

EFFECTS OF CRACK INITIALIZATION ANGLE ON CRACK PROPAGATION PATH OF THIN RIM GEARS FOR WIND TURBINES

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Abstract: Nowadays, wind turbines are one of the main subjects of the designers due to the ever-increasing interest in renewable energy sources. Due to dynamic loads that effect the gear system, cracks may observe on the gear teeth. These cracks may proceed along either the tooth or the rim. In similar cases, if the crack proceeds along with the tooth, crack classified as benign. If the crack proceeds along with the rim direction, the cracks can be classified as catastrophic cracks. In this study, the effects of crack initialization angle and backup ratio on the crack propagation path are investigated numerically for spur gears. The maximum stress location at the gear root is defined as the crack starting point. The initial cracks are opened with 0° - 45° - and 90° crack initialization angles. Also, five different backup ratios are used for crack propagation analysis. The analyses are performed in ANSYS Workbench, SMART Crack Growth module. The crack propagation paths are evaluated for fifteen analyses. As a result, if the rim thickness is high, the crack initialization angle has no effects on the crack paths. It has an influence on the crack propagation paths for the special rim thickness.

Keywords: Wind Turbines, Fracture Mechanics, Crack Propagation, Gears

Çatlak Başlangıç Açısının Rüzgar Türbinlerindeki İnce Rimli Dişlilerin Çatlak İlerleme Yoluna Etkileri

Öz: Günümüzde, rüzgar türbinleri, yenilenebilir enerji kaynaklarına gittikçe artan ilgi nedeniyle dişli tasarımcıların ana konularından birisi haline gelmiştir. Dişli sistemine etki eden dinamik yükler nedeniyle, dişli dişlerinde çatlaklar oluşabilir. Bu çatlaklar diş veya rim boyunca ilerleyebilir. Benzer durumlarda; çatlak diş boyunca ilerliyorsa, çatlak iyi huylu olarak sınıflandırılır. Çatlak rim boyunca ilerliyor ise; bu tip çatlaklar yıkıcı çatlaklar olarak sınıflandırılabilir. Bu çalışmada, düz dişli çarklarda çatlak başlangıç açısı ve rim oranının çatlak ilerleme yolu üzerindeki etkileri nümerik olarak incelenmiştir. Diş kökündeki maksimum gerilme yeri, çatlak başlangıç noktası olarak tanımlanmıştır. İlk çatlaklar, 0° - 45° - ve 90° çatlak başlangıç açıları ile açılmıştır. Ayrıca, çatlak ilerleme analizi için beş farklı rim oranı kullanılmıştır. Çatlak ilerleme analizleri ANSYS Workbench, SMART Crack Growth modülünde gerçekleştirilmiştir. Çatlak ilerleme yolları on beş analiz ile değerlendirilmiştir. Sonuç olarak, rim kalınlığı büyük ise, çatlak başlangıç açısının çatlak ilerleme yolları üzerinde bir etkisinin olmadığı görülmüştür. Çatlak başlangıç açısının özel bir rim kalınlığı için çatlak ilerleme yolları üzerinde bir etkisi olduğu tespit edilmiştir.

Anahtar Kelimeler: Rüzgar Türbinleri, Kırılma Mekaniği, Çatlak İlerlemesi, Dişli Çarklar

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1. INTRODUCTION

Although the standardized dimensions and strength calculation methods, the gears are still the subject of many researches. Due to the high load capacity, durability, and the constant reduction ratio, etc. the gears have a wide range of applications, such as automotive, wind turbine, and aerospace industries. In particular, due to the unexpected operation conditions such as an extreme load concentration in the gear root, the cracks can be observed on the gear teeth. If the crack proceeds along with the tooth, it can be classified as safe cracks for the gearbox system. However, some of these cracks can proceed along with the rim thickness. Therefore, catastrophic consequences may occur. It can be noticed that the crack propagation paths are decisive for the crack classification, and valuable outcomes for the gear designers.

Notably, an occurred crack may cause high economical results in the wind turbine gearbox system, which is used for increasing the low rotation speed of rotor shafts to the high speed needed to the generator. For these aims, many researchers investigated the crack propagation paths in the literature. Mohammed et al. (2012) proposed an analytical crack propagation approach, which is more reasonable and realistic for non-uniform load distribution cases and can be applied for the crack propagation modeling and monitoring simulation. The approach was used for quantifying the loss of time-varying gear mesh stiffness with the presence of crack propagation in the gear root. Jadhav and Choudhary (2016) studied on crack propagation of spur gears and performed finite element analysis and numerical studies. As a result of the study, it was obtained that at higher levels of crack length, the reduction in gear mesh stiffness is higher than predicted curved crack path than the straight crack path, and at lower levels of crack length, the difference in crack intersection angle is minimal. Lewicki (2001) investigated the effects of rotational speed on gear crack propagation paths. The finite element analysis is used in the study. The effect of the backup ratio on crack propagation paths with different speeds was also examined. The analysis was validated with a spur gear fatigue rig. Eriki et al. (2012) studied on crack propagation path analysis of spur gears. The crack propagation direction angle was calculated using stress intensity factors at the crack tip. The spur gear crack propagation path was predicted using mixed-mode criteria, and crack extension criteria. Gunay et al. (1997) investigated the effects of rim thickness of spur gear on the root stresses. A computer program that produces a profile of the gear tooth to obtain mesh region was prepared. Ozer and Gunay (2001) studied the effects of the addendum modification coefficient on the crack propagation path. The stress intensity factors, K_I and K_{II} , were calculated with the J-integral method. It was obtained that the K_{II} factor is very effective on the crack propagation path. Kramberger et al. (2004) examined the bending fatigue life of thin rim spur gears. The continuum mechanic based approach was used for the prediction of the fatigue process initiation phase. The remaining life of gear with an initial crack was evaluated. Pandya and Parey (2013) proposed a cumulative reduction ratio (CRI) that uses a variable crack intersection angle. The effect of different gear parameters on time-varying mesh stiffness was investigated. A linear elastic fracture mechanics based two-dimensional FRANC finite element computer program was used to simulate the crack propagation path. Lewicki and Ballarini (1997) investigated the effect of rim thickness on the crack propagation path. Both experimental and analytical studies were performed. The FRANC program was used principles of linear elastic fracture mechanics. Various fatigue crack growth models were used to estimate the crack propagation life. As the gear rim thickness decreased, the compressive cyclic stress in the gear tooth fillet region increased. Lesiuk et al. (2018) investigated the fatigue crack growth of 42CrMo4 and 41Cr4 steels under different heat treatment conditions. The fatigue tests were carried out. The higher fatigue growth rates were observed for lower tempering temperature. Fajdiga and Sraml (2009) presented a computational model for fatigue contact damage analysis of gear teeth flanks. The fatigue process was divided into crack initiation and a crack propagation period. The virtual crack extension method was implemented in the finite element analysis.

Furthermore, the gear fault diagnostic and monitoring become a very critical subject for the gearbox systems. For this aim, many researchers studied early fault detection in the literature. Doğan and Karpuz (2019) proposed a dynamic transmission error (DTE) based numerical fault detection model. The time-varying mesh stiffness of spur gears with asymmetric tooth profile was calculated for different crack levels, and a 4-DOF dynamic model was developed to calculate dynamic transmission error. As a result of the study, the early stage of tooth errors was detected with DTE. Saxena et al. (2016) presented a computer simulation based analytical approach to quantify the time-varying mesh stiffness reduction of gear pair in case of various gear tooth faults. The presence of gear faults reduces the time-varying mesh stiffness, and it will affect the vibration response of the spur gear pair.

The effects of backup ratio and crack initialization angle on crack propagation path are investigated numerically in this study. The crack initialization point is defined by using static structural stress analysis. Three different crack initialization angles are set for the crack propagation analysis. As a result of the crack propagation analysis, crack paths are defined. It is seen that the crack initialization angle has not great effects on cracks paths. It affects the crack paths for the special rim thickness.

2. MATERIALS AND METHODS

Three different crack initialization angles and five different rim thicknesses are used for the crack propagation analysis. The analyses are performed in ANSYS Workbench, SMART Crack Growth module. The flowchart of the study is given in Figure 1.

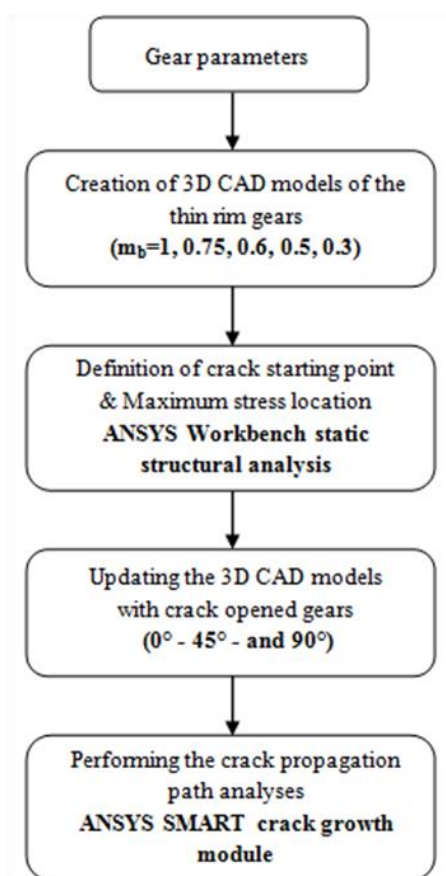


Figure 1:
Flowchart of the study

The backup ratio is defined as the ratio of rim thickness to tooth whole depth (Eq.1) in the literature (Figure 2).

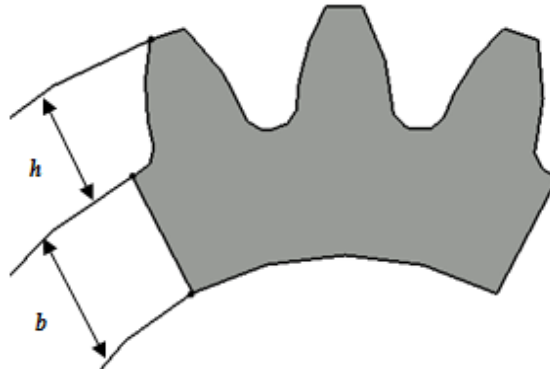


Figure 2:
Definition of the backup ratio

$$m_b = \frac{b}{h} \quad (1)$$

Where,

b = rim thickness, (mm)

h = tooth whole depth, (mm)

2.1. Definition of Crack Starting Point

The first step of the study is determining the crack starting point for the spur gears. Static structural stress analysis is done in ANSYS Workbench to achieve this goal. The CAD geometry of the spur gear is created in CATIA and exported to the ANSYS Workbench static structural module. The gears are designed according to Table 1. The general gear design properties are given in Table 1; also, a gear CAD model which is used in static stress analysis is given in Figure 3.

Table 1. Gear properties of FEA studies

Parameters	Values
Module (mm)	12
Tooth number	25
Pressure angle (deg)	20
Addendum (mm)	1*m
Dedendum (mm)	1.25*m
Face width (mm)	1
Backup ratios	1, 0.75, 0.6, 0.5, 0.3
Crack initial angle (deg)	0, 45, 90

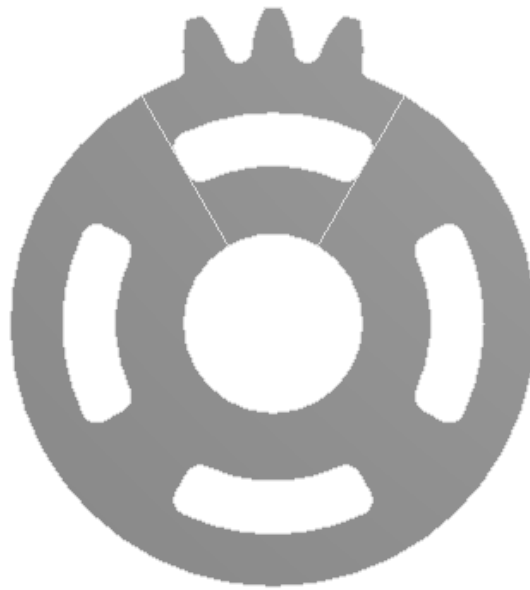


Figure 3:
3D CAD model of the spur gear

After the creation of the gear CAD model, the meshing operation is performed in ANSYS Workbench. The mesh structure consists of hexahedral 36000 elements and 147000 nodes. The mesh structure of the static stress analysis is given in Figure 4.

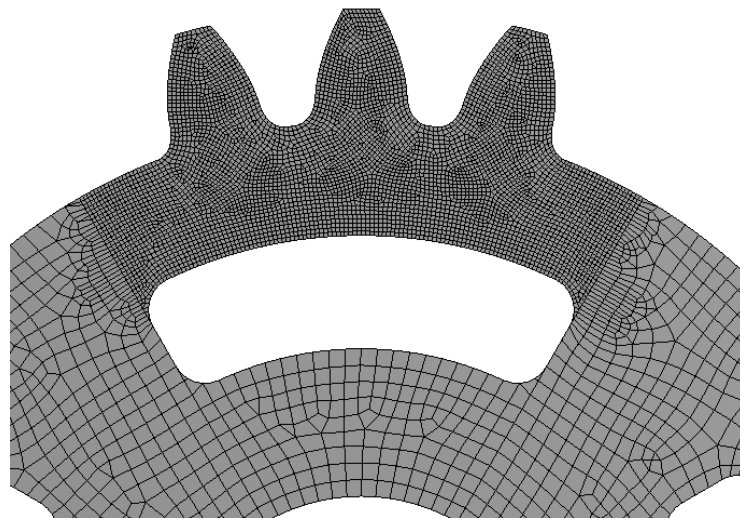


Figure 4:
Mesh structure for the stress analysis

2000 N static tooth load is applied on the tooth flank on the Highest Point of Single Tooth Contact radius as seen in Figure 5. The gear is fully fixed on the hub circle. The boundary conditions of the static stress analysis are seen in Figure 5.

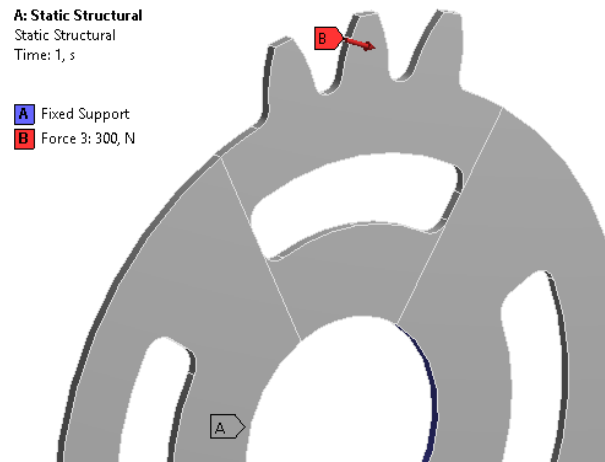


Figure 5:
Boundary conditions of the stress analysis

The maximum principal stress distribution on the tooth root is seen in Figure 6. Maximum stress is defined as 245.37 MPa, and the maximum stress location is defined according to the x, y, and z Cartesian coordinates. In this study, the maximum stress location is defined as the starting point of the tooth cracks.

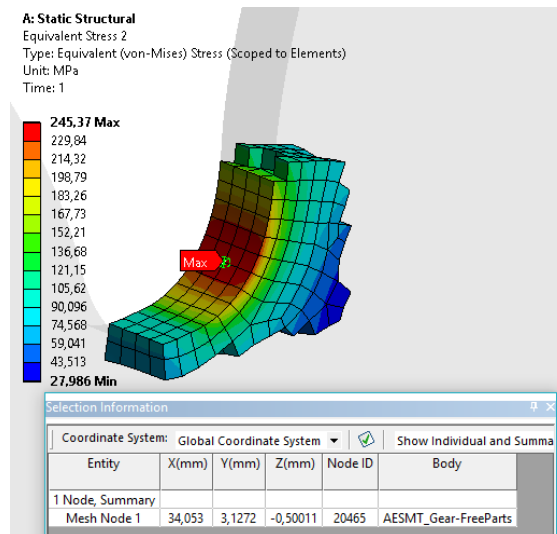


Figure 6:
Stress analysis result and maximum stress location

2.2. Crack Propagation Analysis

In this study, ANSYS Workbench SMART crack growth module is used for the crack propagation analysis. After the definition of the starting point of the cracks, the initial cracks are opened to the CAD geometries with three different initialization angles. The cracks are opened with 0° - 45° - and 90° crack initialization angles. The initial cracks with different initialization angles are seen in Figure 7.

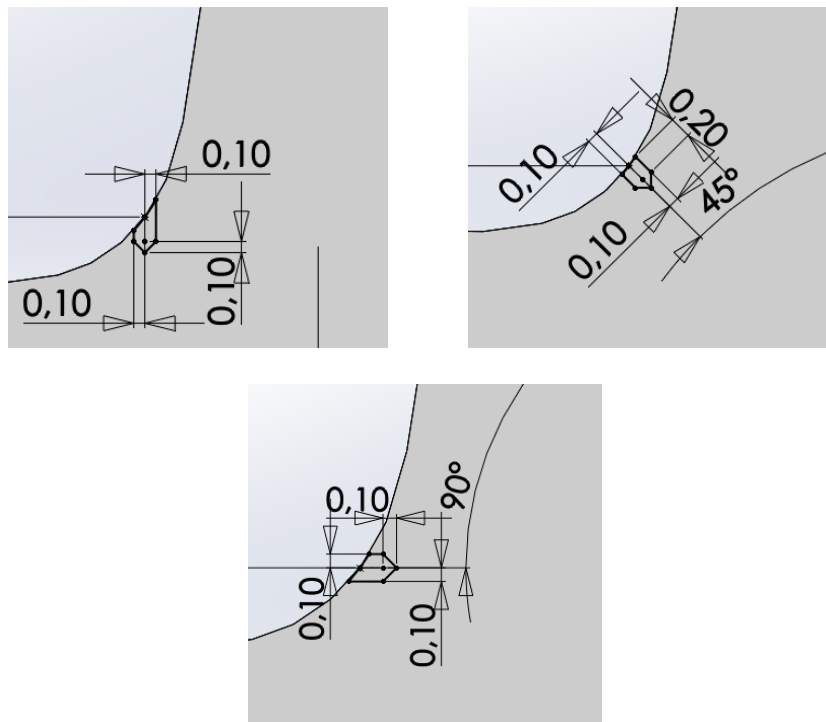


Figure 7:
Crack initialization angles for 0° - 45° - and 90°

Unlike static structural stress analysis, the quadratic tetrahedral mesh structure is used for the crack propagation analysis. The crack propagation algorithm of the SMART Crack Growth supported only quadratic tetrahedral elements. The mesh density is defined according to the distance from the crack zone. The mesh structure was formed more frequently in the region near the crack zone. The mesh structure of the crack propagation analysis is given in Figure 8.

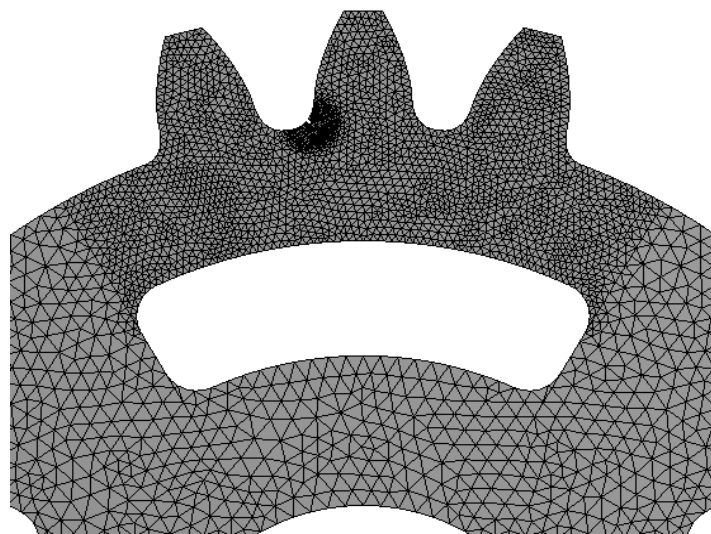


Figure 8:
Finite element mesh structure for the crack propagation analysis

The boundary conditions of the crack propagation analysis are defined same with the static structural stress analysis. 2000 N tooth load is applied on the tooth flank on the Highest Point of Single Tooth Contact radius, as seen in Figure 5. The stress to load ratio is defined as zero ($R=0$). The gear is fully fixed on the hub circle.

The crack propagation analyses are solved step by step, and the amount cracks increment for each step defined with the mesh size, which is 0.15 mm.

3. RESULTS AND DISCUSSION

3.1. Effects of Crack Initialization Angle on Crack Propagation Path

The crack paths are defined; after the crack propagation analyses, the crack paths can be classified as two common types. The first type is safe cracks, and the second type is catastrophic cracks. If the crack propagates along with the tooth, this type of cracks can be said safe cracks. If the cracks propagate along the rim, this type of cracks can be said as catastrophic cracks.

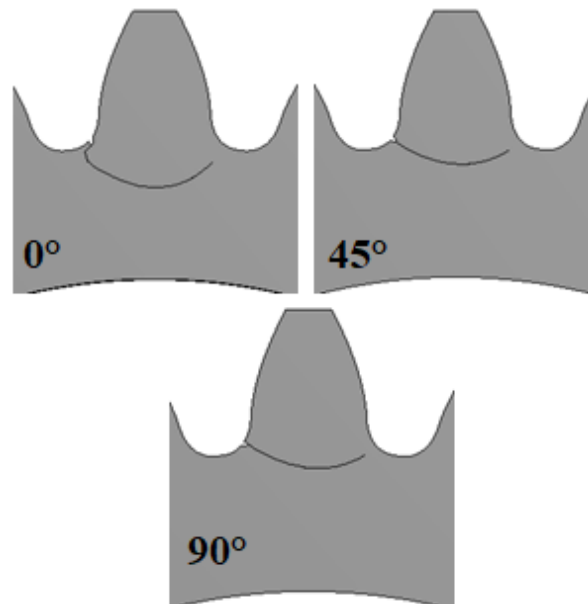


Figure 9:
Crack paths for $m_b=1$

The crack paths for $m_b=1$ is given in Figure 9 for three different crack initialization angle. The cracks propagate through the safe direction for all cases. At the beginning of the crack, the crack propagates along the rim side; however, the direction is changed through the safe direction for the 0° crack initialization angle.

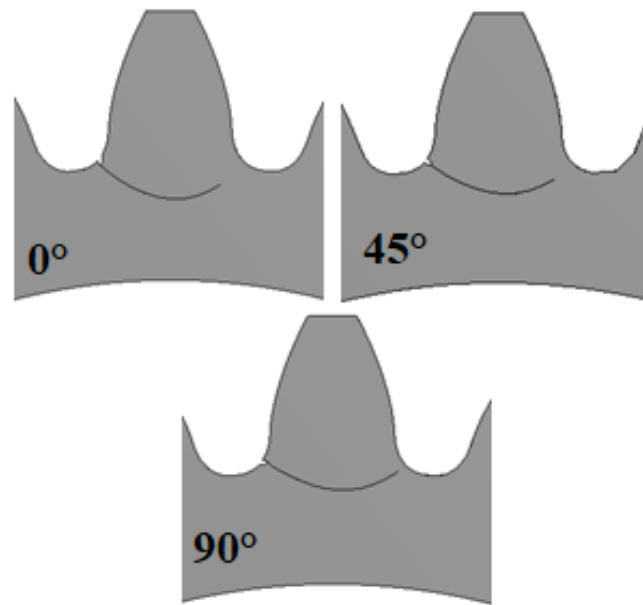


Figure 10:
Crack paths for $m_b=0.75$

Similar to Figure 9, the cracks propagate through the safe direction for the backup ratio 0.75 also, the crack initialization angle has no significant effect for the backup ratio 0.75.

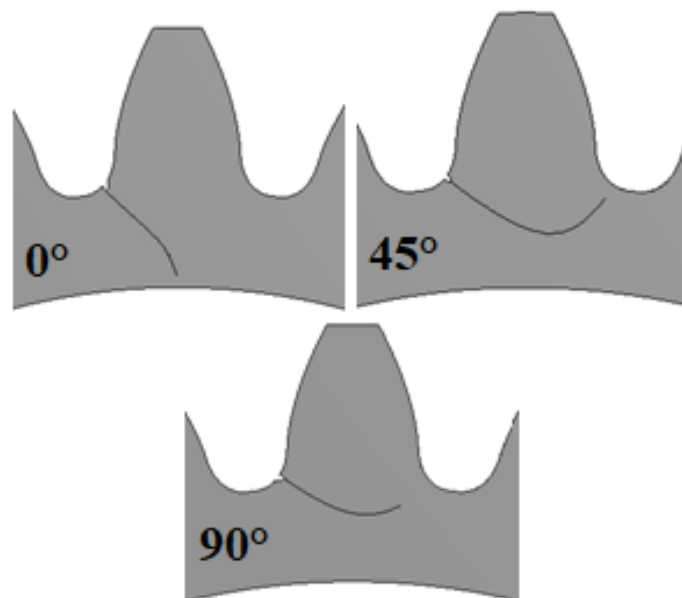


Figure 11:
Crack paths for $m_b=0.6$

The effects of crack initialization angle are clearly seen in Figure 11. The crack paths are given for the backup ratio of 0.6 in Figure 11. The crack propagates along with the rim for the crack initialization angle 0° . However, the cracks propagate along with the tooth for the 45° and 90° initialization angle.

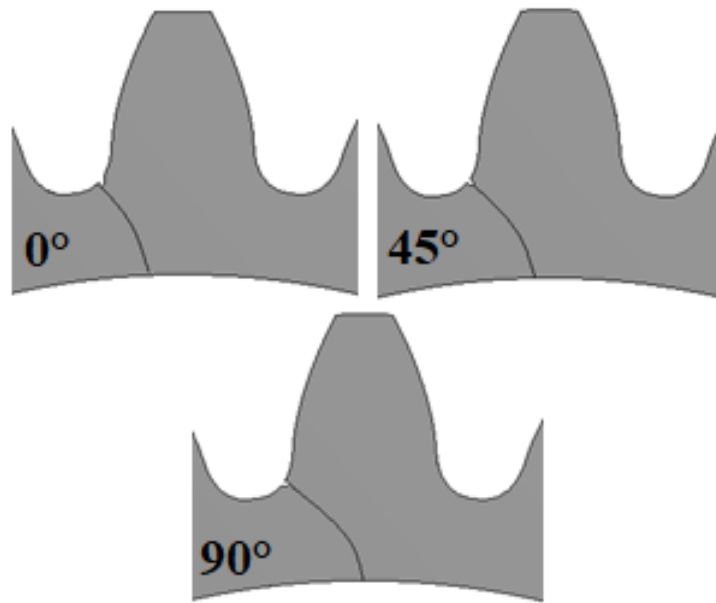


Figure 12:
Crack paths for $m_b=0.5$

Crack paths for the backup ratio 0.5 are given in Figure 12. The cracks propagate along the rim side for all crack initialization angles in this case. The crack propagation angle has no significant effect on the crack path. It can be said that the backup ratio has more influence on the crack paths than the crack initialization angle.

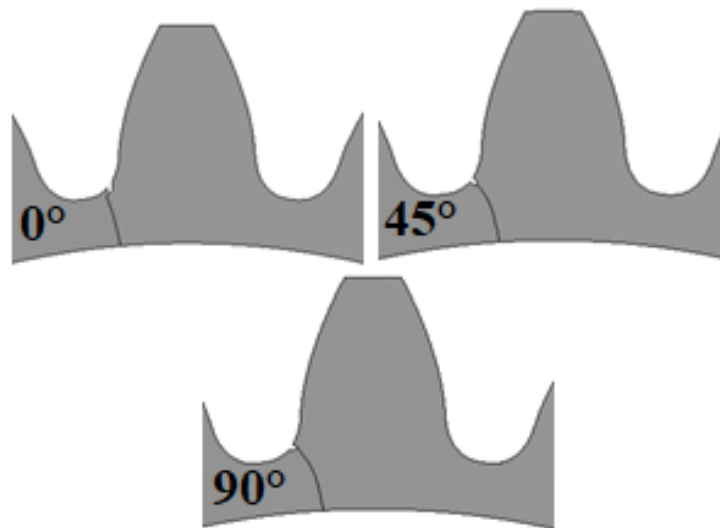


Figure 13:
Crack paths for $m_b=0.3$

The crack paths for the backup ratio 0.3 are given in Figure 13. The cracks propagate along the rim side for all cases. The crack directly breaks the rim for the 0° crack initialization angle. However, for the 45° - 90° crack initialization angle, cracks propagate along the small curvilinear orbit and break the rim.

Table 2. Effects of backup ratio and crack initialization angle on crack propagation path

Backup ratio / Crack angle	0°	45°	90°
$m_b = 1$	safe	safe	safe
$m_b = 0.75$	safe	safe	safe
$m_b = 0.6$	unsafe	safe	safe
$m_b = 0.5$	unsafe	unsafe	unsafe
$m_b = 0.3$	unsafe	unsafe	unsafe

The effects of the backup ratio and crack initialization angle are given in Table 2. The crack initialization angle has no critical effects for backup ratios 1, 0.75, and 0.3. The cracks propagate along the tooth direction for the backup ratio 1 – 0.75 regardless of the initial angle of the crack, so these cracks can be classified as safe cracks. However, for the backup ratio 0.5 and 0.3, the cracks propagate along the rim side, and these types for cracks are more dangerous than the first type. The effects of crack initialization angle on cracks propagation paths are seen for the backup ratio 0.6. The cracks propagate along the rim side for the 0° crack initialization angle. On the other side, the cracks propagate along the tooth side for the 45° and 90°.

3.2. Validation of the Crack Propagation Paths

Lewicki (1995) investigated the effects of backup ratios on the crack propagation paths, both numerically and experimentally. First, crack propagation path analyses are performed with the FRANC computer program. Principles of linear elastic fracture mechanics are used in the study.

Lewicki used external spur gears with different rim thicknesses in the experiments. Four different rim ratios, which are 0.3 – 0.5 – 1 and 3, are tested in the experiments. The test gear material is AISI 9310 steel, which is suitable for the aerospace industry. The gears are hardened, the hardness of the surface is 60 Rc, and the core hardness is 38 Rc. Artificially a notch is opened to the tooth root for each gear to propagate crack with the lower forces. The paths are determined with NASA Lewis spur gear fatigue rig. The test gear velocity was defined as 10000 rpm for all cases. After reaching the full speed, the load was applied to the gears. Basically, the test procedure is the same for all experiments. During the tests, the crack continuously propagates, and until the tooth failure, the tests are continuing. The vibration signals on the test rig were collected during all tests. After the tooth failure, these signals and the crack propagation paths are evaluated. Crack propagation behaviors of the gears investigated with the evaluation of these signals by using statistical indicators. The results of the crack propagation paths are given in Figure 14 and Figure 15.

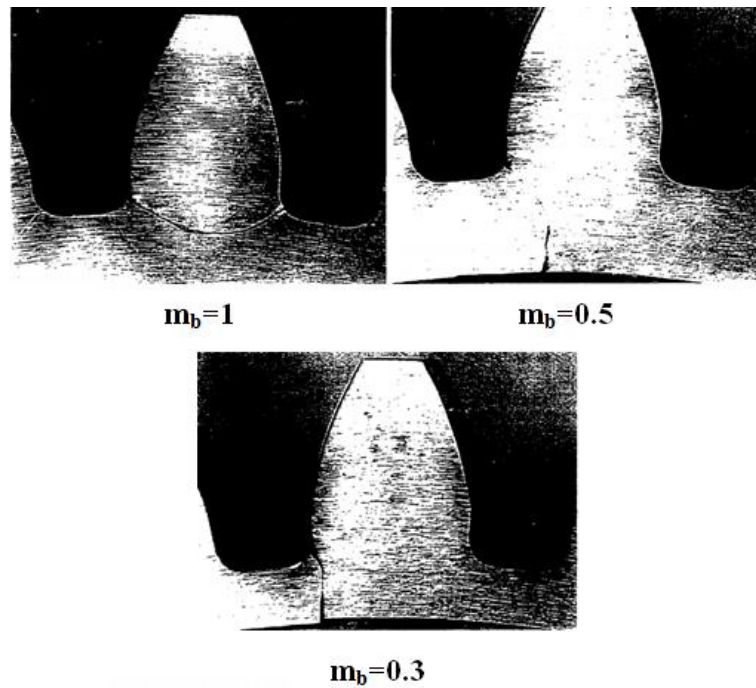


Figure 14:
Experimental validation of the crack propagation paths (Lewicki, 1995)

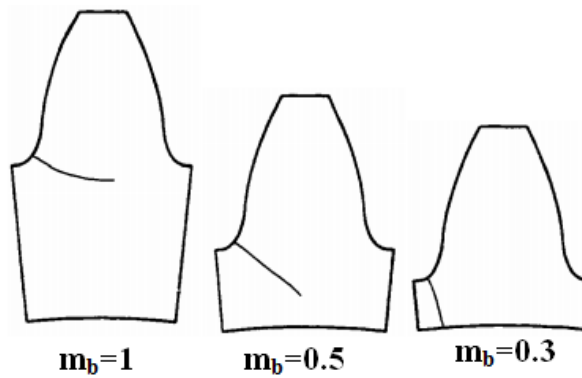


Figure 15:
Numerical validation of the crack propagation paths (Lewicki, 1995)

The results of Lewicki (1995) are coherent with the present study, considering the given results in Figure 9, Figure 12, and Figure 13. Therefore, it can be distinguished that the model used in this study is validated according to Lewicki (1995).

4. CONCLUSIONS

The effects of crack initialization angle and backup ratio on the crack propagation paths are investigated numerically in this study. The CAD geometries of the spur gears are created in CATIA and then imported to the ANSYS Workbench for the static structural analysis. The cracks are initialized, where the maximum principal stress is the highest value. Three different crack starting angle and five different backup ratios are defined for the crack propagation analysis. The crack propagation analyses are performed in ANSYS SMART crack growth module. As a result of the finite element analysis, the crack paths are defined. The crack paths are divided into two types. If the cracks propagate along the rim, these types of cracks are defined as unsafe. If the cracks propagate along with the tooth, these types of cracks are determined as safe cracks. If the rim thickness is high, the cracks propagate along with the tooth, and the crack initialization angle has no effects on the crack paths. Moreover, the crack initialization also has no significant impact on the thin rim gears; the cracks are directly breaking the rim. The crack initialization angle has effects on the crack paths only for the backup ratio 0.6.

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