Strojniški vestnik - Journal of Mechanical Engineering 70(2024)11-12, 582-594

DOI:10.5545/sv-jme.2024.1033
Original Scientific Paper
Received for review: 2024-04-30
Received revised form: 2024-07-15
Accepted for publication: 2024-09-10

The Impact of Micro-texture Distribution on the Frictional Performance of Straight Bevel Cylindrical Gears

Tiantian Xu[1,2] – Qingyu Guan[1] – Chunlu Ma[1,*]
[1] Changchun University, School of Mechanical and Vehicle Engineering, China
[2] Harbin University of Science and Technology, School of Mechanical and Power Engineering, China

In the gear transmission process, the tooth surface friction environment is very complex, and the gear surface is prone to high stress, strain and wear, which can easily cause gear failure. In order to alleviate the wear of the gear tooth surface and improve the anti-glueing ability of the tooth surface during gear transmission, this paper solves this problem by introducing micro-texture in the meshing gear. Firstly, three kinds of micro-textured gears are designed based on the mechanism of micro-textured structure in the friction vice and the meshing position during gear transmission. Secondly, finite element simulation tests were conducted with and without micro-textured gears, and the stresses, strains, and wear levels experienced by the micro-textured gears during transmission were analyzed. The study found that torque and rotational speed have a direct impact on the gear surface. Compared to traditional gears, gears with micro-textures distributed above the pitch circle promoted a 51.57 % reduction in stress and a 61.81 % reduction in strain, also altering the concentration locations of stress and strain on the tooth surfaces, which led to a 50.51 % reduction in wear. This research has significant implications for improving the frictional performance of gears, with micro-textures on the tooth surfaces acting as containers for lubricants and metal filings, preventing abrasive wear of the friction pairs on the tooth faces and enhancing the durability of the gears.
Keywords: gear transmission, micro-texture, friction, wear, stress-strain, temperature

Highlights
- *In order to optimize the tribological performance of traditional gears and prolong their service life, micro-textured gears are proposed according to the principle of tribology.*
- *The excellent friction reduction and anti-wear performance of micro-textured gears is verified through the friction and wear test between gear pairs.*
- *Compared with conventiona gears, the concentration location of high stress and strain areas of micro-textured gears is changed.*
- *Compared with conventional gears, the surface wear rate of micro-textured gears is reduced.*

0 INTRODUCTION

Gear transmission is one of the most important methods in mechanical transmission, with various forms widely used in fields such as automobiles, aerospace, and mechanical equipment [1] to [3]. In terms of usage, it can be categorized into high-speed and low-speed, as well as light and heavy loads. Different usage conditions lead to significant differences in the failure modes of gears [4] and [5]. Lubrication is indispensable in gear transmission. For gears operating at low speeds, a layer of lubricating oil covers the gear surface, maintaining a hydrodynamic lubrication state throughout the operation. This avoids direct contact between the friction pairs, with the oil film bearing the pressure instead of the gears [6] to [8]. With increasing speed and load, the temperature of the oil film rises, causing a significant increase in viscosity and noticeable viscous phenomena. This results in areas of the gear meshing surfaces experiencing insufficient or lack of oil, leading to increased contact area and contact stress, causing phenomena such as surface adhesion and pitting [9]. Typically, measures such as increasing gear surface hardness, reducing surface roughness values, selecting appropriate viscosity lubricating oil, and using helical gear transmission are adopted to alleviate gear surface wear and prolong gear life.

As research into bionics and surface tribology deepens, it has been discovered that friction pairs with smooth surfaces struggle to form a complete lubricating oil film, leaving the gear surfaces in a state of boundary lubrication for prolonged periods, leading to increased wear [10] and [11]. To promote the formation of lubricating oil films on gear surfaces, researchers have found that organisms develop structures with unique functions in different body parts to adapt to environmental changes, thus enhancing their chances of survival. Therefore, by studying the micro-textures of biological epidermis and approaching from perspectives of reducing friction, wear, and adhesion, suitable micro-textures are extracted from biological body parts and combined with gear surfaces to achieve the goals of reducing friction, adhesion, and wear [12] to [14]. Consequently, researchers have begun applying micro-textures to

*Corr. Author's Address: Changchun University, School of Mechanical and Vehicle Engineering, China, , machunlu1009@163.com

gear faces to enhance the tribological performance of gears. Experimental research shows that gears with micro-textures have a friction coefficient approximately 64 % lower than that of traditional gears without micro-textures, and their wear resistance is increased by 16 % [15]. By altering the shape of the surface micro-textures and the area ratio occupied by gear face micro-textures, researchers have explored the impact of surface texturization on surface lubrication, surface friction, and wear [16] and [17]. Micro-textures are now divided into three main categories: convex, concave, and grooved micro-textures, and are widely used in tools like lathe tools, milling cutters, bearings, and gears [18] to [20]. Studies have shown that laser-processed surfaces with regular micro-textures can significantly enhance load capacity, wear resistance, and friction coefficient, and can also serve as micro reservoirs for lubricants under insufficient lubrication conditions [21]. Chen et al. [22] studied the impact of micro-textured gears under dry friction and heavy load conditions on tribological properties, finding that the presence of micro-textures on gear surfaces increased friction stability by 52 % and reduced torque by 26.2 %, providing a theoretical basis for gear engagement without lubrication oil. Wang et al. [23] have simulated the effects of micro-textures on gear surface lubrication and friction reduction through finite element simulations, finding that under low-speed conditions, the presence of micro-textures reduces the oil film thickness, weakening the load-bearing capacity, but as the speed increases, the oil film thickness gradually increases. The above research shows that altering the frictional characteristics of gear surfaces to adjust the impact of frictional forces on gear transmission states is of significant importance.

Previous studies have shown that surface micro-textures can effectively improve the lubrication state between gear teeth, reducing the friction and surface wear of friction pairs. Currently, the design of micro-textured gear surfaces, friction and wear tests, and contact bearing analysis are at an initial stage. Therefore, this article extracts a type of rectangular micro-texture with grooves by observing the epidermal structures of organisms in nature, and constructs three different micro-textures at various positions above and below the gear pitch circle to conduct gear friction and wear tests. Using stress, strain, and wear as evaluation criteria, it compares and analyzes the performance of gears with and without micro-textures, providing a theoretical foundation for subsequent research on microtextured gears.

1 THEORETICAL ANALYSIS

1.1 Metal Friction Theory

At the microscopic level, it is considered that the contact between two objects is actually the contact between micro-protrusions on the surfaces of the objects. When subjected to an external load, the point contact between the two objects turns into a small plane contact. As the load continues to increase until it can bear the entire load, the contact area stops increasing. Fig. 1 shows the schematic diagram of the relationship between contact area and load, from which Eq. (1) can be derived:

$$F_N = A_r \times \sigma_S, \tag{1}$$

where F_N is the load, A_r the contact area, and σ_S the compressive yield strength.

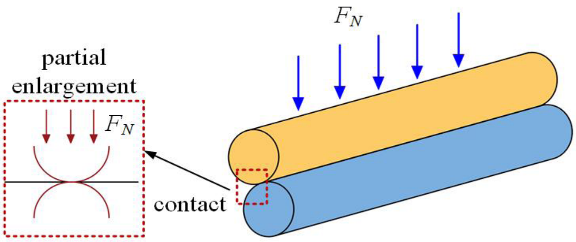


Fig. 1. *Schematic diagram of contact area and load*

Eq. (2) represents the frictional force between contact surfaces, which arises from the friction generated when the two surfaces are sheared under the action of tangential force.

$$F_f = A_r \tau'_b, \tag{2}$$

where F_f represents the friction force, τ'_b the shear strength of the bonding point contact and Ar is the contact area of the bonding point.

Substituting Eq. (2) into Eq. (1), the expression for the friction coefficient is:

$$u = \frac{F_f}{F_N} = \frac{\tau'_b}{\sigma_S}. \tag{3}$$

Therefore, it can be seen from Eq. (3) that when the surface material is certain, the friction force is proportional to the load. From the above equation, it can be seen that the bond point contact area is positively correlated with the surface friction. Fig. 2 shows the micro-texturing action mechanism. Eq. (4) is expressed as the actual contact length between the micro-textured friction pair:

$$L = L_S - nM, \tag{4}$$

where L is micro-texture contact length, L_S actual contact length, n number of micro-textures and M micro-texture length.

Eq. (5) represents the contact area of micro-textured:

$$A'_r = W \times L, \tag{5}$$

where W is micro-texture width and A'_r micro-textured contact area.

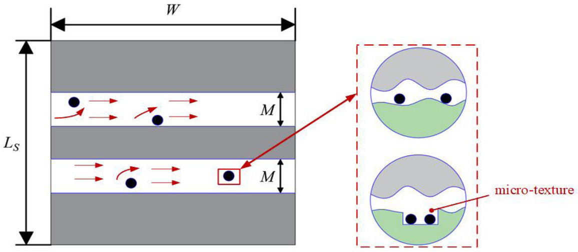


Fig. 2. *Mechanism of action of micro-textures*

Through the above analysis of the mechanism of micro-texture friction vice, it can be seen that the micro-texture prepared between the contact surfaces can reduce the actual contact area of the surface, which in turn affects the friction state of the surface and reduces the friction resistance generated. At the same time, the micro-textured part can be used as a storage container for tiny chips, and the surface chips can enter the friction surface and cause abrasive wear.

In the gear transmission process, the friction environment of the friction interface is very complex, the surface of the gear teeth to produce a large stress, temperature and in the state of lack of oil lubrication, all of which will lead to the failure of the gear, seriously affecting the service life of the gear. According to the Hertz contact theory [24], it can be concluded that the form of contact when gear meshing is face contact. So the combination of micro-textured structure and gear surface, the use of surface micro-textured mechanism, the manufacture of high-quality and high-precision gear pair.

1.2 Selection of Groove Micro-Texture

Existing types of micro-textures are divided into three main categories: dimples, bumps, and grooves. Considering the actual machining conditions of gear tooth surfaces and the area occupied by micro-textures on the tooth surfaces, this paper selects grooved micro-textures integrated with tooth surfaces for study [25] to [27]. Rectangular grooves have strong directionality and are easy to produce, process, and apply. During gear transmission, grooved micro-textures can store lubricating oil, increase the oil film thickness, and reduce wear on the gear surface. Micro-textured gears are shown in Fig. 3.

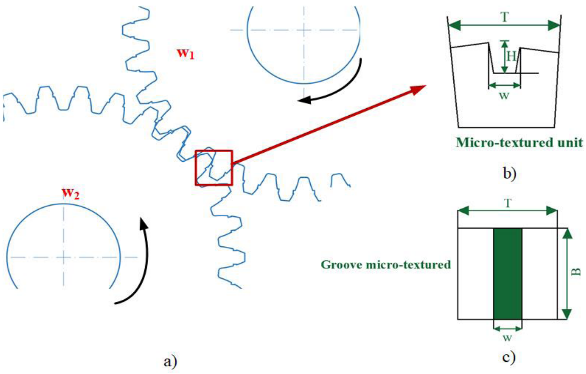
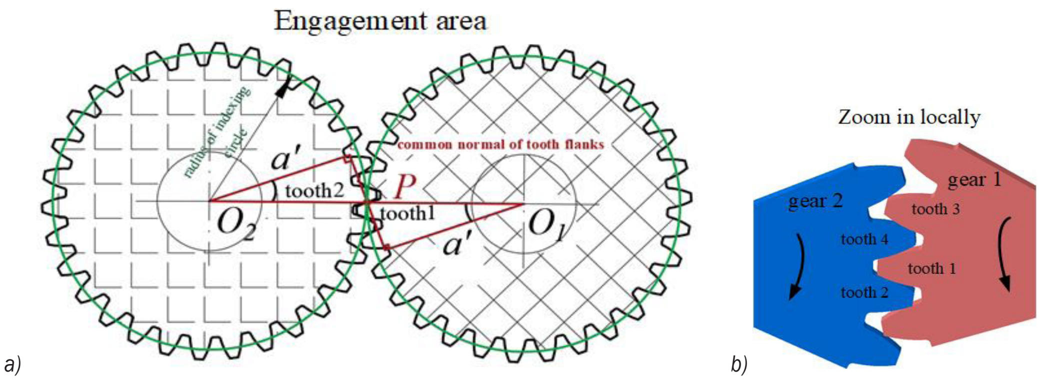


Fig. 3. *Grooved micro-textured gear, a) Grooved micro-textured gear, b) micro-textured section, and c) micro-texture surface*

Surface micro-texture dimensions are generally at the micrometer level, while gear dimensions are typically at the millimeter level. The distribution of the dimensions of each unit's micro-texture is on the friction pair. For transmission gears, the contact area of the contact zone is small, and the size of the micro-textures will be limited. If the micro-texture dimensions are too large, it can cause the lubricant to overflow, weakening the hydrodynamic lubrication mechanism, and may lead to increased wear in the contact area due to lack of oil. Fig. 4 shows the gear meshing principle diagram.

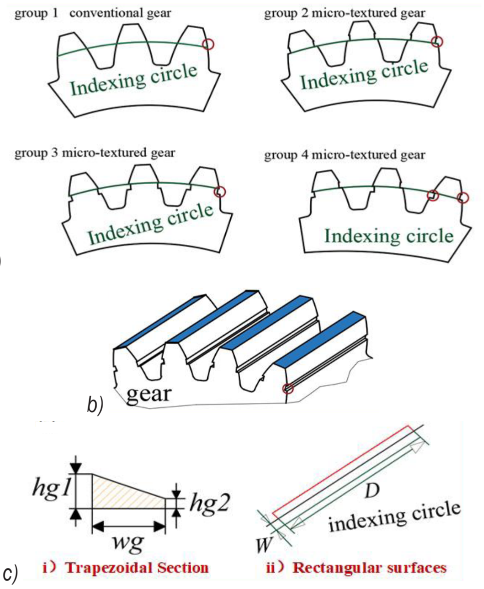
During the gear transmission process, the gear surfaces develop micro-cracks under the cyclic contact stress, which, as the gear operation time extends, expand causing the metal blocks on the surface to peel off and leading to pitting on the gear surfaces. Pitting usually occurs near the root of the tooth close to the pitch circle [28] to [31]. In this paper, the selected micro-texture has a width of 300 µm, a minimum depth of 13 µm, and a depth of 120 µm, with the micro-texture area ratio set at a fixed value of 13 %. For spur gears, the line of action typically lies on the pitch circle. In this paper, three pairs of engaging gears with different positions but the same shapes are machined based on the gear pitch circle as the reference. These include Gear A (where the micro-texture for the same tooth is located above the pitch circle), Gear B (where it is below the pitch circle for the same tooth), and Gear D (where, for the same tooth, the left micro-texture is below and the right is above the pitch circle), with traditional gears named



a) b)

Fig. 4. *Gear meshing principle, a) principles of gear engagement, and b) local magnification diagram of the meshing area*

G, serving as the control group in experiments. The distribution of micro-textures is shown in Fig. 5.



a) b) c)

Fig. 5. *Micro-texture distribution location; a) gear models, b) micro-textured distribution, and c) micro-textured shape*

2 SPUR CYLINDRICAL GEAR FRICTION WEAR TEST

During gear transmission, the complexity of gear surface friction and lubrication issues makes both theoretical analysis and experimental research challenging. Under reasonable assumptions, using simplified models can quickly and effectively simulate gear conditions, providing theoretical support for the experimental study of micro-textured gears and preventing the waste of materials and resources.

2.1 Establishment of the Three-Dimensional Model of Straight-Tooth Cylindrical Gears and Finite Element Simulation Experiments

In the actual working process of gears, bending stress occurs at the tooth root, contact stress occurs on the tooth surface, and wear is produced due to the relative sliding friction between the tooth surfaces. Gear meshing is a complex motion process involving alternating rolling and sliding movements, hence a three-dimensional simulation model is constructed for research. The model is meshed, setting the maximum mesh size to 1mm for simulation accuracy and precision, and refining the mesh at the gear teeth meshing area to a minimum size of 0.1 mm. The gear material is low carbon steel with an initial temperature of 20 °C, and the finite element simulation mesh model of the model is shown in Fig. 6. The test conditions are set for high and low speeds and light and heavy loads, with Tables 1 and 2 showing the finite element simulation test plans for gear friction wear, where Table 1 has the same speed with varying torque test groups, and Table 2 has the same torque with varying speed test groups. Straight bevel cylindrical gears are tested using finite element simulation according to Tables 1 and 2 to explore the effects of torque and speed on friction performance.

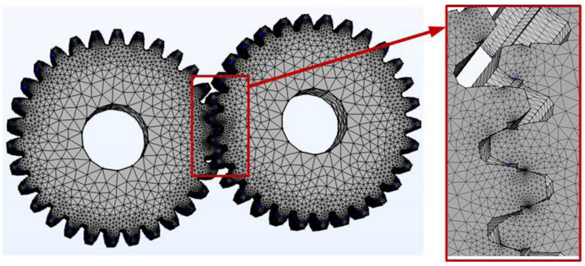


Fig. 6. *Gear mesh grid division*

At the same point of contact, the linear velocities of the two teeth of a meshing gear pair are not the same, so there is relative sliding between the gears, which leads to wear or gluing between the teeth. In tribology, there is a type of wear known as adhesive wear, where Archard's wear calculation [32] and [33] is Eq. (6):

$$Q = \frac{k}{3} \times \frac{N}{\sigma_b} \times L, \tag{6}$$

where Q is the total wear volume, k probability coefficient; N normal phase load; L sliding distance and σ_b is the compressive yield strength of the material.

Therefore, in this paper, the Archard wear model is invoked for the friction wear test of the gear pair, which can relate the wear rate to the contact pressure, sliding speed and material hardness, and is widely used in gear wear simulation.

Table 1. *Simulation experiment group*

Group	1	2	3	4	5
Rotation speed [rad/s]			10		
Torsion [N·mm]	500	600	700	750	1000

Table 2. *Simulation experiment group*

Group	6	7	8	9	10
Torsion [N·mm]			500		
Rotation speed [rad/s]	10	15	20	25	30

2.2 Analysis of Simulation Results for Spur Gears

2.2.1 The Influence of Torque and Speed on Stress Distribution and Stress Values

Cracks on the tooth surface are among the main reasons for gear failure. The stress values and distribution locations on the gear surface are used as the main basis for the initiation and expansion of cracks. Fig. 7 shows the stress distribution on the surface of traditional gears under different torques. During the gear transmission process, the relative engagement positions of the teeth vary, usually alternating between two-tooth engagement and single-tooth engagement. At the point of single-tooth engagement, where the driving gear meshes with the driven gear, instantaneous stress occurs at the meshing position, causing the teeth to deform under stress. For the same tooth surface, the bending stress in the middle is greater than at the ends, leading to stress concentration on the gear surface, which makes it prone to wear. From the figure, it is evident that the maximum stress is distributed near the tooth root at the pitch circle, indicating that fatigue is more likely to occur at the tooth root.

The collection of maximum and minimum surface stresses produced at different torques and speeds is depicted in the stress variation diagram shown in Fig. 8. From Fig. 8, it is evident that both maximum and minimum stresses increase with the increase in torque and speed. In gear transmission, torque refers to the moment of force applied on the gears, directly affecting the contact stress on the gear surfaces. As the torque increases, the contact pressure between gear faces also increases. With increasing speed, the relative movement speed between gear faces increases, and higher speeds lead to increased friction between gear faces. This increased friction exacerbates gear surface wear and consequently raises the surface stress on the gears. Rotation speed and torque are two key factors that need to be considered together when designing and operating gears. They directly determine the load capacity, fatigue life and operating efficiency of the gear. From Fig. 8a, it can

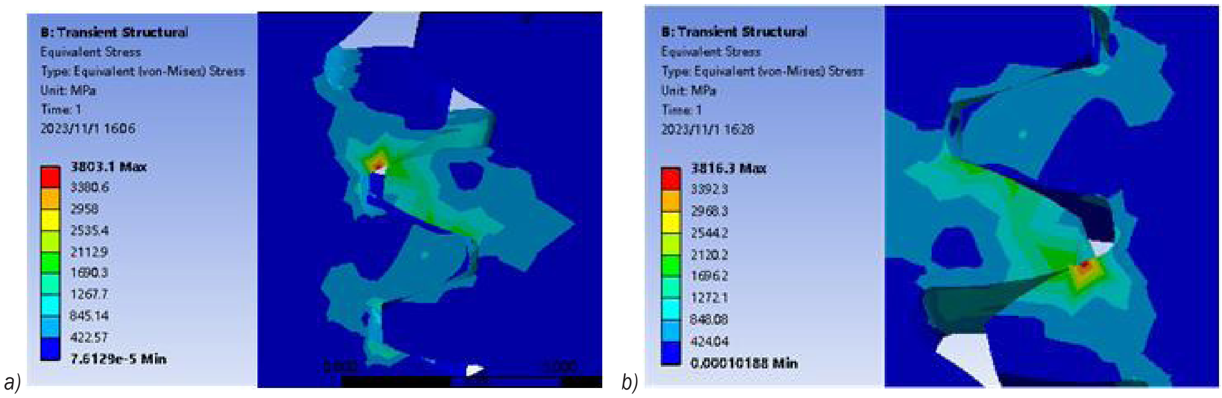


Fig. 7. *Stress distribution in traditional gears at different torques, a) M = 500 N·mm, and b) M = 1000 N·mm*

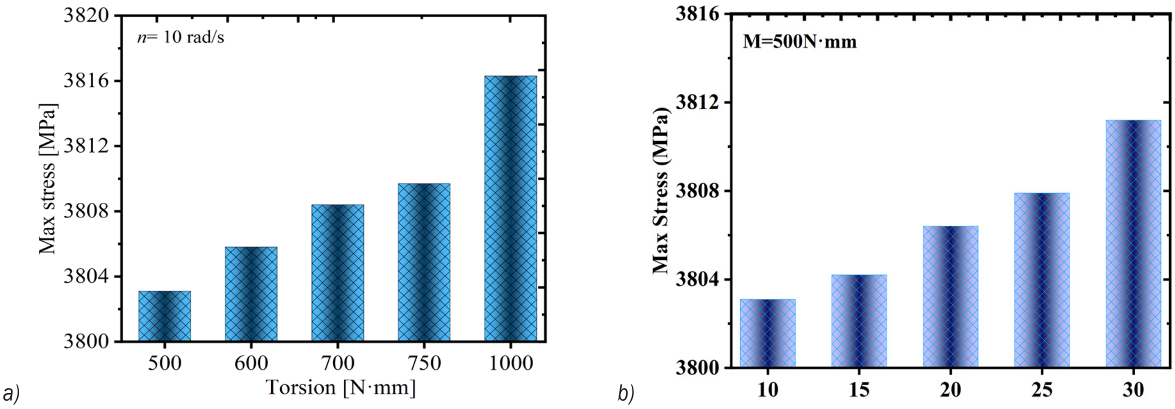


Fig. 8. *The influence of torque and speed on stress; a) the impact of torque on stress, and b) the impact of rotational speed on stress*

be seen that the maximum stress is generated when the rotational speed is 10 rad/s and the torque is 1000 N·mm. From Fig. 8b it can be seen that the maximum stress is generated when the torque is 500 N·mm and the torque is 30 rad/s. Therefore, in practical engineering fields, the impacts of torque and speed on traditional systems must be considered to ensure the stable operation and service life of gear transmission systems.

2.2.2 The Impact of Speed and Load on Strain and Wear

Gear surface strain has a significant impact on wear. During gear transmission, surface strain occurs on the gear faces due to external loads and stress concentration. Surface strain leads to changes in the micro-texture of the gear material. Under cyclic loading, changes in the surface structure intensify, leading to the formation of cracks and ultimately fatigue wear. Fig. 9 shows the strain distribution between meshing gear faces at a torque of 500 N·mm and a speed of 10 rad/s. The figure indicates that the gear faces undergo microscopic contact deformation under the influence of external loads, causing surface strain, especially near the edges of the contact area. This is due to friction between gear faces during transmission, causing plastic deformation and resulting in surface strain. Additionally, surface strain can lead to reduced lubrication performance, particularly in high-strain areas, diminishing the lubrication effectiveness of the gear surfaces.

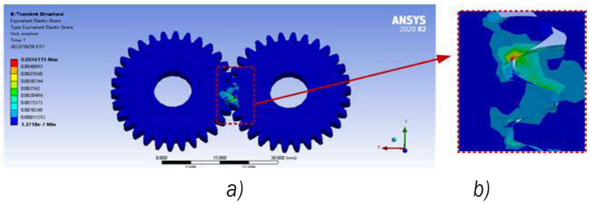


Fig. 9. *Gear meshing strain distribution locations; a) gear surface strain, and b) partial enlargement*

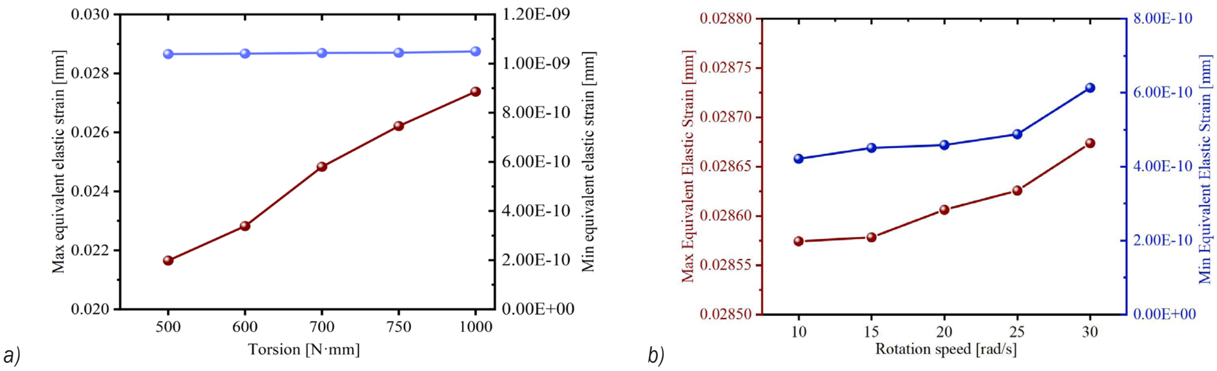


Fig. 10. *The impact of torque and rotational speed on strain; a) the effect of torque on corresponding deformation, and b) the impact of rotational speed on strain*

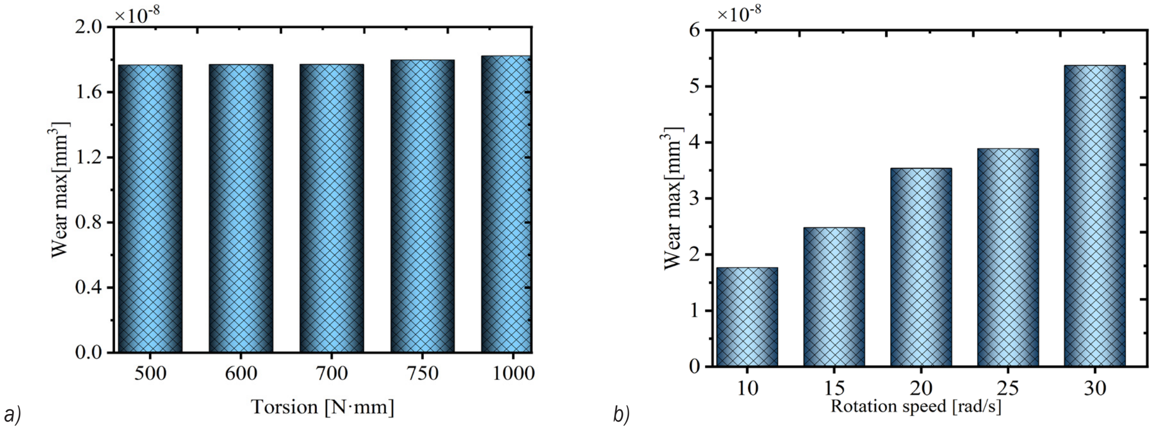


Fig. 11. *Impact of torque and rotational speed on the wear of straight bevel gears; a) the impact of torque on wear, and b) the impact of rotational speed on wear*

Data on the maximum and minimum surface strains generated under different torques and rotational speeds were collected and plotted as shown in Fig. 10. From Fig. 10, it can be seen that the strain gradually increases with the increase of torque and rotational speed. This is because, as the torque and rotational speed increase, the number of gear pairs engaging per unit time increases, surface friction intensifies, frictional resistance increases, and friction causes localized deformation on the gear surface, leading to increased strain. Additionally, during the gear transmission process, due to the action of external loads on the contact area of the tooth surface, minor deformations occur, affecting the mechanical properties and wear resistance of the gear surface, leading to wear on the tooth surface.

Wear on the gear surface causes changes in tooth thickness, which intensifies with increased working time, reducing transmission accuracy and reliability. Wear is usually quantified by the amount of wear, and in this paper, it is represented by wear volume. The amount of wear on the gear surface affects the precision of the gear; if the precision does not meet requirements, it can cause vibrations, noise, and transmission errors. In this paper, under the same time and working conditions, the amount of wear is collected and depicted in Fig. 11 as shown. From Fig. 11, it is evident that the wear amount gradually increases with increasing torque and speed.

Wear is typically divided into three stages. In the initial wear stage, friction occurs between two contact surfaces. Under the influence of load and frictional forces, the micro-topography changes, surface material is removed, and slight wear marks may appear on the surface. The second stage is the surface fatigue wear stage, where, as the load continues to act on the contact surfaces and the material reaches its fatigue limit, small cracks form on the surface. These micro-cracks expand under the repeated cyclic alternating loads, forming larger cracks and eventually leading to the detachment of gear surface material. In the final stage of wear, the intense friction generates heat, which causes the surface material to flow, and new surface texture structures begin to form at the crack sites, reducing wear at this stage. In the gear transmission process, the stages of wear are usually continuous, with gear surfaces repeatedly cycling through the aforementioned wear stages.

Through the aforementioned finite element simulation experiments on spur gears, it is evident that with the increase of torque and speed, stress, strain, and wear all show an upward trend. Moreover, the maximum values of stress and strain are concentrated in the contact area of single tooth meshing, specifically at the bottom of the tooth root at the pitch circle. Therefore, in order to mitigate gear usage lifespan, micro-textures should be constructed at the pitch circle position of the gear, aiming to reduce friction and wear resistance by altering the friction state in the contact area.

3 FRICTION AND WEAR TEST OF MICRO-TEXTURED SPUR GEARS

3.1 Micro-texture Gear Test

Gears, as important transmission components, possess advantages such as strong load-bearing capacity and high transmission efficiency, making their reliability and precision especially crucial for transmission

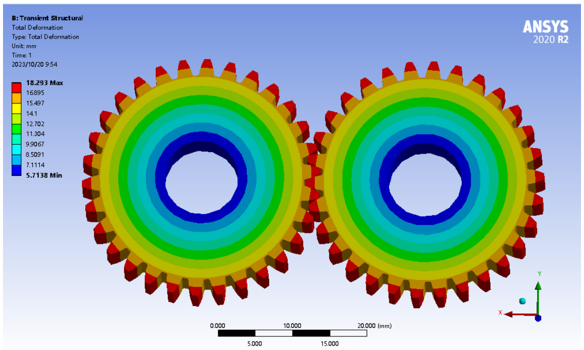


Fig. 12. *Gear deformation; M = 500 N·mm, n = 10 rad/s*

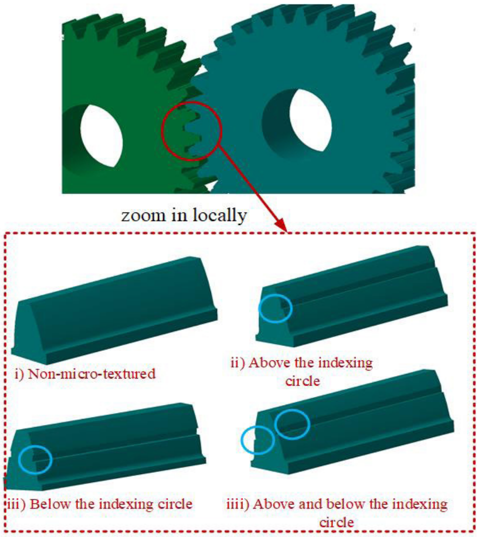


Fig. 13. *Three-dimensional model of micro-texture gear*

systems. Under dry and oil-deficient conditions, surface fatigue can easily occur, specifically manifesting as pitting and spalling on the tooth surface, or even tooth surface fracture failures. Based on this, how to change the frictional state of the contact interface and enhance the load-bearing capacity of the gear surface has become a current research focus. Fig. 12 shows the deformation of the gear surface during the gear transmission process.

The diagram shows that under the effects of high torque and high rotational speed, bending deformations occur between the gear tooth contact surfaces, altering the overall shape of the gear and significantly affecting its transmission accuracy. Therefore, this paper establishes three different micro-texture positions on the gear's pitch circle. Fig. 13 shows the three-position micro-texture gear model. Finite element simulation experiments are conducted under the speed and torque conditions shown in Table 1 and Table 2, to study the impact of micro-textures on gear surface stress, strain, and wear.

3.2 Impact of Micro-texture Distribution Location on Stress Distribution and Stress Values

During gear transmission, the contact surfaces of the friction pairs are subjected to high stress over a long period, which is a main reason for the propensity of gear roots to fracture. Fig. 14 illustrates the impact of micro-texture locations on the stress distribution on gear surfaces. As shown in the figure, for conventional gears, the stress at the tooth surface is much lower than at the root, where stress and strain are more likely to cause root fillet failure. Conversely, gears with micro-textures on the tooth surface reduce stress concentration at the root, distributing high stress areas across the tooth surface, and it is found that under the same operating conditions, the maximum stress values of micro-textured gears are significantly lower than those of traditional gears. This is because for micro-textured gears, by creating micro-textures on the gear surface, the mechanical properties of the tooth surface are altered, changing the contact area's friction state, reducing friction resistance, and consequently lowering the stress values. Another reason is that the sides of the micro-textures on the tooth surface are perpendicular to the surface, easily forming stress concentration points, thus achieving the purpose of altering the stress distribution on the tooth surface. Therefore, in the gear meshing process, arranging the positions of micro-textures on the gears wisely to influence stress distribution is very important.

Stress data collected during the experiment were used to create the impact diagram of micro-textures on tooth surface stress as shown in Fig. 15. From Fig. 15, it is evident that the stress on the gear surface increases sharply with both speed and torque, consistent with the results from traditional gear experiments. At a torque of 500 N·mm and a speed of 10 rad/s, the three types of micro-textured gears facilitated a stress reduction of 51.72 %, 25.14 %, and 41.27 %, respectively. The stress increase at the tooth root is less than the stress reduction at the tooth surface, suggesting that arranging micro-textures on the tooth surface can alleviate the generation of stress. Among them, Gear A, with micro-textures distributed above the pitch circle, shows the most significant effect in reducing stress.

When gears operate, the cyclic load on the contact surface of the gears leads to stress accumulation, resulting in pitting on the tooth surfaces. However, for micro-textured gears, the depth of the stress

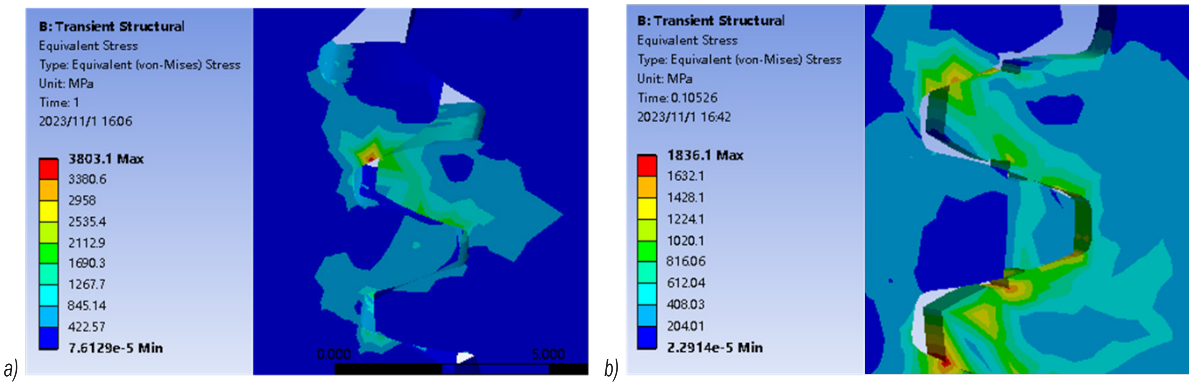


Fig. 14. *Impact of micro-texture position on stress distribution, a) gear G surface stress distribution, and b) gear A surface stress distribution*

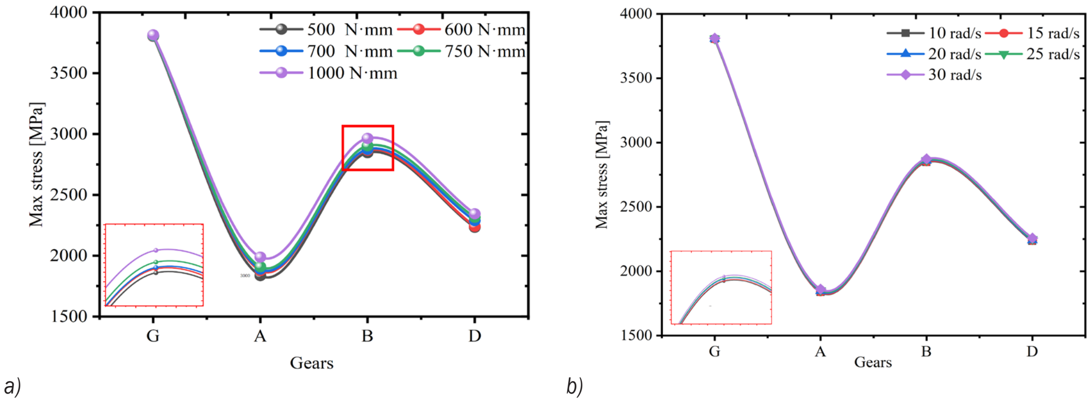


Fig. 15. *The impact of micro-texture location on stress distribution location; a) the influence of torque on stress values at rotational speed n = 10 rad/s, and b) the influence of torque m = 500 N·mm on the corresponding stress values*

accumulated on the surface is generally less than the depth of the micro-texture, so surface micro-cracks cannot continue to propagate. Additionally, the presence of surface micro-textures accelerates surface cooling, reduces contact area, and increases the rate of heat exchange between the gear and the air, delaying the local temperature rise on the tooth surface, thereby enhancing the gear's service life.

3.3 Impact of Micro-texture Distribution Location on Strain and Wear

Fig. 16 shows the strain distribution of micro-textured gears and non-micro-textured gears during gear transmission under the same operating conditions. From Fig. 16, it can be observed that the maximum strain of ordinary gears is concentrated at the tooth root, with no significant strain concentration on the tooth surface. In contrast, the strain values of micro-textured gears decrease compared to ordinary gears, and strains are generated in some areas with micro-textures. This is because during continuous meshing, ordinary gears cannot effectively release stress during the meshing process, while micro-textured gears have larger clearances near the pitch circle on the friction surface, allowing for a significant release of stress. Therefore, micro-textures promote the reduction of strain.

In the gear transmission process, lubricants are commonly added to change the contact state between tooth surfaces, shifting from solid-to-solid contact to solid-to-liquid contact, thereby reducing wear on the tooth surfaces. However, an excess of lubricant can lead to pitting on the tooth surfaces, and the lubricant can be depleted over time, leaving the gears in a state of oil shortage, which can cause gear failure. For micro-textured gears, if there is too little lubricant, the micro-textured areas can serve as storage containers for the lubricant, continuously supplying oil to the contact area during gear operation, providing secondary lubrication and preventing direct contact between the two tooth surfaces. If there is too much lubricant, the micro-textured areas can generate

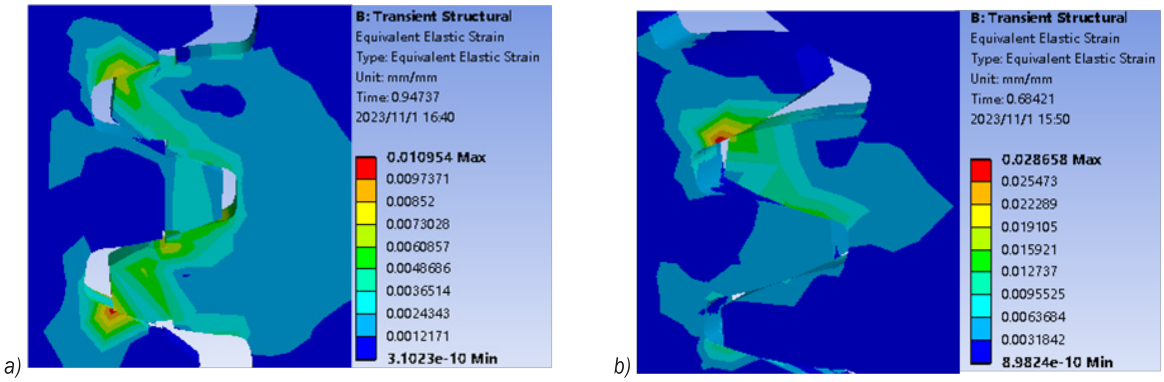
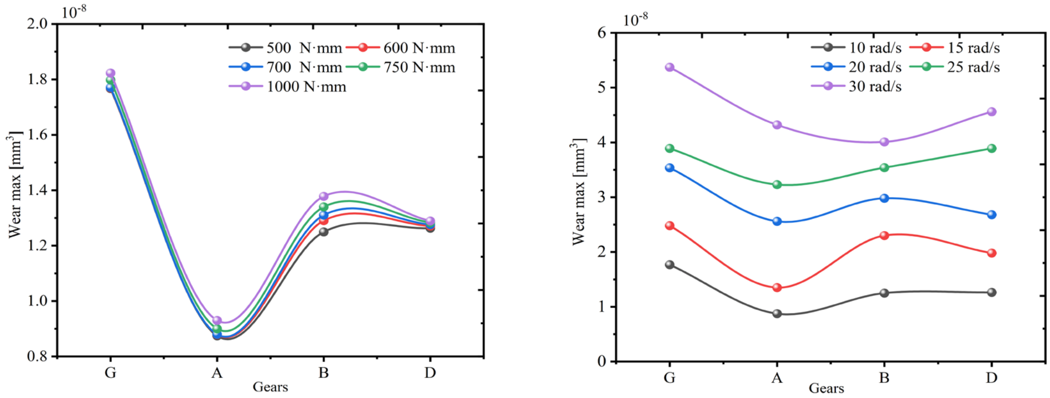


Fig. 16. *Change in strain location of micro-textured gear vs. non-micro-textured gear at M = 500 N·mm; a) strain distribution in traditional gear, and b) micro-texture gear strain distribution*



a) b)

Fig. 17. *The Impact of micro-texture on gear wear; a) the impact of torque on wear at a speed of n = 10 rad/s, and b) the impact of torque M = 500 N·mm and rotational speed on wear*

fluid dynamic pressure, promoting the formation of hydrodynamic lubrication on the tooth surfaces.

Fig. 17 shows the changes in wear amounts between micro-textured gears and non-micro-textured gears under the same operating conditions during the gear transmission process. From the figure, it is evident that the wear amount of gear A, which has a symmetric micro-texture arranged above the pitch circle, is significantly lower than that of ordinary gears. Under the same operating conditions and wear duration, the maximum wear amount of the micro-textured gear is reduced by 50.51 %. This means that the micro-textured gear effectively improves the wear process during meshing, enhancing the durability of the gear. It is also found that, with increasing torque and speed, gear A still maintains good friction-reducing and wear-resistant characteristics.

Surface texturing of gears belongs to subtractive manufacturing. This paper optimizes the performance of gear surfaces by machining groove micro-textures at the pitch circle position. During gear operation, the contact surfaces are squeezed together. Under high-speed heavy load conditions, the metal material on the gear teeth surface wears out, forming small particles of iron debris. For traditional gears, the iron debris squeezed between the contact surfaces causes abrasive wear. However, the grooved structure of micro-textured gears can accommodate iron debris that falls onto the tooth surface and store it inside the micro-textures, alleviating surface wear. At the same time, since the micro-textured areas are perpendicular to the gear tooth surface, under external loads, the edges of the micro-textures can shear the iron debris, promoting the formation of small fragments and extending the gear's service life.

The research indicates that appropriately designing micro-textures on tooth surfaces can change the concentration positions of high stress and strain, and promote the reduction of maximum stress and strain values. Additionally, micro-textures contribute to reduced wear on the tooth surfaces, improve the frictional state between contact surfaces, and enhance the stability of the gear transmission system and the service life of the gears.

3.4 Effect of Micro-Texture Distribution Location on Temperature

In the gear meshing process, the high temperature region is often concentrated in the contact between the tooth surface, due to the mutual contact and sliding between the two wheels' teeth during meshing, which will lead to heat generated by friction in the region, resulting in a localized increase in the temperature of the tooth surface. Under high speed and heavy load conditions, the heat dissipation ability of the gear tooth root and the bottom of the tooth groove is poor, which is easy to cause heat accumulation. Therefore, in order to extend the service life, this paper increases the surface heat dissipation area by preparing micro-textures on the tooth surface, which helps the surface heat transfer and reduces the gear wear caused by the localized temperature rise on the tooth surface. Fig. 18 shows a surface temperature map of the micro-texture gear.

Fig. 19 shows the variation of the temperature of the micro-textured gear and the conventional gear during the gearing process under the same working conditions, from which it can be seen that the heat generated by the friction between the gear pairs rises with the torque of the rotational speed and the continuous increase of the rotational speed. For Fig. 19a, the temperature is highest when the rotational speed n = 10 rad/s and M = 500 N·mm, where gear A generates a significantly lower temperature than the other three gears. For Fig. 19b, the temperature is highest when the rotational speed n = 30 rad/s, M = 500 N·mm, and the temperature generated by gear A is less than that of gear D and less than that of gear B under the same meshing conditions, and the temperature generated by the conventional gear is the highest.

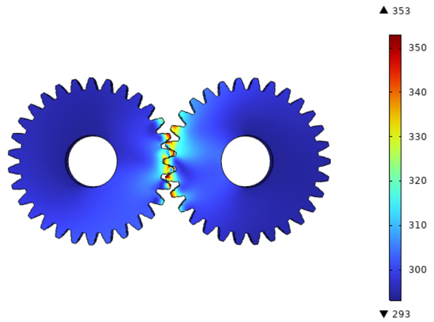
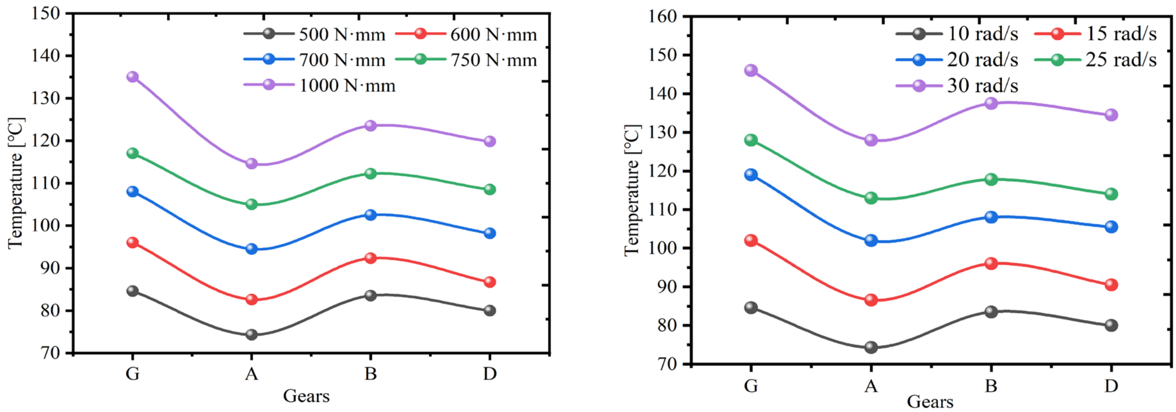


Fig. 18. *Surface temperature map of micro-textured gear pair, body temperaure in [K]*

This is due to the same working conditions, due to the micro-textured gear compared with conventional gears, due to the presence of surface micro-texture will make the tooth surface contact area is reduced, the coefficient of friction and friction are reduced, so that the gear amplitude is reduced to improve the transmission of the gear flat and stable. At the same time, due to the existence of surface micro-texture, the gear surface heat dissipation space increases, the efficiency of heat transfer between the gear surface and the air, slowing down the rate of temperature rise



a) b)

Fig. 19. *Effect of micro-texture on gear temperature; a) the impact of torque on temperature at a speed of n = 10 rad/s, and b) the impact of torque M = 500 N·mm and rotational speed on temperature*

of the tooth surface, prolonging the service life of the gear.

4 CONCLUSIONS

This paper addresses the issues of pitting and wear on gear surfaces under dry, heavy-load conditions and, through theoretical analysis of the frictional state of contact surfaces, proposes the theory that micro-textured gears can improve the contact characteristics of gear surfaces. The paper evaluates the impact of micro-textures on gear mesh transmission through extensive finite element simulation tests, using stress, strain, and wear amount as evaluation criteria, and arrives at the following conclusions:

1. Through finite element simulation tests, it is known that for traditional gears, as torque and speed increase, the stress, strain, and wear on the tooth surface contact areas increase. Typically, the high stress and strain areas are concentrated near the tooth root, close to the pitch circle.
2. For micro-textured gears, the presence of micro-textures on the tooth surfaces can effectively reduce the magnitude and distribution of stress and strain on the gear teeth. Moreover, for gears with three different micro-texture distribution positions, the micro-textures symmetrically arranged above the pitch circle result in a 51.57 % reduction in stress and a 61.81 % reduction in strain, yielding the best tribological performance.
3. Arranging micro-textured structures on the gear tooth surface reduces the actual contact area of the friction partner between the tooth surfaces, and the micro-textured structures act as storage containers for the tiny iron chips generated during the meshing transmission, avoiding the abrasive wear caused by the chips extruded between the tooth surfaces for a long time, improving the durability of the gears, and providing a theoretical basis for subsequent research on the micro-textured gears.

5 REFERENCES

[1] Li, X., Song, C., Yang, Y., Zhu, C., Liao, D. (2020). Optimal design of wave generator profile for harmonic gear drive using support function. *Mechanism and Machine Theory*, vol. 152, 103941, **DOI:10.1016/j.mechmachtheory.2020.103941**.

[2] Deng, X., Wang, S., Hammi, Y., Qian, L., Liu, Y. (2020). A combined experimental and computational study of lubrication mechanism of high precision reducer adopting a worm gear drive with complicated space surface contact. *Tribology International*, vol. 146, 106261, **DOI:10.1016/j.triboint.2020.106261**.

[3] Thirumurugan, R., Gnanasekar, N. (2020). Influence of finite element model, load-sharing and load distribution on crack propagation path in spur gear drive. *Engineering Failure Analysis*, vol. 110, 104383, **DOI:10.1016/j.engfailanal.2020.104383**.

[4] Chen, Z., Zeng, M., Fuentes-Aznar, A. (2020). Computerized design, simulation of meshing and stress analysis of pure rolling cylindrical helical gear drives with variable helix angle. *Mechanism and Machine Theory*, vol. 153, 103962, **DOI:10.1016/j.mechmachtheory.2020.103962**.

[5] Wang, S., Zhou, Y., Tang, J., Tang, K., Li, Z. (2022). Digital tooth contact analysis of face gear drives with an accurate measurement model of face gear tooth surface inspected by CMMs. *Mechanism and Machine Theory*, vol. 167, 104498, **DOI:10.1016/j.mechmachtheory.2021.104498**.

[6] Feng, G., Xie, Z., Zhou, M. (2019). Geometric design and analysis of face-gear drive with involute helical pinion. *Mechanism and Machine Theory*, 134, p. 169-196, **DOI:10.1016/j.mechmachtheory.2018.12.020**.

[7] Sheng, L., Li, W., Wang, Y., Fan, M., Yang, X. (2019). Nonlinear dynamic analysis and chaos control of multi-freedom semi-direct gear drive system in coal cutters. *Mechanical Systems and Signal Processing*, vol. 116, 62-77, **DOI:10.1016/j.ymssp.2018.06.043**.

[8] Xiao, Z., Zhou, C., Chen, S., Li, Z. (2019). Effects of oil film stiffness and damping on spur gear dynamics. *Nonlinear Dynamics*, vol. 96, p. 145-159, **DOI:10.1007/s11071-019-04780-6**.

[9] Liu, H., Liu, H., Zhu, C., Parker, R.G. (2020). Effects of lubrication on gear performance: A review. *Mechanism and Machine Theory*, vol. 145, 103701, **DOI:10.1016/j.mechmachtheory.2019.103701**.

[10] Hou, Q., Yang, X., Cheng, J., Wang, S., Duan, D., Xiao, J., Li, W. (2020). Optimization of performance parameters and mechanism of bionic texture on friction surface. *Coatings*, vol. 10, no. 2, 171, **DOI:10.3390/coatings10020171**.

[11] Huang, Q., Shi, X., Xue, Y., Zhang, K., Wu, C. (2021). Optimization of bionic textured parameter to improve the tribological performance of AISI 4140 self-lubricating composite through response surface methodology. *Tribology International*, vol. 161, 107104, **DOI:10.1016/j.triboint.2021.107104**.

[12] Atwal, J.C., Pandey, R.K. (2021). Performance analysis of thrust pad bearing using micro-rectangular pocket and bionic texture. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, vol. 235, no. 6, p. 1232-1250, **DOI:10.1177/1350650120940076**.

[13] Huang, S., Wu, H. (2021). Texture recognition based on perception data from a bionic tactile sensor. *Sensors*, vol. 21, no. 15, 5224, **DOI:10.3390/s21155224**.

[14] Zhang, K., Wu, C., Shi, X., Xue, Y., Huang, Q. (2023). Investigations of tribological performance of slewing bearing raceway with bionic textured composite surface under grease lubrication. *Tribology International*, vol. 184, 108469, **DOI:10.1016/j.triboint.2023.108469**.

[15] Chang, X., Renqing, D., Liao, L., Zhu, P., Lin, B., Huang, Y., Luo, S. (2023). Study on hydrodynamic lubrication and friction reduction performance of spur gear with groove texture.

Tribology International, vol. 177, 107978, **DOI:10.1016/j.triboint.2022.107978**.

[16] Bergseth, E., Olofsson, U., Lewis, R., Lewis, S. (2012). Effect of gear surface and lubricant interaction on mild wear. *Tribology Letters*, vol. 48, p. 183-200, **DOI:10.1007/s11249-012-0004-y**.

[17] Feng, Y., Ada, Y., Bian, C. (2023). Basic research on the influence of the area ratio and shape of gear surface microtextures on their friction performance. *Machine Tool & Hydraulics*, vol. 51, no. 03, p. 91-95.

[18] Cui, X., Duan, S., Guo, J., Ming, P. (2022). Bionic multifunctional surface microstructure for efficient improvement of tool performance in green interrupted hard cutting. *Journal of Materials Processing Technology*, vol. 305, 117587, **DOI:10.1016/j.jmatprotec.2022.117587**.

[19] Gajrani, K.K., Reddy, R.P.K., Sankar, M.R. (2016). Experimental comparative study of conventional, micro-textured and coated micro-textured tools during machining of hardened AISI 1040 alloy steel. *International Journal of Machining and Machinability of Materials*, vol. 18, no. 5-6, p. 522-539, **DOI:10.1504/IJMMM.2016.078982**.

[20] Vidyasagar, K.C., Pandey, R.K., Kalyanasundaram, D. (2021). Improvement of deep groove ball bearing's performance using a bionic textured inner race. *Journal of Bionic Engineering*, vol. 18, no. 4, p. 974-990, **DOI:10.1007/s42235-021-0056-5**.

[21] Yang, S., Liu, W., Zhang, Y., Wan, Q. (2018). Experimental evaluation on micro-texture parameters of carbide ball-nosed end mill in machining of titanium alloy. *The International Journal of Advanced Manufacturing Technology*, vol. 96, p. 1579-1589, **DOI:10.1007/s00170-017-0659-5**.

[22] Chen, Z., Zhou, J., Liu, B., Fu, H., Meng, X., Ji, J., Zhang, Y., Hua, X., Xu, X., Fu, Y. (2023). Meshing frictional characteristics of spur gears under dry friction and heavy loads: Effects of the preset pitting-like micro-textures array. *Tribology International*, vol. 180, 108296, **DOI:10.1016/j.triboint.2023.108296**.

[23] Wang, X., Huang, H., Song, J., Wang, Y., Ruan, J. (2023). Numerical analysis of friction reduction and atslb capacity of lubricated MTS with textured micro-elements. *Lubricants*, vol. 11, no. 2, 78, **DOI:10.3390/lubricants11020078**.

[24] Li, Z., Chen, J., Shen, J.L., Liu, K. (2018). Study on elastic deformation of surface morphology under line contact roll/slip condition. *Journal of Mechanical Engineering*, vol. 05, p. 142-148.

[25] Jia, X., Zhang, Y., Dong, X., Wang, Z. (2024). Enhanced lipophilicity and wear resistance of 20CrMnTi induced by laser surface texturing. *Optics & Laser Technology*, vol. 170, 110329, **DOI:10.1016/j.optlastec.2023.110329**.

[26] Sun, Y., Shimada, K., Xu, S., Mizutani, M., Kuriyagawa, T. (2018). Friction reduction by micro-textured surfaces in lubrication. *International Journal of Automation Technology*, vol. 12, no. 4, p. 603-610, **DOI:10.20965/ijat.2018.p0603**.

[27] Zhao, C., Long, R., Zhang, Y., Wang, Y., Wang, Y. (2022). Influence of characteristic parameters on the tribological properties of vein-bionic textured cylindrical roller thrust bearings. *Tribology International*, vol. 175, 107861, **DOI:10.1016/j.triboint.2022.107861**.

[28] Zhao, J., Li, Z., Zhang, H., Zhu, R. (2021). Effect of micro-textures on lubrication characteristics of spur gears under 3D line-contact EHL model. *Industrial Lubrication and Tribology*, vol. 73, no. 9, p. 1132-1145, **DOI:10.1108/ILT-11-2020-0423**.

[29] Pan, C., Chang, J., Gu, Y., Wang, C. (2023). Application of surface microtexture technology. *Recent Patents on Engineering*, vol. 17, no. 1, p. 42-57, **DOI:10.2174/1872212116666220107121835**.

[30] Bharatish, A., Rajkumar, G.R., Gurav, P., Babu, G.S., Murthy, H.N., Roy, M. (2021). Optimization of laser texture geometry and resulting functionality of nickel aluminium bronze for landing gear applications. *International Journal of Lightweight Materials and Manufacture*, vol. 4, no. 3, p. 346-357, **DOI:10.1016/j.ijlmm.2021.04.004**.

[31] Ruan, J., Wang, X., Wang, Y., Li, C. (2022). Study on anti-scuffing load-bearing thermoelastic lubricating properties of meshing gears with contact interface micro-texture morphology. *Journal of Tribology*, vol. 144, no. 10, 101202, **DOI:10.1115/1.4054400**.

[32] Sun, Y., Li, Y., Zhang, Q., Qin, X., Chen, K. (2023). Wear analysis and simulation of small module gear based on Archard model. *Engineering Failure Analysis*, vol. 144, 106990, **DOI:10.1016/j.engfailanal.2022.106990**.

[33] Liu, B., Bruni, S., Lewis, R. (2022). Numerical calculation of wear in rolling contact based on the Archard equation: Effect of contact parameters and consideration of uncertainties. *Wear*, vol. 490-491, 204188, **DOI:10.1016/j.wear.2021.204188**.