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Crack propagation behavior in planet gears

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Abstract

Aim of this work is to investigate crack propagation paths in planet gears for aerospace applications in order to find how gears parameters may affect the crack path and, consequently, may provide information about gears design to avoid catastrophic failures. The research activity has been carried on by means of extended finite element models (XFEM).

In particular, the effect of rim thickness (expressed as backup ratio) and crack initiation point on crack paths has been considered. Obtained results have been compared with those available for standard gears, to highlight the different behavior in crack propagation.

Keywords: Fracture mechanics; crack path; crack propagation; gears; XFEM; speed

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1. Introduction

In aerospace transmissions planetary gearboxes are mainly used to reduce speed from the engine shaft to the propeller or fan shaft. In these applications, planet gears are usually supported by roller bearings with the bearing outer race integral to the gear hub.

Due to high loads, these components need accurate design, especially about possible failure modes, in order to guarantee the airplane safety.

Because of both specific design and shape, this kind of planet gears may be classified as thin rim gears. When a crack nucleates in a thin rim gear, it may cause catastrophic or safe failures.

The first case is when the crack propagates through the rim and the second one when the crack propagates through the tooth.

In the literature, it is possible to find some works related to the crack propagation path in thin rim gears, but all these works refer to “standard” gears that involve different working and boundary conditions with respect to planet

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gears. It is important to highlight that the load conditions of planet gears are more severe respect to those applied to standard gears.

In particular, planet gears teeth engage in two opposite sides and each tooth is subjected to bending force in both tooth sides, reducing its fatigue limit Curà (2015).

Most of these works originate from the researches of Lewicki et al. (1996, 1997, 1998, 2001, 2005) who investigated the effect of rim thickness from both experimental and numerical points of view.

Kramberger et al. (2000, 2004) investigated by finite element and boundary element methods the effect of rim thickness on bending fatigue life of a thin-rimmed spur gear for truck gearbox. Many others papers, Glodez et al. (1995, 1997, 1998, 2008), Amiri Rad et al. (2014) and Curà et al. (2014, 2015), deal with crack propagation paths, but no one specifically for planet gears.

As a matter of fact, in planet gears forces are applied in a different way with respect to standard gears. They are idle and they have two opposite teeth in contact simultaneously; as stated before, usually their rim is the bearing outer race that produces different constraint conditions with respect to the normal wheels.

Second important difference, with respect to traditional gears, is that the considered planet wheels do not have web connecting the rim to the hub, and hence, no torque is transmitted along their axes. By considering all these aspects, authors are expecting that crack propagation paths are modified by the particular planet geometry and working conditions.

Aim of this work is to investigate crack propagation paths in planet gears for aerospace application in order to find how gears parameters may affect the crack path and, consequently, may provide information about gears design to avoid catastrophic failures.

The research activity has been carried on by means of extended finite element models (XFEM) and using a 3D model. In particular, the effect of the rim thickness (expressed as backup ratio) on crack paths has been considered.

Obtained results have been compared with those available for standard gears, to highlight the different behavior in crack propagation.

Nomenclature

z	number of gear teeth
d	gear pitch diameter
m	gear module
s	tooth thickness
h	tooth height
B	face width
m_b	backup ratio
θ	angle of crack propagation

2. Materials and Methods

In order to study the crack propagation in a tooth root fillet of a planet gear, two XFEM models have been adopted.

A 2D model of the planet gear cross section has been developed using Simulia Abaqus.

In this particular case, the elements are plain strain quad (CPE4R) with different refinements according to the interested zone. In Fig. 1 the resultant meshed model can be seen.

The second model is a 3D model of the entire planet gear again set~~ting~~ up using Simulia Abaqus. In this case, the elements are solid and, in particular, the zone interested by the presence of the crack is modeled using hexahedral 3D elements (C3D8R), whereas the rest is modeled using tetrahedral linear elements (C3D4), as shown in Fig. 2.

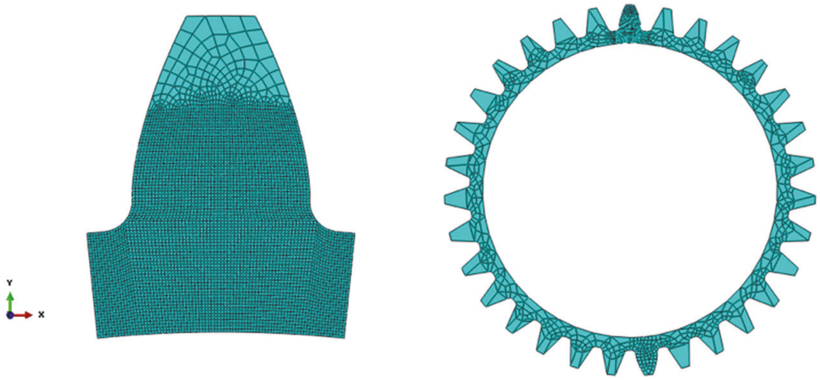

Fig. 1. 2D model.

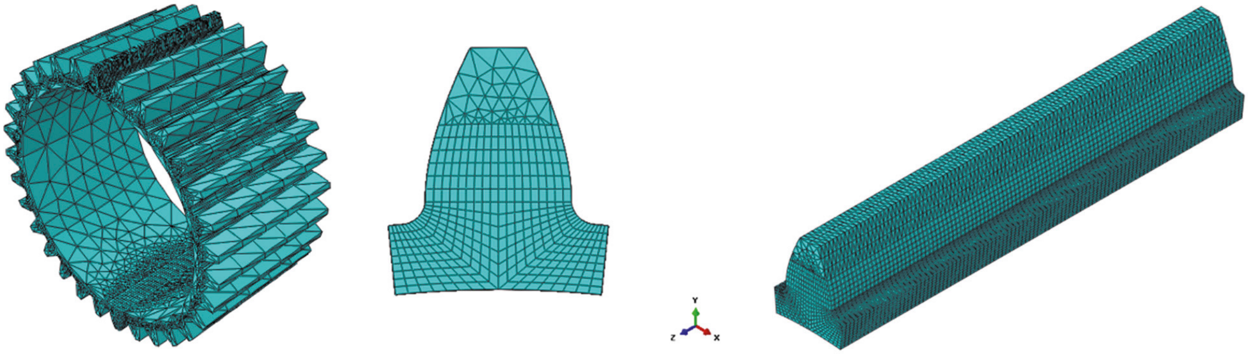

Fig. 2. 3D model and relative details.

A planet gear is usually free to rotate around a pin mounded on a bearing. That bearing can be rolling or journal, depending on the application; in the aerospace application, in order to reduce weight and friction, the rolling bearings are used and usually the gear rim is directly the outer ring of the rolling bearing.

In a first attempt, and trying to adopt the same procedure used in Curà at al. (2014, 2015), the discontinuous support given by the rollers is not taken into account; further investigations are in progress for considering this aspect. Therefore, the boundary conditions have to consider the planet gear able to rotate around its axis.

The equilibrium to rotation is provided by the contemporaneous contact between to opposite teeth, so the model has to take into account also this aspect.

According to those reasons, the bending force produced by engagement is applied on the HPSTC of the tooth where crack propagation is expected; on the opposite tooth, at the HPSTC is applied a simple constraint whose direction of action is directed as gear line of action.

In order to complete the set of boundary conditions, a radial constraint is applied on the inner surface of the rim. Those conditions are valid for both 2D and 3D models.

In 3D models, the simple constraint on the tooth and the force are split along the face width and an axial constraint is added in the inner surface of the rim. In Fig. 3, the boundary conditions are shown.

The main characteristics of the considered gear are shown in Table 1.

Table 1. Gear parameters.

Geometrical data		Material features	
Number of teeth ($\mathbf{z}$)	31	Young modulus E [MPa]	210000
Pitch diameter ($\mathbf{d}$[$\mathbf{mm}$])	93	Density ρ[kg/m^3]	7800
Module ($\mathbf{m}$[$\mathbf{mm}$])	3		
Tooth thickness at the pitch($\mathbf{s}$[$\mathbf{mm}$])	4.71		
Tooth thickness at the root ($\mathbf{s_p}$[$\mathbf{mm}$])	7.55		
Tooth height (h[mm])	6.75		
Face width (B[mm])	51		

3. Results and discussion

The initial crack has been placed at the point in the tooth root fillet where the maximum equivalent stress (Von Mises) is reached.

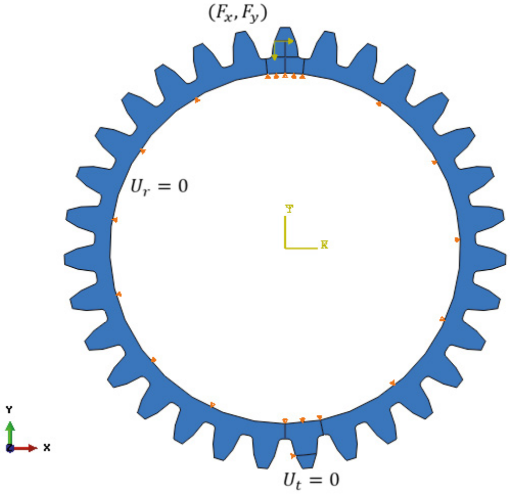

Fig. 3. Boundary conditions applied to the models.

To identify this point, 3D static simulations have been performed, Fig. 4 shows an~~d~~ example of the obtained results.

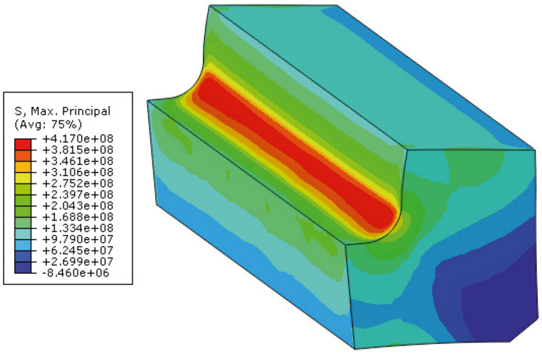

Fig. 4. Static simulation to identify the most stressed point in the tooth root fillet.

These preliminary 3D simulations have been run showing that the crack firstly propagate mainly in axial direction and then, when the crack reached both the face width extremities, it start the propagation inside the tooth (see Fig. 5).

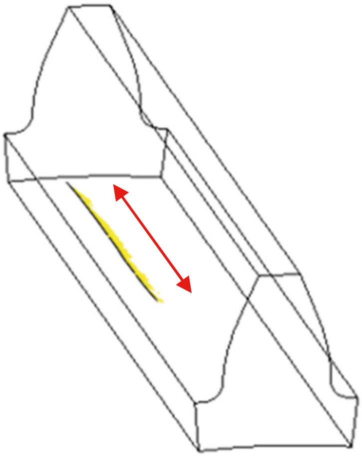

Fig. 5. Crack propagation in a 3D XFE model.

To reduce the calculation time 2D, models have been used to perform all ~~the~~ simulations, also because ~~the~~ 3D models did not add substantial information in this study.

As found in the literature, Curà et al. (2014), the crack initiation point may be a very important factor to determine benign or catastrophic failures. For this reason, starting from the point with maximum equivalent stress, other three different initiation points have been considered for each model.

Fig. 6 shows the crack propagation paths for the 5 backup ratios with initiation point at the maximum equivalent stress.

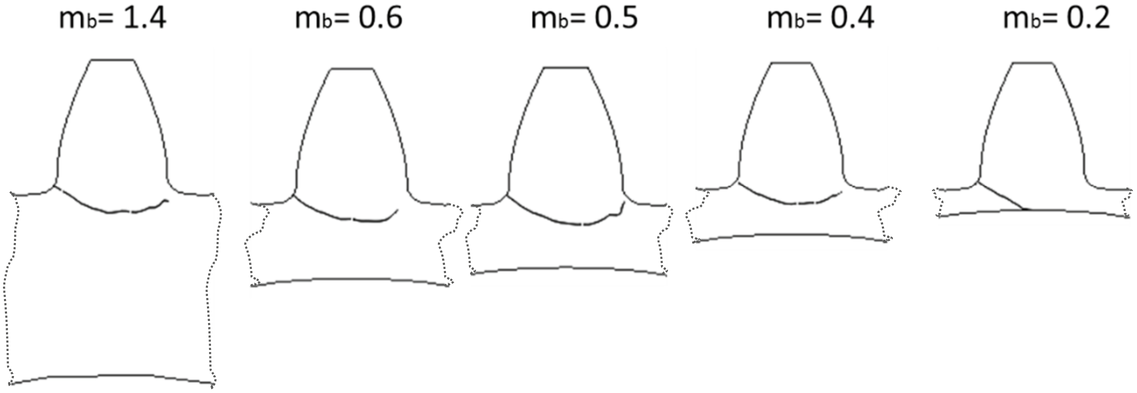

Fig. 6. Crack propagation paths for crack initiation at the point with maximum equivalent stress.

In some cases, Curà et al. (2014) and Lewicki (2001), the crack initiation point may be a key factor to achieve benign or catastrophic failure. For this reason, starting from the point where the maximum equivalent stress is reached, other three points (two down and one over the maximum equivalent stress point) have been considered as crack initiation point.

The position of the crack initiation point has been defined by the angle θ. This angle, as shown in Fig. 7, is the one described between a horizontal line by the tooth root fillet center and a line joining the crack initiation point with the tooth root fillet center; in this way a crack nucleating at θ = 90° means that this point is the lowest point of the tooth root fillet.

Totally twenty simulations have been run (five wheels with different backup ratios and four different crack initiation points) and the obtained results are resumed in Table 2.

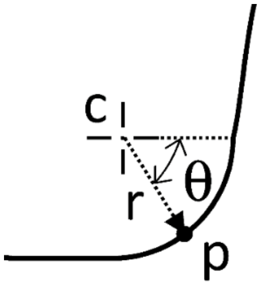

Fig. 7. Identification of crack initiation position by angle θ.

These results show a different behavior between planets gears and “standard thin rim gears. In particular, it is possible to observe that the crack propagation paths have different behavior related to the rim thickness respect to those found in the literature for thin rim gears as in Lewicki (2001).

Table 2. Crack propagation results (S= safe failure, C= catastrophic failure).

m_b	θ[°]			
	60	68.8	80	90
1.4	S	S	S	S
0.6	S	S	S	S
0.5	S	S	S	C
0.4	S	S	S	C
0.2	S	C	C	C

Considering backup ratios lower than 0.5, according to Curà et al. (2014), the cracks should propagate always through the rim, but in planet gears, this phenomenon seems to depend from the crack initiation point. This information is very important because it allows having more thin rims with safe crack propagations and as a consequence lighter gears.

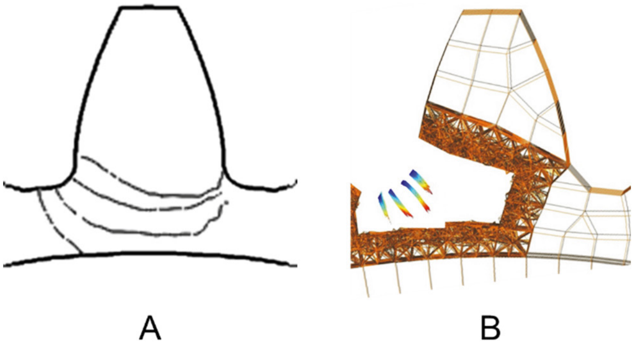

Fig. 8. Comparison of crack path in planet gears (A) and thin rim gear, Curà et al. (2014) (B).

As an example, Fig. 8shows a comparison between the planet gear with $m_b = 0.4$ (A) and a thin rim gear with the same backup (B) ratio, as in Curà et al. (2014). It is possible to observe the different crack path behavior, in particular in the most cases of analyzed planet gears, the crack propagates in a safe way, while in the corresponding thin rim gear the crack always propagate through the rim.

Concerning backup ratios values higher than one and comprised between 0.5 and 1, the behavior seems the same as standard thin rim gears. If the backup ratio is higher than one the crack propagation is safe (through the tooth), while for backup ration comprised between 0.5 and 1 the crack propagation direction depends from other parameters (as in this this work form the crack initiation point).

4. Conclusions

In this work the crack propagation path in planet gears for aerospace applications have been investigated. Planet gears for aerospace applications usually include bearing tracks in the inner diameters and need accurate dimensioning in order to avoid catastrophic failures. These kind of gears differs from standard thin rim gears because they have two opposite engaging teeth; they have inner bearing tracks and do not have any web.

The investigation has been carried on by means of XFE models. The effect of rim thickness and crack initiation position have been investigated.

The crack propagation path behavior of planet gears has been compared with that of standard thin rim gears with the same geometry (backup ratio).

Results shows that, as in standard thin rim gears, the crack initiation point may dramatically affect the crack direction (bringing to catastrophic rather than safe failures). It is possible to observe that the limit in rim thickness (given as backup ratio) where the crack propagation is always safe is higher respect to standard thin rim gears. This allow designing planet gears with rim thickness lower than standard thin rim gears reducing the wheel weight.

Future developments may include the better simulation of bearing rolling elements in order to investigate the effect of the number of rolling elements.

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