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Analysis of the Effect of an Initial Crack on the Von Mises Stress Distribution and Elastic Strain of a Reverse Idler Spur Gear Using Finite Element Analysis

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A B S T R A C T

The reverse idler spur gear is a key component in a manual transmission system that reverses the output shaft rotation during reverse operation. Due to high stress concentration at the tooth root, this component is susceptible to crack initiation and structural failure. This study investigates the effect of an initial crack on the distribution of Von Mises stress and equivalent elastic strain using the Finite Element Method (FEM). Two three-dimensional models were developed: an uncracked model and a cracked model with a semicircular crack of 0.5 mm depth at the tooth root. SCM415 steel was used as the material, and a torque load of 6226.03 Nm was applied. The simulation results showed that the uncracked model produced a maximum Von Mises stress of 805.92 MPa and a maximum equivalent elastic strain of 4.3922 × 10^{-3}. In the presence of the initial crack, the maximum stress increased to 1335 MPa and the maximum strain to 6.5499 × 10^{-3}, representing increases of 65.65% and 49.13%, respectively. The highest stress and strain concentrations were observed at the crack tip. These findings indicate that even a small initial crack significantly increases local stress concentration and deformation, thereby accelerating crack propagation and increasing the risk of fatigue failure in reverse idler spur gears.

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1. Introduction

A manual transmission system transmits power and torque from the engine to the drive wheels through a combination of gear pairs with specific transmission ratios [1,2]. One of the essential components in this system is the reverse idler spur gear, an intermediate gear that reverses the rotational direction of the output shaft, enabling the vehicle to move backward [3]. Unlike gears used during forward driving, which operate under continuous meshing conditions, the reverse idler gear experiences more complex operating conditions due to direct gear engagement, reversal of rotational direction, and impact loading during reverse gear shifting. These operating characteristics result in a non-uniform stress distribution at the tooth root and significantly increase the likelihood of structural failure during service [4,5]. Recent studies on idler gear systems have demonstrated that high loading conditions combined with changes in rotational direction generate substantial dynamic responses, thereby accelerating crack initiation and failure at the tooth root [3,6].

Gear failure remains one of the most critical issues affecting the reliability of automotive transmission systems [7,8]. Common failure modes include wear, pitting, plastic deformation, tooth fracture, and fatigue cracking [9,10]. Among these, tooth root cracking is considered the primary cause of gear failure because the tooth root is subjected to repeated bending and contact stresses during power transmission [11]. Several studies have reported that more than half of gearbox failures originate from gear damage initiated by tooth root fatigue cracks, which reduce gear mesh stiffness and increase transmission vibration [12,13].

The presence of an initial crack has become an important concern in gear reliability studies because it significantly alters the stress and strain distributions within the gear structure. An initial crack produces a high stress concentration at the crack

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tip, which accelerates localized deformation and subsequent crack propagation [7,8]. Studies employing the Extended Finite Element Method (XFEM) have shown that increased tangential stress at the tooth root can modify the crack propagation path and accelerate gear fatigue failure [14]. Furthermore, three-dimensional crack propagation analyses of spur gears have demonstrated that crack growth is influenced not only by the applied load but also by tooth geometry, crack location, and the local stress field surrounding the tooth root [1–3].

Advances in computational technology have enabled detailed mechanical analyses of gears using the Finite Element Method (FEM). This numerical approach accurately models complex geometries and predicts stress and strain distributions, deformation, and crack propagation behaviour with high precision [7,8]. FEM also enables the evaluation of operating conditions that are difficult to reproduce experimentally, including variations in crack size, crack location, tooth root geometry, and loading conditions [7,8]. Consequently, finite element analysis has become one of the most widely adopted approaches for failure analysis and design optimization of modern gear systems.

In recent years, numerous studies have investigated the influence of cracks on the mechanical behaviour of spur gears and helical gears. Cooley et al. reported that tooth root cracks reduce mesh stiffness and increase static transmission error, leading to higher vibration levels in transmission systems [14]. Güven employed the Extended Finite Element Method (XFEM) to investigate crack propagation in spur gears and demonstrated that additional stresses induced by assembly conditions can significantly accelerate crack growth [15]. Other studies have shown that increasing crack length directly increases the stress intensity factor and consequently reduces the fatigue life of gears [16]. Moreover, recent dynamic models incorporating both crack and wear damage have revealed that crack defects exert a more dominant influence on the dynamic response of transmission systems than other surface damage mechanisms [17].

Despite extensive investigations on spur gears, helical gears, planetary gears, and industrial transmission systems, studies specifically addressing the stress and strain distributions in reverse idler spur gears remain limited. Most previous research has focused on crack propagation, vibration characteristics, and fatigue life of primary transmission gears. In contrast, comparative analyses of conditions with and without an initial crack in reverse-idler applications have received relatively little attention. Furthermore, information regarding the influence of an initial crack on the Von Mises stress distribution and elastic strain of reverse idler gears operating under actual vehicle torque conditions is still scarce. Therefore, further investigation is required to understand better the mechanical behaviour of reverse idler gears under conditions representative of real operating environments.

Based on these considerations, this study aims to analyse the stress distribution and elastic strain of a reverse idler spur gear under two different conditions, namely, the without initial crack model and the with initial crack model, using the Finite Element Method (FEM). The analysis is conducted to evaluate the effect of the initial crack on stress concentration, strain distribution, and the potential for structural failure. The findings of this study are expected to contribute to the development of more reliable reverse idler gear designs, extend the service life of transmission components, and support the implementation of predictive maintenance strategies in automotive transmission systems.

2. Materials and Methods

2.1 *Research Object*

The research object of this study was a reverse idler spur gear used in a passenger vehicle manual transmission system. The geometric specifications and material properties of the gear are presented in **Table 1**. This component functions as an intermediate gear that reverses the rotational direction of the output shaft, enabling the vehicle to move in reverse. Unlike gears operating under forward transmission, which remain in continuous mesh, the reverse idler gear experiences more complex loading conditions due to reversal of rotational direction, intermittent gear engagement, and impact loading during engagement. These operating conditions generate high stress concentrations, particularly at the tooth root, thereby increasing the risk of structural failure during service.

A three-dimensional (3D) model of the reverse idler spur gear was developed using Computer-Aided Design (CAD) software based on the actual dimensions of the component. To investigate the influence of an initial defect on the mechanical behaviour of the gear, two numerical models were established: one without an initial crack and one with an initial crack containing a tooth root defect. The crack was introduced at the tooth root because this region experiences the maximum bending stress and is widely recognized as the primary initiation site of fatigue failure in transmission gears. The initial crack was modelled as a semicircular surface crack with a depth of 0.5 mm [21], oriented perpendicular to the principal stress direction and propagating toward the gear core. This crack configuration was selected to represent early-stage damage commonly induced by cyclic loading during service. The CAD models of the reverse idler spur gear with and without an initial crack are illustrated in **Figure 1**.

Table 1. Geometric parameters and material properties of the reverse idler spur gear [7,8,18–20

Parameter	Symbol	Value	Unit
Number of teeth	z	31	–
Module	m	4.5	mm
Pressure angle	α	20	°
Face width	b	40	mm
Pitch diameter	d	139.5	mm
Outside diameter	d_o	148.5	mm
Material	–	SCM415 steel	–
Density	ρ	7800	kg/m³
Young's modulus	E	205	GPa
Poisson's ratio	ν	0.29	–
Yield strength	σ_y	545	MPa
Ultimate tensile strength	σ_u	800	MPa
Initial crack length	a	0.5	mm
Reverse gear ratio	i_R	7.839	–

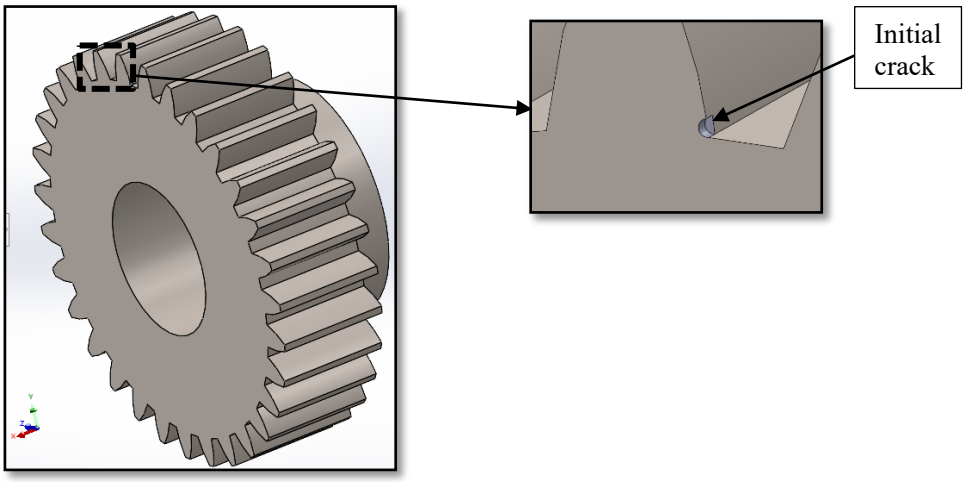


Figure 1. CAD models of the reverse idler spur gear with and without an initial crack.

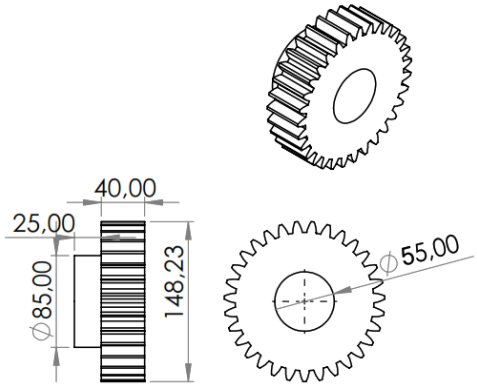


Figure 2. Main dimensions of the reverse idler spur gear (mm).

The principal dimensions of the reverse idler spur gear are presented in Figure 2. The gear consists of 31 teeth, a module of 4.5 mm, and a pressure angle of 20°. The face width is 40 mm, resulting in a pitch diameter of 139.5 mm, which is calculated as the product of the module and the number of teeth. The corresponding outside diameter is 148.5 mm. The gear material is SCM415 alloy steel, which is widely used in automotive transmission systems due to its excellent mechanical strength and fatigue resistance [18,19].

The material properties used in the finite element simulations include a density of 7800 kg/m³, Young's modulus of 205 GPa, Poisson's ratio of 0.29, yield strength of 545 MPa, and ultimate tensile strength of 800 MPa. These geometric and material parameters were used as the basis for all finite element analyses conducted in this study.

2.2. Meshing

The mesh generation process was performed to discretize the three-dimensional geometry of the reverse idler spur gear into finite elements for numerical analysis. Mesh quality plays a critical role in determining the accuracy of finite element results, particularly in predicting stress and strain distributions in regions with severe stress concentrations, such as the tooth root and crack tip.

In this study, the gear model was discretized using three-dimensional tetrahedral elements, which are well suited for representing complex gear geometries, especially in the tooth root fillet and crack regions. An element size of 0.5 mm was adopted based on previous studies [21]. Local mesh refinement was applied in the vicinity of the tooth root and crack tip to improve the accuracy of stress and strain predictions while maintaining computational efficiency.

The final finite element model consisted of 873,153 nodes and 520,192 tetrahedral elements. This mesh density was selected to achieve a balance between computational efficiency and numerical accuracy. The generated mesh of the reverse idler spur gear is presented in Figure 3.

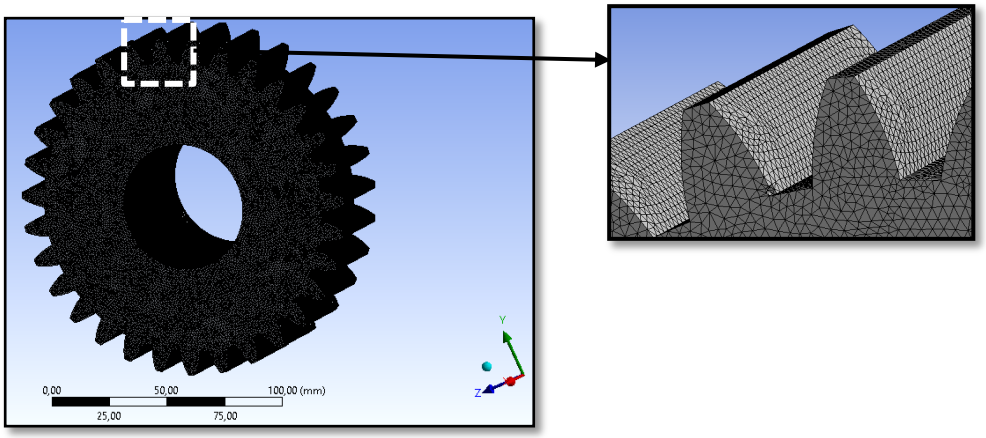


Figure 3. Finite element mesh of the reverse idler spur gear.

The mesh was used as the basis for finite element simulations to evaluate the Von Mises stress and equivalent elastic strain distributions in both the models without an initial crack and with an initial crack.

2.3. Loading and Boundary Conditions

Finite element simulations were conducted to evaluate the stress and strain distributions of the reverse idler spur gear under loading conditions representative of reverse gear operation. The loading condition was determined based on vehicle specifications, where the maximum engine torque was 81 kg·m, equivalent to 794.34 Nm. When the transmission operates in reverse gear, the transmitted torque is amplified according to the reverse gear ratio of 7.839. This ratio reduces the rotational speed of the input shaft while proportionally increasing the transmitted torque at the output shaft. Accordingly, the torque applied to the reverse idler spur gear was calculated as 6226.03 Nm by multiplying the engine torque by the reverse gear ratio. This value represents the maximum operating load condition considered in the finite element analysis.

The load was applied to the loaded tooth flank, representing the contact surface responsible for power transmission to the mating gear. A fixed support boundary condition was assigned to the entire bore surface of the gear, constraining all translational and rotational degrees of freedom. This setup allows the stress and strain distributions to represent the structural response of the reverse idler spur gear under maximum static loading conditions.

The loading location and boundary conditions applied in the finite element model are illustrated in Figure 4, where A indicates the applied load on the loaded tooth flank, and B denotes the fixed support at the gear bore.

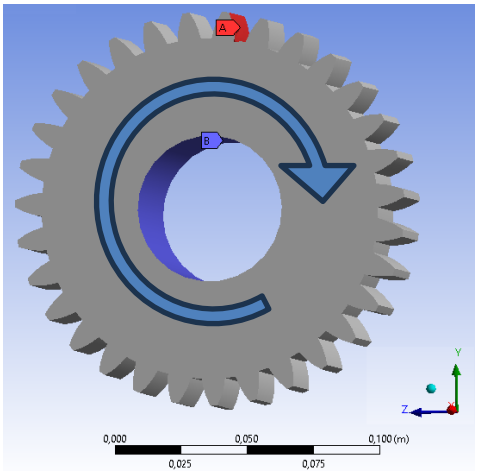


Figure 4. Loading and boundary conditions of the reverse idler spur gear model: (A) applied load on the loaded tooth flank and (B) fixed support at the gear bore.

The analysis was performed under static structural conditions to determine the maximum Von Mises stress and equivalent elastic strain distributions within the gear. This approach provides a reliable prediction of the mechanical response of the reverse idler spur gear and facilitates the identification of critical regions susceptible to stress concentration and potential failure.

3. Results and Discussion

A finite element method (FEM) analysis was performed to evaluate the structural response of the reverse idler spur gear under two conditions: the without initial crack model and the with initial crack model. The analysis focused on the Von Mises stress and equivalent elastic strain distributions under an applied torque of 6226.03 Nm. The results were used to identify regions of maximum stress concentration and assess the effect of the initial crack on the gear's mechanical behaviour.

Stress and strain distributions are key parameters for evaluating gear structural integrity, as they represent the material response to external loading during power transmission. Excessive stress may exceed the material strength and lead to plastic deformation and structural failure, while high strain indicates significant local deformation. In addition, regions

with high stress concentration are potential sites for crack initiation and subsequent propagation under cyclic loading, ultimately leading to fatigue failure.

Therefore, a comparative analysis between the model without an initial crack and the model with an initial crack was conducted to evaluate changes in stress and strain distribution and to identify critical failure-prone regions in the reverse idler spur gear.

3.1 Von Mises Stress Distribution of the Gear without Initial Crack

The Von Mises stress distribution of the reverse idler spur gear without an initial crack condition was analysed using the Finite Element Method (FEM) under an applied torque of 6226.03 Nm. This analysis aimed to identify the stress distribution pattern in the intact configuration, which serves as the baseline condition for evaluating the effect of an initial crack on the structural response of the gear. The simulated Von Mises stress distribution is presented in Figure 5.

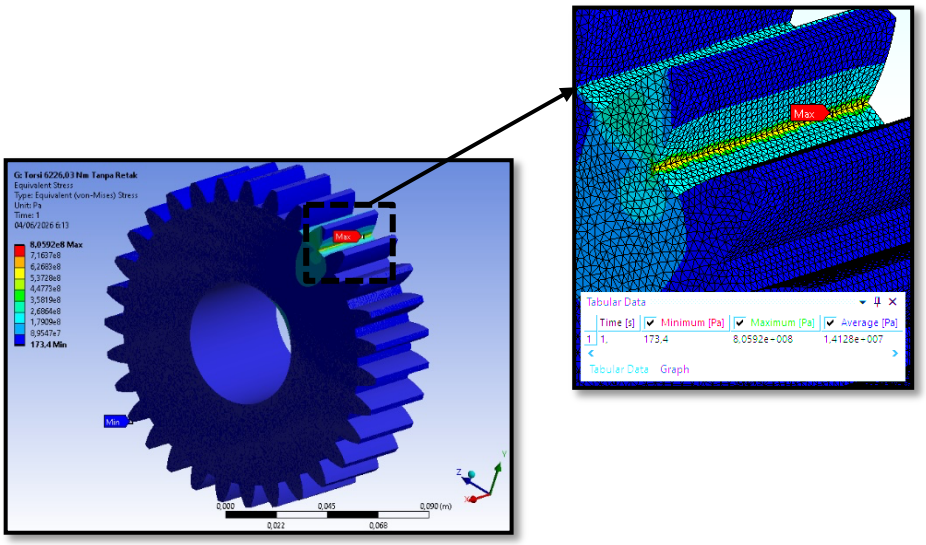


Figure 5. Von Mises stress distribution of the reverse idler spur gear without an initial crack

The finite element simulation results indicate that the maximum Von Mises stress is 805.92 MPa, while the minimum and average stress values are 0.0001734 MPa and 14.128 MPa, respectively. The maximum stress value corresponds to 805.92 MPa, converted into MPa for consistency. The stress contour shows that most regions of the gear experience relatively low stress, as indicated by the dominant blue region. In contrast, higher stress concentrations occur in the tooth region directly subjected to loading during torque transmission.

The maximum stress is highly localized at the tooth root region near the loaded contact area, as indicated by the red-to-yellow zones in the contour plot. This stress concentration is attributed to the combined effects of bending stress and contact stress generated during gear meshing. In addition, the geometric discontinuity at the tooth root fillet intensifies the local stress concentration compared with other regions of the gear.

The stress distribution also indicates that stress transfer within the gear body remains continuous, without interruption from geometric discontinuities such as cracks. The stress generated at the tooth root gradually dissipates into the gear body, resulting in a smooth stress gradient. This behaviour suggests that the specimen without an initial crack condition maintains sufficient structural stiffness to distribute the applied load effectively under the given operating condition.

Although no crack is present in the model, the results confirm that the tooth root remains the most critical region in terms of structural integrity. This is consistent with the general behaviour of spur gears, where the tooth root experiences maximum bending stress due to the tangential force acting on the tooth surface. The relatively high maximum Von Mises stress indicates that the tooth root operates under severe loading conditions and may become the initiation site for fatigue cracks under repeated cyclic loading.

Overall, the stress concentration is confined to the tooth root region and does not exhibit redistribution effects associated with geometric discontinuities such as cracks. Nevertheless, the high local stress at the tooth root suggests that this region

is highly susceptible to fatigue crack initiation. This observation is consistent with gear failure theory, which identifies the tooth root as the most critical region due to combined bending stress and geometric stress concentration at the fillet region.

The results obtained from the condition without an initial crack are used as a reference for evaluating the effect of an initial crack on the Von Mises stress distribution in the reverse idler spur gear. Compared with the initial-crack condition, the no-initial-crack condition is expected to exhibit a lower maximum stress and a more uniform stress distribution. Therefore, the condition without an initial crack represents the normal operating state before crack-induced structural degradation in service.

3.2 Von Mises Stress Distribution with Initial Crack

The Von Mises stress distribution of the reverse idler spur gear with an initial crack condition was analysed using the Finite Element Method (FEM) under an applied torque of 6226.03 Nm. An initial crack with a length of 0.5 mm was introduced at the tooth root region to represent early-stage damage commonly induced by cyclic loading during transmission operation. The simulated stress distribution for the cracked condition is presented in Figure 6.

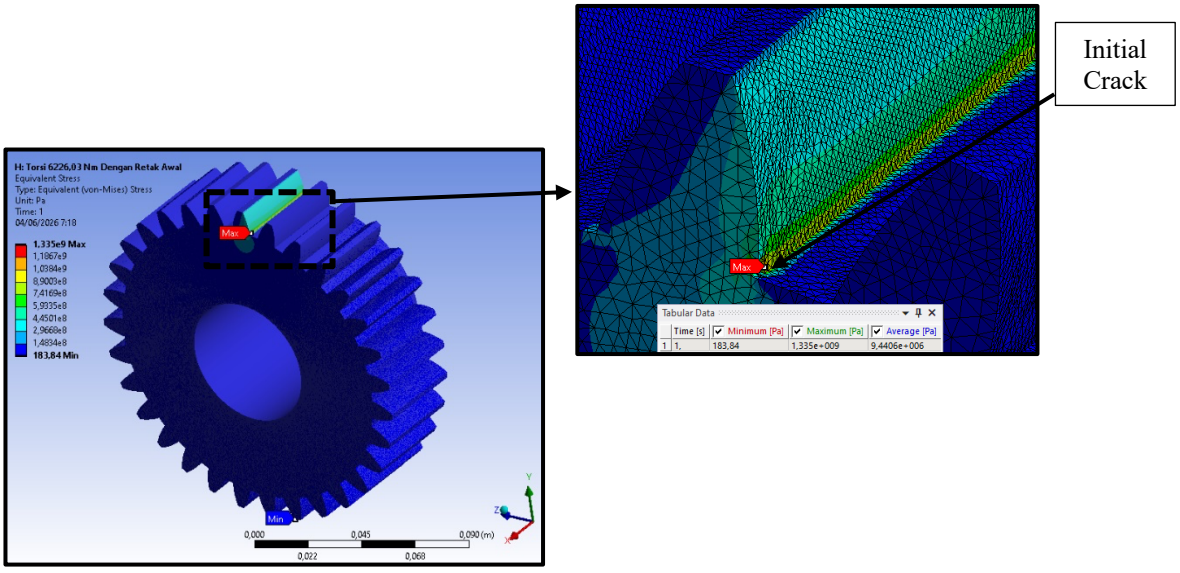


Figure 6. Von Mises stress distribution of the reverse idler spur gear with an initial crack

The simulation results indicate that the maximum Von Mises stress reaches 1.335×10^9 Pa (1335 MPa), while the minimum and average stress values are 183.84 Pa and 9.4406×10^6 Pa (9.441 MPa), respectively. The maximum stress is located at the crack tip region near the tooth root, as indicated by the red zone in the contour plot. In contrast, most regions of the gear experience relatively lower stress levels, represented by the dominant blue-to-green contours.

The presence of an initial crack significantly alters the stress distribution compared with the condition without one. In the without-initial-crack condition, the maximum stress was 805.92 MPa, whereas it increased to 1335 MPa in the with-initial-crack condition, corresponding to an increase of approximately 65.65%. This result confirms that the initial crack acts as a strong stress concentration site, disrupting uniform load transfer across the gear structure.

The stress concentration at the crack tip is attributed to the loss of material continuity at the tooth root. Under loading, the stress flow is redistributed and becomes highly concentrated in the vicinity of the crack tip, where the local radius of curvature is extremely small. This results in a steep stress gradient and a significant increase in local stress magnitude. This

behaviour is consistent with fracture mechanics theory, which identifies the crack tip as the region of maximum stress concentration and the primary site for crack propagation under cyclic loading.

The results further show that the maximum stress in the initial crack condition exceeds both the yield strength (545 MPa) and the ultimate tensile strength (800 MPa) of SCM415 steel. This indicates the possibility of localized plastic deformation around the crack tip, which may accelerate crack growth and eventually lead to structural failure.

In addition, the critical region shifts from the tooth root fillet in the without initial crack condition to the crack tip region in the with initial crack condition. This demonstrates that the initial crack significantly reduces the load-carrying capacity of the gear by altering the stress distribution and intensifying local stress concentration. Consequently, the risk of crack propagation and fatigue failure increases substantially.

These findings are consistent with previous studies reporting that initial cracks in gear tooth roots lead to increased stress concentration, reduced local stiffness, and accelerated crack growth under repeated loading. Overall, the results demonstrate that even a small initial crack of 0.5 mm significantly affects the mechanical response of the reverse idler spur gear, increasing the maximum stress by 65.65% compared with the condition without an initial crack. This highlights that early-stage cracks can substantially compromise structural integrity and accelerate gear failure during service.

3.3 Equivalent Elastic Strain Distribution of the Gear without an Initial Crack

Strain is an important parameter in structural analysis as it represents the degree of deformation experienced by a material in response to an applied load. The equivalent elastic strain distribution of the reverse idler spur gear without an initial crack is presented in Figure 7.

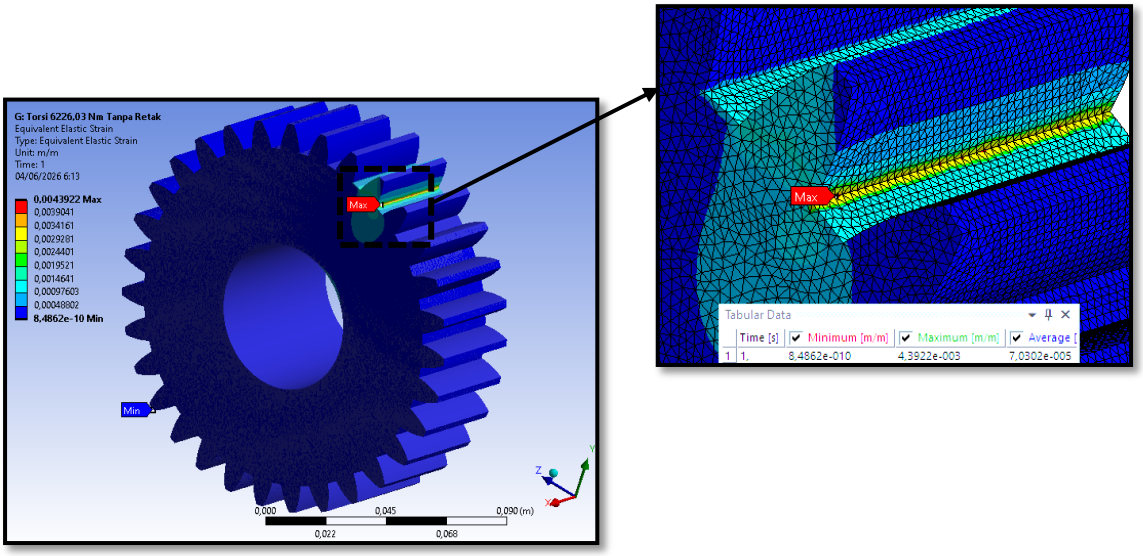


Figure 7. Equivalent elastic strain distribution of the reverse idler spur gear without an initial crack.

The simulation results indicate that the maximum equivalent elastic strain is 4.3922×10^{-3} m/m, while the minimum and average values are 8.4862×10^{-10} m/m and 7.0302×10^{-5} m/m, respectively. The strain distribution shows that most regions of the gear experience relatively small deformation, as indicated by the dominant blue region in the contour plot. Higher strain values are concentrated in the tooth region directly subjected to loading during torque transmission.

The maximum strain is localized at the tooth root region near the loaded area, as shown by the red-to-yellow contours. This location coincides with the region of maximum Von Mises stress obtained in the stress analysis. This indicates a consistent relationship between stress and strain distributions, where regions with higher stress levels correspond to higher elastic deformation, in agreement with linear elasticity theory.

The strain concentration at the tooth root is caused by the combined effects of bending stress and contact stress generated during gear meshing. As the load is transmitted through the gear teeth, the tooth root undergoes bending deformation due to the moment acting on the tooth cross-section. Consequently, this region represents the most critical area in terms of mechanical response compared with other regions of the gear. The strain distribution pattern in the condition without an

initial crack remains continuous, indicating that load transfer occurs smoothly throughout the gear structure. The absence of geometric discontinuities allows strain to be gradually distributed from the contact region to the gear body, suggesting that the structure maintains sufficient stiffness under the applied loading condition.

The maximum strain value of 4.3922×10^{-3} m/m indicates a relatively significant deformation at the tooth root under an applied torque of 6226.03 Nm. This result is consistent with the Von Mises stress distribution, which showed a maximum stress of 805.92 MPa at the same location. The strong correlation between stress and strain confirms that the tooth root is the most vulnerable region to structural damage under repeated loading conditions.

Although no initial crack is present in the model, the results indicate that the tooth root already experiences relatively high strain compared with other regions. This suggests that this area is a potential site for fatigue crack initiation during service. Therefore, the strain distribution obtained under the condition without an initial crack can serve as a baseline for evaluating the influence of an initial crack on deformation behaviour and strain redistribution in the reverse idler spur gear.

Overall, the results show that the equivalent elastic strain in the reverse idler spur gear without an initial crack is concentrated at the tooth root, which coincides with the region of maximum stress. This region represents the most critical area of the gear and is highly susceptible to fatigue crack initiation and failure under long-term cyclic loading conditions.

3.4 Equivalent Elastic Strain Distribution of the Gear with an Initial Crack

The equivalent elastic strain distribution of the reverse idler spur gear with an initial crack was analysed using the Finite Element Method (FEM) to evaluate the influence of crack presence on the deformation response under an applied torque of 6226.03 Nm. An initial crack with a length of 0.5 mm was introduced at the tooth root region, which is considered a critical location due to the combined effects of bending and contact stresses during gear meshing. The simulated equivalent elastic strain distribution for the cracked model is presented in Figure 8.

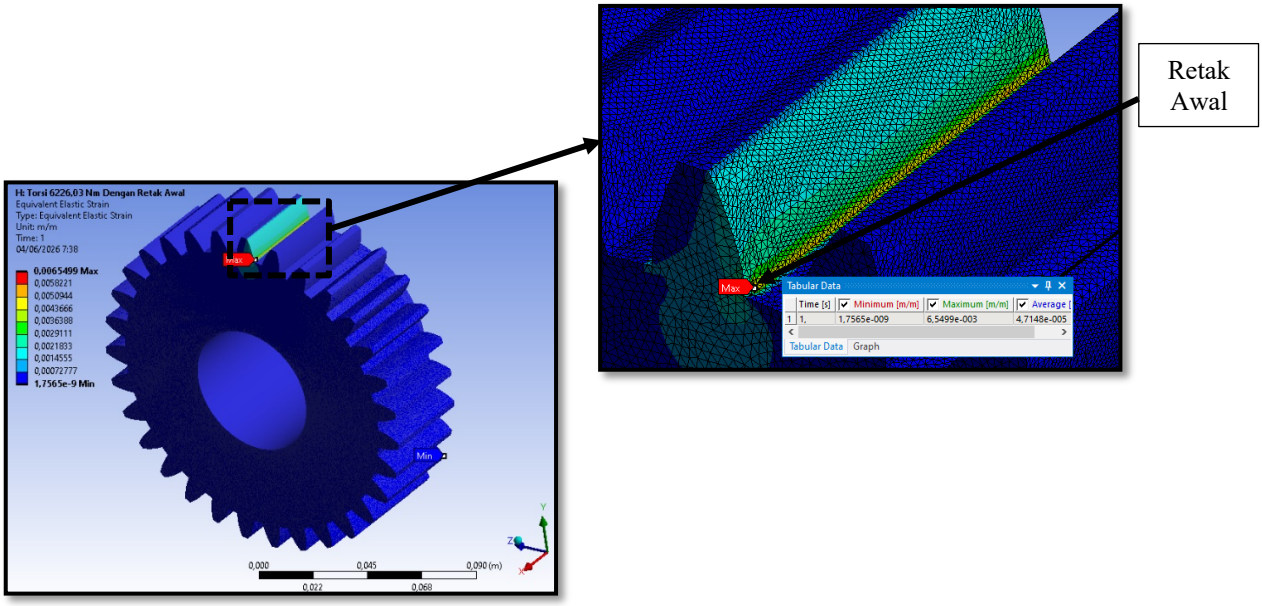


Figure 8. Equivalent elastic strain distribution of the reverse idler spur gear with an initial crack

The simulation results indicate that the maximum equivalent elastic strain is 6.5499×10^{-3} m/m, while the minimum and average values are 1.7565×10^{-9} m/m and 4.7148×10^{-5} m/m, respectively. The strain contour shows that most regions of the gear still experience relatively low deformation, as indicated by the dominant blue region. However, a significant increase in strain is observed in the vicinity of the crack tip, represented by the yellow-to-red zones.

The maximum strain is located at the crack tip near the tooth root, adjacent to the loaded region. This indicates that the presence of a crack leads to a more localized deformation response compared with the uncracked model. The crack reduces the effective load-bearing area of the material, resulting in stress and strain concentration around the crack tip rather than a uniform distribution across the gear structure. Compared with the uncracked model, the maximum strain increases from 4.3922×10^{-3} m/m to 6.5499×10^{-3} m/m, corresponding to an increase of approximately 49.13%. This confirms that the

presence of an initial crack significantly affects the deformation response of the gear structure, leading to higher localized strain at the crack tip.

The increase in strain is strongly correlated with the increase in Von Mises stress observed in the previous analysis, where the maximum stress increased from 805.92 MPa (uncracked model) to 1335 MPa (cracked model). According to linear elasticity theory, higher stress levels directly result in higher strain at the same location. Therefore, the crack tip region simultaneously experiences both maximum stress and maximum strain.

In addition to increasing the maximum strain, the presence of an initial crack also alters the strain distribution pattern. In the uncracked model, strain is distributed more smoothly from the contact region toward the gear body. In contrast, in the cracked model, deformation becomes highly localized around the crack tip, resulting in a steeper strain gradient. This behaviour indicates a reduction in local stiffness due to material discontinuity introduced by the crack. From a damage mechanics perspective, the elevated strain concentration at the crack tip represents a critical indicator of potential crack propagation. Regions with high strain undergo larger cyclic deformation during repeated loading, which accelerates damage accumulation and promotes crack growth toward the gear core. If this condition persists, it may eventually lead to tooth fracture and transmission system failure.

Interestingly, although the maximum strain increases significantly, the average strain decreases from 7.0302×10^{-5} m/m (uncracked model) to 4.7148×10^{-5} m/m (cracked model). This indicates that deformation becomes more localized around the crack tip rather than being distributed across the entire gear structure. Such behaviour is characteristic of damaged structures, where load transfer becomes concentrated in critical regions.

Overall, the results demonstrate that the presence of a 0.5 mm initial crack increases the maximum equivalent elastic strain by 49.13% compared with the uncracked model. The highest strain concentration occurs at the crack tip, coinciding with the maximum stress region. These findings confirm that initial cracks significantly accelerate localized deformation and crack propagation, thereby reducing the structural integrity and service life of the reverse idler spur gear.

4. Conclusion

Based on the finite element analysis (FEM) of the reverse idler spur gear under an applied torque of 6226.03 Nm, it can be concluded that the presence of an initial crack significantly influences the stress and equivalent elastic strain distributions within the gear structure. For the uncracked model, the maximum Von Mises stress is 805.92 MPa, while the minimum and average stresses are 1.734×10^{-4} MPa and 14.128 MPa, respectively. The maximum equivalent elastic strain is 4.3922×10^{-3} m/m, with minimum and average values of 8.4862×10^{-10} m/m and 7.0302×10^{-5} m/m, respectively. The highest stress and strain concentrations occur at the tooth root region, which is subjected to direct loading during torque transmission, making it the most critical region for potential failure initiation. For the cracked model with an initial crack length of 0.5 mm, the stress and strain distributions become highly localized around the crack tip region. The maximum Von Mises stress increases to 1335 MPa, while the minimum and average values are 183.84 Pa and 9.4406 MPa, respectively. The maximum equivalent elastic strain also increases to 6.5499×10^{-3} m/m, with minimum and average values of 1.7565×10^{-9} m/m and 4.7148×10^{-5} m/m, respectively. Compared with the uncracked model, the presence of the initial crack results in increases of approximately 65.65% in maximum stress and 49.13% in maximum strain, indicating that the crack acts as a strong stress concentration site that significantly alters load distribution and promotes localized deformation. The results demonstrate that even a small initial crack substantially increases stress and strain concentrations, thereby accelerating crack propagation and reducing the structural integrity of the gear. Furthermore, the maximum stress in both conditions exceeds the yield strength of SCM415 steel (545 MPa), indicating a high risk of localized plastic deformation in critical regions, which may act as initiation sites for structural failure. Therefore, early detection of cracks at the tooth root and the implementation of predictive maintenance strategies are essential to prevent severe damage and extend the service life of the reverse idler spur gear in transmission systems. In addition, the finite element method has proven to be an effective approach for evaluating the influence of initial defects on the mechanical behaviour of gear components. It can serve as a reliable basis for improving gear design to enhance fatigue resistance and structural reliability.

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