corresponds to a defect or inclusion. In other cases it has not been possible to observe the crack nucleation. All the crack nucleation points detected are near the surface of the tooth, Figure 16. Some other authors [6], for the same material, have proposed the possibility of nucleation at the case-core interface. In this test campaign such kind of nucleation has not been observed. As the explanation of the phenomenon is based on stress gradients and on the relation between the case depth and case vs. core characteristics, it seems reasonable to maintain that local conditions at the tooth root of the cited paper could have been different from those of the present case.

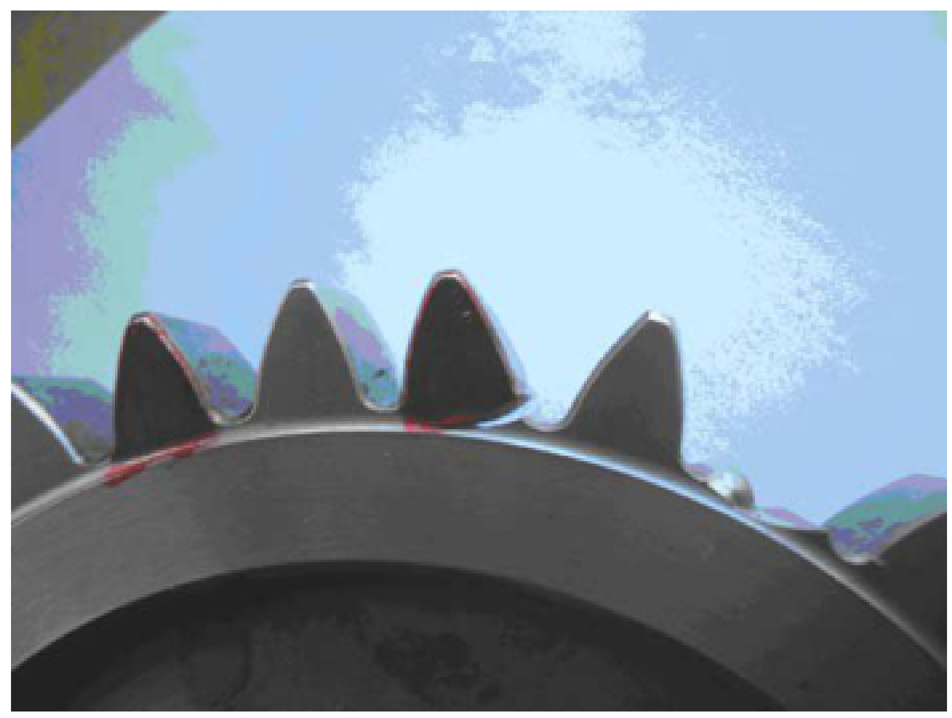

Figure 15. Typical appearance of the failure surface

In some cases crack growth marks have been found on the failure surface, as shown in Figure 17.

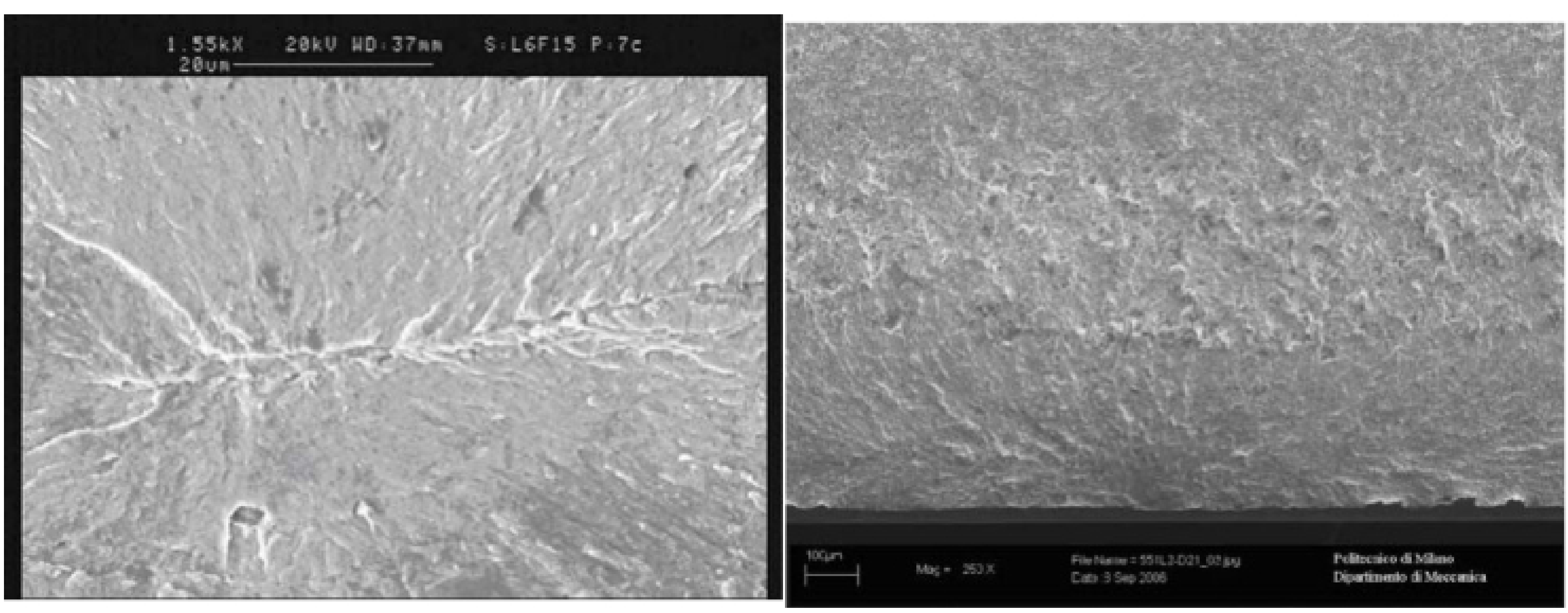

Figure 16. Examples of crack nucleation corresponding to a non-homogeneity of the material (left) and not corresponfing to a defect or inclusion (right)

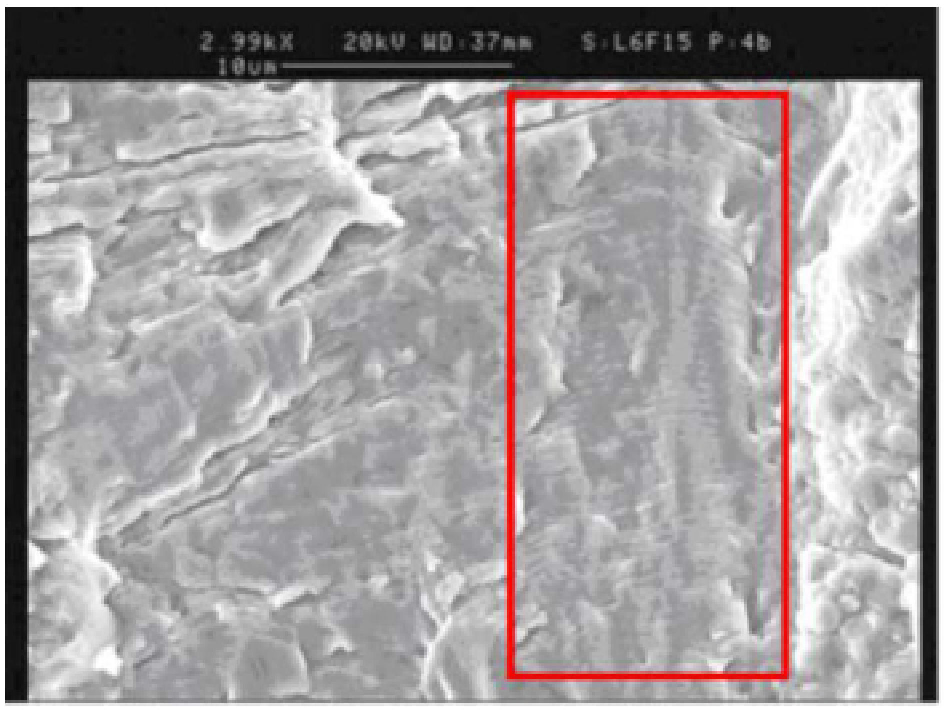

Figure 17. Crack growth marks

Conclusion and future developments

The extensive campaign of tests has given precise information concerning the fatigue limits of the four tests groups both in absolute and relative terms. The results have been analyzed by means of different curves shape, from both AgustaWestland experience and from other sources, and the most appropriate have been selected. Very high cycle tests confirm the estimations done on the basis of the shorter tests, both in term of fatigue limit and of curve shapes.

The test procedure developed has now become the standardized approach at AgustaWestland to evaluate, compare and qualify new materials, new processes, new designs and therefore the test program is continuing with tests on nitriding gears.

In the first phase of the research, with tests up to 10 million cycles, *102* gear tooth specimens have been tested for an amount of *434* million cycles, while in the second phase, up to 100 million cycles, 8 specimens have been tested for an amount of *734* million cycles.

In order to have a deeper understanding of the fatigue behavior in the low cycle range, further investigations in this field have been programmed. A campaign of tests on carburized case hardened gears with an hydraulic testing machine is also in progress, both under constant and variable amplitude loading. In order to improve the transferring of test data to transmission design, some bending fatigue tests on a back-to-back rig have also been planned.

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