Experimental investigation on crack propagation paths in spur gears

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Abstract. Spur gears subjected to bending fatigue may nucleate cracks at the tooth root fillet. In thin rim gears these cracks may propagate in a safe way (through the tooth) or in catastrophic way (through the rim). Crack propagation direction is mainly influenced by both wheel geometry parameters and crack initiation point, as already pointed out by theoretical and numerical results available in literature. Aim of this work is to set up an experimental activity in order to verify the onset of the bending crack and its propagation path in spur gears with different geometries. In particular, a special device connected to a standard fatigue machine was realized to perform bending tests for both standard and thin rim gears. During bending tests, an IR thermocamera was utilized to monitor the surface thermal profile in the tooth root fillet zone.

1. Introduction

Crack propagation in gears is a problem related not only to the life of the components, but also to the concept of failsafe design. Fail safe design means to design a component in order that, if a failure occurs, this may cause a "safe failure". This aspect is very important above all in aerospace industry. As a matter of fact, in aerospace applications the need of reducing weight brings to produce gears with very thick rim and web. Considering thin rim gears, when a crack is nucleated near the tooth root, it may propagate through the tooth (causing the loss of the entire tooth or a portion of it) or the propagation may follow a path across the wheel diameter (causing the projection of big parts of the gear that may break the gearbox and may cause serious damage to the aircraft). The first failure mode is defined as "*failsafe failure*" and the second one as "*catastrophic failure*" and, of course, has to be avoided.

Designers need to have robust design criteria in order to predict crack propagation paths and to avoid catastrophic failures. An increasing number of variables of interest, under the hypothesis of isotropic material, have been taken into account during the years and utilised in numerical simulations to achieve that goal. Traditional 2D and 3D finite elements (FEM) and extended finite elements (XFEM) models have been run, focusing on both crack initiation point and corresponding propagation direction.

On the basis of previous simulations results [1-3], it was noted that the crack propagation direction was mainly influenced by both wheel geometry parameters and crack initiation point. Results related to gear models with different web and rim thicknesses were also interpreted in ISO Standard environment [4], relating the crack path to the so called gear blank factor C_R, useful in cases of mating gears consisting of rims and webs. Results showed that the interaction between web and rim thickness may influence the crack propagation and the corresponding safe or catastrophic failure mode [1-3], [5-6].

For specific geometry configurations, crack propagation paths may be affected also by other parameters such as the centrifugal load. For this reason, the effect of the centrifugal load (proportional to wheel speed), related to the bending one, was investigated by means of dedicated simulations [2].

Many studies were carried on during the years, above all from the numerical point of view, but there is a lack in literature for as concerns experimental tests to verify the obtained results in term of crack path typologies. Some evidence of experimental activities can be found in [7], where test were run on wheel models.

Aim of this work is to set up an experimental activity in order to verify the onset of the bending crack and its propagation path in spur gears with different geometries. In particular, a special device connected to a standard fatigue machine was realized to perform bending tests for both standard and thin rim gears. Three gears with different geometry configurations (back ratio and web ratio values) were tested. During the bending tests, an IR thermocamera was utilized to monitor the surface thermal profile and to emphasize the stress variation in the tooth root fillet zone. Both crack initiation point and propagation path direction were pointed out, and this information was compared to the corresponding available in literature from numerical simulations.

2. Materials and Methods

Three types of spur gears (one *standard* and two *thin-rim* gears) were designed to be tested in this activity under bending fatigue conditions.

Geometrical parameters of each gear are resumed in Table 1. In particular are shown: pitch diameter (*dp*), face width (*b*), number of teeth (*z*), modulus (*m*), backup ratio (rim dimension respect to the tooth height) (*mb*), web ratio (web thickness respect to the face width) (*mw*) and gear blank factor (C_R) [4]. As an example, technical drawings of Gear 1 and Gear 2 are shown in Figure 1.

Table 1. Gears geometry.

	dp [mm]	*b* [mm]	*z*	*m* [mm]	*mb*	*mw*	C_R
Gears 1	96	20	32	3	1	1	1
Gears 2	96	20	32	3	0,3	0,1	0.63
Gears 3	96	20	32	3	0,5	0,1	0.59

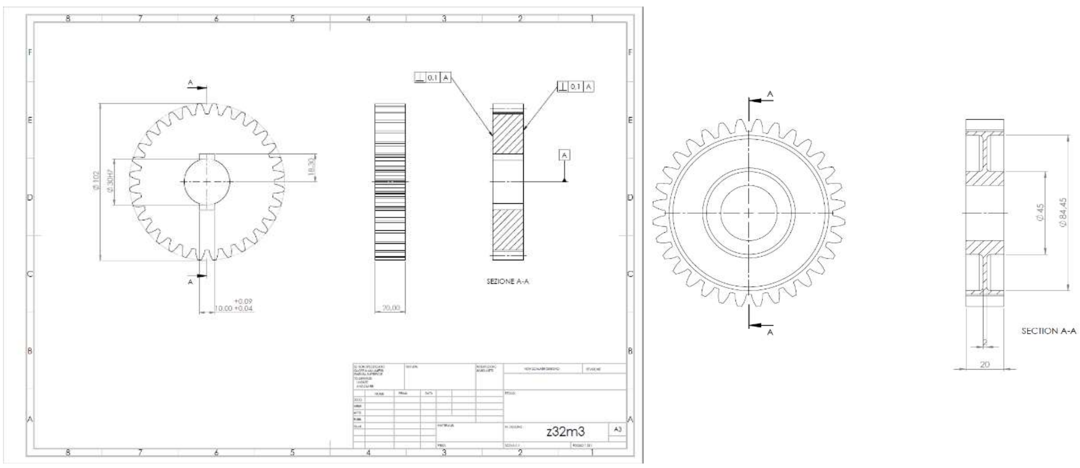

Figure 1. Technical drawings of Gear 1 and Gear 2.

Each gear is made of C45 steel without thermal treatments.

A special device connected to a standard fatigue machine was realized to perform bending tests for both standard and thin rim gears (see Figure 2, left side). A punch integrated into the device was able to apply the pulse loading to the gear tooth. In particular this punch was designed in order to load the tooth along its involute profile in both position and direction referred to the single contact point [8].

Figure 2. Test apparatus.

Fatigue tests were run with 20 Hz excitation frequency. Maximum and mean force were respectively 12200 N and 6200 N, a small static load was always applied to guarantee the contact between punch and tooth.

During bending tests, an IR thermocamera (*IR tech Timage Radiamatic "XT"*) was utilized to monitor the surface thermal profile in the tooth root fillet zone (see Figure 2, right side). The thermal detector was located at a distance of 60 mm from the gear. A reference specimen (see Figure 2, right side) allowed to acquire the environmental temperature during each test. Gears and reference specimen were both covered by black spray paint to generate a surface with an emissivity close to 0,95. Two different thermal profiles were extracted from each thermogram near the root tooth fillet, respectively an *aera* and a *point* of 2x2 pixel (located inside the area close to the crack initiation point). The relative temperature ΔT (difference between the absolute temperature and the temperature of the reference specimen) was computed for Gears. Figure 3 illustrates an example of the area position near the tooth root fillet.

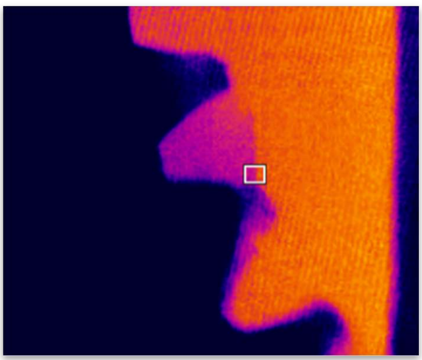

Figure 3. Position of the area.

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3. Results
Results obtained in this work concern crack propagation paths caused by bending fatigue cycles. For sake of brevity, only results referred to Gear 1 and Gear 2 are reported in this paper.

Figure 4 shows, as an example, Gear 1 and Gear 2 and their failure typologies. As it can be observed, Gear 1 crack path (on the left) corresponds to a classical fail safe condition, while in Gear 2 (on the right) a crack path directed through the rim can be pointed out.

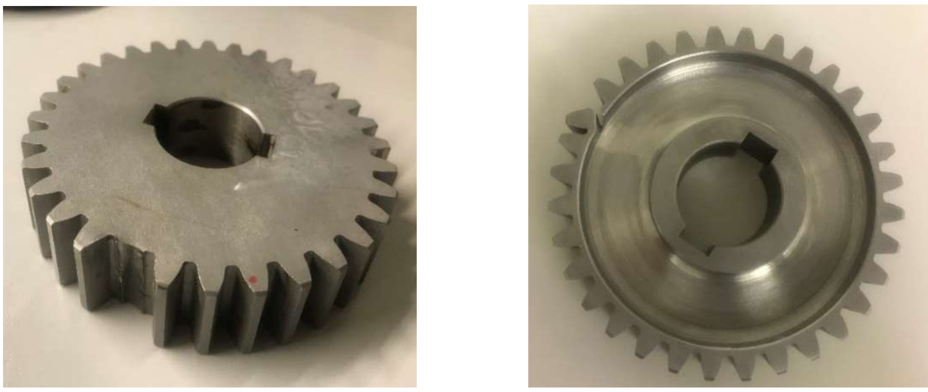

Figure 4. Gear 1 (left) and Gear 2 (right) crack paths.

Figure 5 shows an example of thermal images recorded during fatigue tests. More in detail, the left image is related to Gear 1 and, as in Figure 4, a crack propagating through the tooth can be appreciated. The right image shows the crack propagating through the rim, as predicted for Gear 2 already in the design phase.

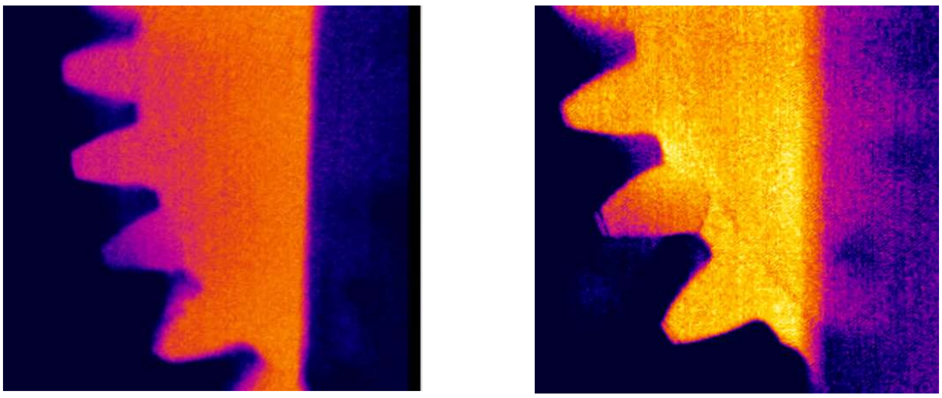

Figure 5. Thermal images of Gear 1 (left) and Gear 2 (right).

As a matter of fact, geometrical parameters of Gear 2, in particular its backup and web ratio values, were chosen to verify the corresponding catastrophic failure already emphasised by numerical simulations, and now demonstrated by fatigue tests. Rim and web geometries may be related to the well known CR parameter [4] (see Table 1), as a function of both backup ratio and web ratio values. As already indicated in [2], the position of this parameter respectively in the tooth failure zone, in the uncertainty zone or in the rim failure zone of its graph (see Figure 6 [2]) allows us to draw some hypothesis about the possibility of safety or unsafety fracture basing only on the gear geometry.

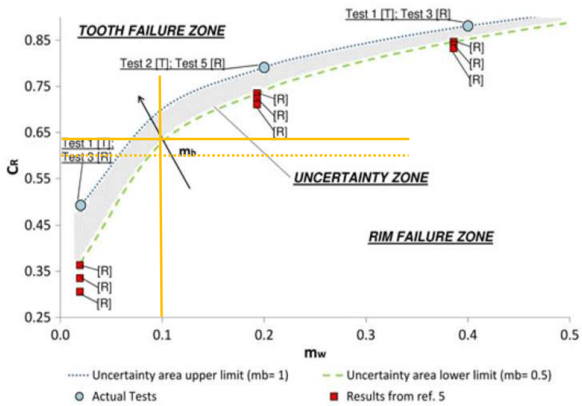

Figure 6. CR factor [2].

Figure 6 points out CR parameter values for Gears 2 and 3, characterised by different back up ratio (m_b) values and with the same web ratio (m_w), driving respectively to fail safe and catastrophic failures. Finally, Figures 7 and 8 show the thermal profiles monitored during the fatigue tests respectively for Gear 1 and Gear 2. In particular, in each Figure is reported the difference temperature ΔT (respect to the ambient temperature or reference specimen) as a function of the number of cycles, referred to both crack nucleation point and to an area around the nucleation point (nucleation area, mean value of temperature).

From the analysis of these Figures, it can be noted the increase of thermal profiles in the first phase of the test, then a stabilised condition of temperature and, finally, an abrupt variation corresponding to the failure. Nucleation point and area profiles show in both cases identical trends.

The comparison between Figures 7 and 8 shows that the fatigue life of Gear 2 is lower than that of Gear 1 in term of number of cycles (118000 cycles for Gear 1 and 104300 cycles for Gear 2), as expected. Moreover, the relative temperature ΔT level is higher for Gear 1 than for Gear 2. This unexpected result may be interpreted as a strong dissipation flow in the case of Gear 2 within the whole wheel body, due to the high displacements involved in fatigue tests.

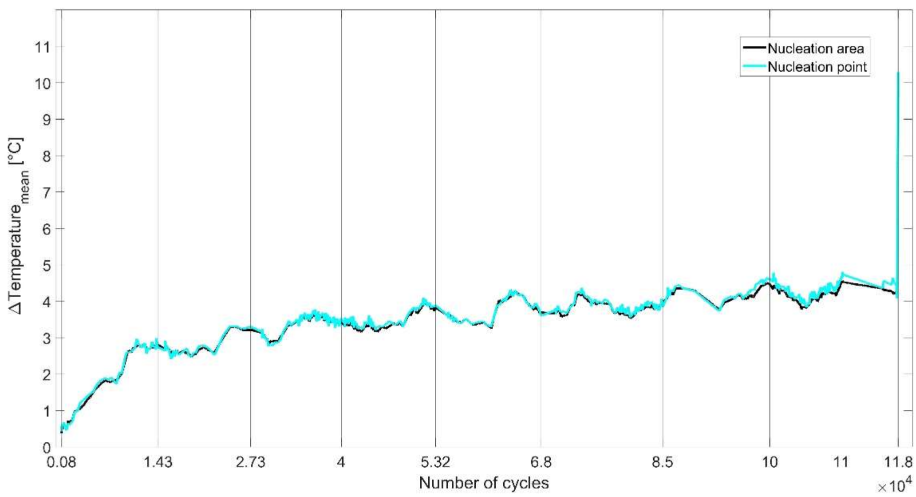

Figure 7. Gear 1 thermal profiles.

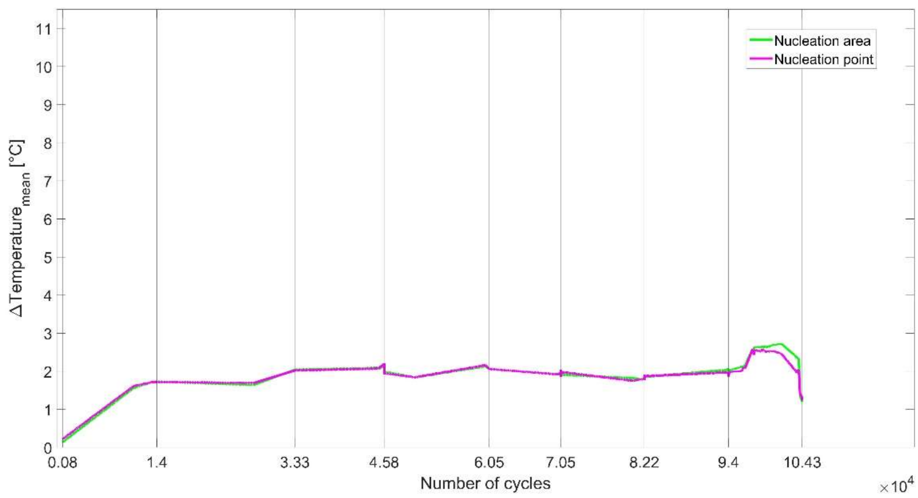

Figure 8. Gear 2 thermal profiles.

4. Conclusions

The present work represents a first step in the experimental verification of crack propagation paths in light weight gears.

To this aim, an experimental activity was set up in order to verify the onset of the bending crack and its propagation path in spur gears with different geometries. To perform bending tests, a special device connected to a standard fatigue machine was realised, consisting in a system to clamp the wheel to the machine and in a punch useful to apply the pulse loading. This loading entity was intended to be applied on a tooth involute profile in point and direction corresponding to the so called single contact point. This way, the effect of the sharing condition for the gear subjected to bending test was neglected.

During bending tests, an IR thermocamera was utilized to monitor the surface thermal profile in the tooth root fillet zone. The monitoring of surface thermal maps made possible the identification of both crack initiation point and its propagation in the first phase of the phenomenon, and not only in the last phase when fracture occurs.

On the basis of previously obtained results, based on numerical simulations, the geometry of gears was designed in order to predict the corresponding crack propagation path. Experimental results confirmed that geometrical parameters and corresponding blank factor values may represent an useful point of view providing a realistic design map for thin rimmed gears and for aerospace gears with particular web geometries.

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