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Techniques for Dimple Surface Modification and Tribology Performance: A Systematic Review

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ABSTRACT

This paper systematically reviewed and evaluated the existing literature on dimple profile modification methods and parameters to enhance surface tribology in various engineering applications. A comprehensive search was conducted using Scopus, ASME, and Mendeley databases, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standard. The search focused on publications from 2021 to 2024, yielding 1635 related articles, of which 66 were shortlisted for full review based on inclusion criteria. These studies were categorized into four primary themes: Dimple Profile Application, Dimple Profile Modification Techniques, Tribological Performance Enhancement, and Future Trends in Dimple Profile Development. The review highlights the critical role of dimple profiles in reducing friction, improving lubrication, and enhancing wear resistance, which are pivotal for the reliability and efficiency of mechanical systems. A variety of techniques for dimple fabrication, such as laser texturing, through-mask electrochemical machining (TMECM), and electrical discharge machining, were analyzed, showcasing their respective advantages and limitations. Furthermore, the influence of parameters such as dimple shape, size, depth, and density on tribological performance was thoroughly examined. The findings contribute to a deeper understanding of the interplay between surface topography and tribology, offering insights into optimizing dimple profiles for specific applications. The review also identifies existing challenges and outlines future research directions to advance surface engineering solutions in tribological systems.

Keywords: Surface tribology; dimple profiles; friction; systematic review; PRISMA

INTRODUCTION

Dimple surface modification is a technique to improve engineering performance. This method involves introducing dimples on the surface to improve heat dissipation, aerodynamics, and tribology. This systematic review focuses on a comprehensive analysis of the techniques employed for dimple profile modification in surface tribology. Friction, lubrication, and wear are crucial factors in mechanical systems' reliability, efficiency, and lifespan, which are studied in surface tribology. In recent years, advancements in laser surface texturing have been pivotal in optimizing tribological performance by improving surface lubrication and wear resistance properties (Mao et al. 2020). These improvements underscore the importance of laser techniques in creating precise dimple profiles for diverse engineering applications. The present study is critically evaluated to identify advances, challenges and possible directions for future explorations. The paper is divided into three sections: an introduction to the principles of tribology and the effect of surface topography on friction, lubrication and wear; a thorough study of dimple profile modification techniques, including experimental and numerical approaches; and an investigation of the effects of changing the dimple profile on tribological performance, including cutting parameters, shape and size, friction reduction, wear resistance, and contact pressure distribution. The review concludes with a summary of key findings, highlighting the potential for future research and applications in this area. The aim is to contribute to developing innovative strategies and solutions in surface tribology.

MATERIAL AND METHODS

IDENTIFICATION

The initial systematic literature review (SLR) process included three phases: identifying keywords, then identifying relevant phrases and generating search strings in databases such as Scopus, ASME Digital Collection and Mendeley. In the initial phase, the keyword search identified 1635 articles from these three databases, indicating the effectiveness of this strategy in selecting relevant publications (Table 1).

TABLE 1. The database search string

Scopus	TITLE-ABS-KEY (dimple AND tribology) AND (LIMIT-TO (DOCTYPE , “ar”)) AND (LIMIT-TO (SRCTYPE , “j”)) AND (LIMIT-TO (LANGUAGE , “English”)) AND (LIMIT-TO (PUBSTAGE , “final”)) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2024))
ASME Digital Collection	dimple AND tribology
MENDELEY	dimple AND tribology

SCREENING

The screening process for a study containing 1530 articles commenced using the criteria described in Table 2. The initial phase involved the elimination of 1530 manuscripts, encompassing research articles, books, book series, chapters, reviews, meta-synthesis, meta-analysis, and conference proceedings. The review was limited to the domain of English literature. Initially, 105 journals were screened, and any duplicate papers were eliminated, resulting in 91 records. The study specifically examined tribology and conducted research on dimples. A total of 25 publications were considered ineligible for inclusion in the study (Figure 1). The Endnote program was used to document replicated journals to enhance comprehension.

TABLE 2. The chosen parameters for selection.

Criterion	Inclusion	Exclusion
Language	English	Non-English
Timeline	2021-2024	<2021
Manuscript type	Journal (research articles)	Journal (book, book chapter, conference proceeding, review paper)
Publication stage	Final	
Document type	Article	

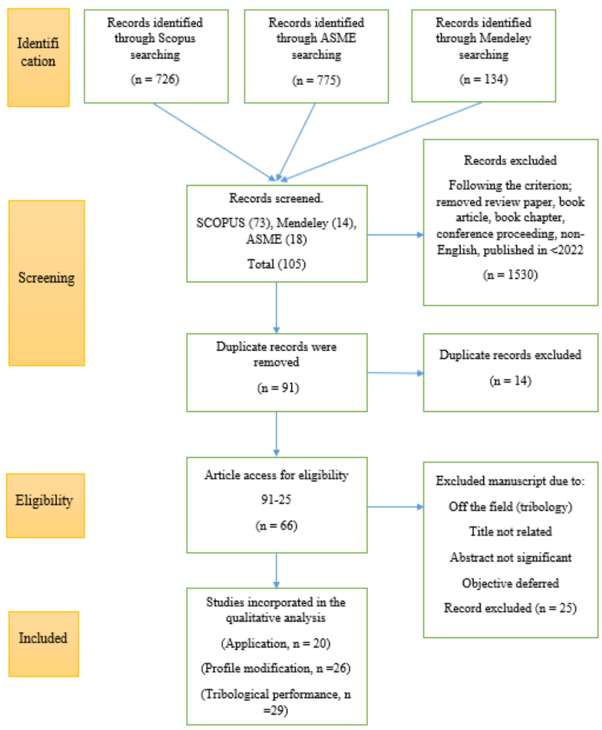

FIGURE 1. Diagram showing the flow of the suggested search study (Moher 2019)

ELIGIBILITY

During the eligibility phase, 66 papers were reviewed to ensure they met the study’s objectives and satisfied the inclusion criteria. Three sections were created out of the articles: tribological performance, profile alteration, and application. 20, 26, and 20 articles in each area were left open for revision (Figure 2).

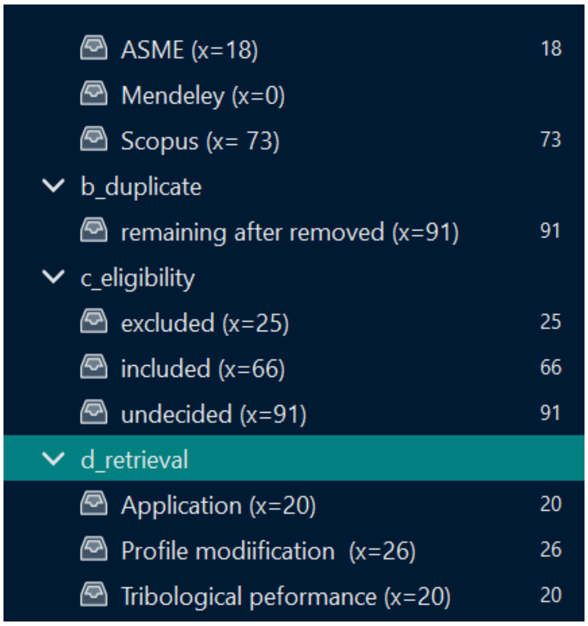

FIGURE 2. Snapshot of Endnote software

RESULTS

DIMPLE PROFILE APPLICATION

Research projects have explored using dimple profiles to improve tribological performance in various engineering scenarios. Studies have revealed that dimple textures reduce frictional losses, improve wear resistance, extend scuffing time, and enhance tribological performance. Various studies on using dimple profiles to address tribological issues in engineering applications. Key findings include reducing frictional losses in axial piston pumps, enhancing tribological performance through laser texturing of piston rings, improving solid lubricant properties in dimples on diesel engine cylinders, and optimizing surface textures for rotary compressor thrust bearings. These studies highlight the flexibility and effectiveness of dimple profiles in addressing friction and wear issues, thereby enhancing performance and longevity in various industrial sectors. Figure 3 summarizes the application based on the journal in 2021–2024.

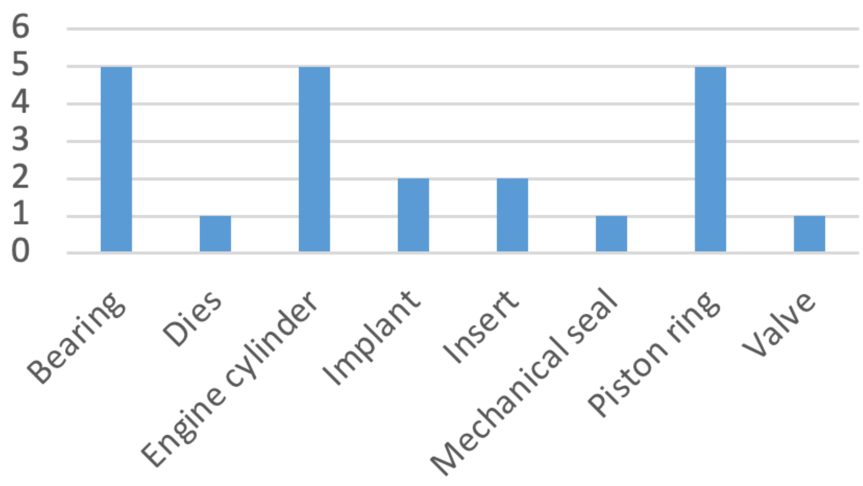

FIGURE 3. Summarizing the application of dimple profile modifications based on journal 2022-2024.

These citations are related to the work presented in this paper. Chen et al. (2022) studied the dimple on the engine cylinder and valve. Chevron micro-textures reduced frictional loss at the axial piston pump's valve plate/ cylinder block interface. A similar study by Fu et al. (2022) on engine cylinders demonstrated that WS_2, when encapsulated within surface dimples using a hot pressing method, exhibited superior tribological characteristics at elevated temperatures. The dimples acted as reservoirs for WS_2, enabling its gradual release to form a solid lubricating film, which significantly reduced the average friction coefficient compared to both the original untextured cylinder and the cylinder with dimples alone. Similar work has also been pursued by Ferreira et al. Ferreira et al. (2023) on dimple profile on Piston ring. Micro dimples can decrease friction-induced wear. Textured samples exhibited enhanced tribological performance with less weight loss. Alternative approaches have similarly been proposed by Han et al. (2022). The investigation revealed that a 5% area density yielded the lowest friction and wear loss coefficient. Additionally, the presence of a dimpled surface roughness extended the duration of scuffing on the piston ring. Surface texturing on engine cylinder liner-piston rings improved friction during initial break-in, with optimal running-in quality achieved through co-texture, a combination of dimple and groove textures (Miao et al. 2021).

The study by Shen et al. (2023) revealed that the double-sided textured design of the cylinder liner and piston ring (CLPR) demonstrated a lower coefficient of friction and wear depth under various strengthening loads and temperatures. Recent work by Söderfjäll and Gachot (2023) showed that using a dimple-type texture with a 300 µm diameter and 3 µm depth significantly reduced friction during sliding lubricated circumstances, especially at high sliding speeds of the engine cylinder. It was pointed out by Xu et al. (2022) that micro-dimples on the liner surface of the piston ring significantly reduced surface wear from abrasive wear, with the small dimple texture's superior anti-wear impact.

Taking advantage of the benefit of dimple surface modification, Dong et al. (2022) applied dimple on the insert surface. Since WC-Co is widely used in cutting tool, understanding it's interaction with textured surface is essential. The study showed that dimples on WC-Co surface could support the formation of tribofilms when sliding against CCF-PEEK, thus, improving frictional performance. However, the same textured WC-Co surface did not yield similar benefits with CCF-epoxy, which lacked the ability to form tribofilms. This indicates the material compatibility in textured tribosystems is importance. Another study by Nayak and Chetan (2023) focusing on dimple on cutting tool surface. The findings demonstrated that, compared to plain and normal textures insert cutting tools, the use of solid lubricant-impregnated texture and coated textures results in a significant reduction in cutting forces and chip-tool interface friction.

This tribological effect on bearing surfaces was done by Gimeno et al. (2023). They studied the textured finished product, which had an 18% improvement in friction test results. This argument is consistent with the findings of Kumar and Tyagi (2022). The performance of dimples on bearing surfaces is influenced by their density and shape, with lower density and bi-triangular shape resulting in higher performance. Another study by Long et al. (2022) under stepped load and starved lubrication circumstances on bearing, dimple-textured bearings demonstrated a 47% reduction in average coefficients of friction when compared to smooth bearings. These findings are in line with those found in the literature, where Wang and Zhang (2022) claimed the coefficient of friction (ACOF) curve was significantly influenced by the density of dimple textures, with the lowest values observed at 100 µm dimple diameter and 24% area density on bearing surface. Wang et al. (2022) found that the load-bearing capacity of elliptical bearings increases with micro-texture depth, with the lowest friction and best capacity at a dimensionless texture depth of 0.03. Another study by Lyu et al. (2021) investigated the compressor's performance, which was enhanced using a textured thrust bearing, resulting in reduced friction force and increased energy efficiency despite a decrease in input power.

This issue was explored by Shrivastava et al. (2023) using a laser texturing technique, where the results significantly reduced the friction coefficient and improved surface finish in textured dies, highlighting its potential for use in sheet metal forming operations. The application of dimples on Orthopedic implants was done by Soltani-Kordshuli et al. (2023). The study revealed that creating microscale dimples on titanium implants resembling natural articular cartilage pores significantly improves their tribological performance and wear resistance, potentially increasing their durability.

DIMPLE PROFILE MODIFICATION TECHNIQUES

The surface modification for the tribological study was performed using various techniques like laser texturing, electrical discharge machining (EDM), CNC milling, CNC turning, and abrasive jet. The laser texturing technique is the most commonly reported manufacturing method (15 studies), while simulation approaches are also widely used to optimized dimple profiles prior to fabrication. The modifications vary according to several techniques. These techniques regulate dimple properties such as size, depth, density and shape. Laser texturing research focused on dimple size, depth, spacing and density using a single machine. The most effective reduction in the coefficient of friction occurs at certain dimple densities. Surfaces with groove textures, especially those created by EDM using multiple machines, can decrease COF under lubricated conditions. Through-mask electrochemical machining (TMECM) is an advanced technique for efficiently fabricating large-area micro-dimple arrays on metallic surfaces, enhancing their adaptability and tribological performance (Wang et al. 2024). Table 3 shows the compiled table for dimple profile modification studies.

LASER

Cao et al. (2023) produced round dimples utilizing laser peen texturing (LPT). The size of the dimples is 2 millimetres in diameter and has a depth ranging from 8.82 to 36.34 micrometres. The texture density ranges from 8.7% to 78.5%. The study investigated many factors including laser settings, micro-dimple shape, residual stress, and microstructure in the LPT process. The laser power density setting was 7.96 (GW/cm2). It aimed to uncover the wear mechanism that occurs under starved lubrication conditions. The study found that an LPT density of 20% resulted in the lowest coefficient of friction (COF) of 0.011. Similar work has also been pursued by Chen and Wu (2022). They used laser applications to fabricate round-shaped dimples on WC/Co discs. The dimple size was 40μm, while the depth was 50μm with dimple-distance of 150μm–250μm. The friction coefficient of textured cutting tools with solid lubricants is reduced by 50% compared to smooth samples and by 65% for ceramic balls, with textured dimple density not significantly affecting friction. COF recorded between 0.3-0.8. A dimple pattern was fabricated using a laser texturing approach to modify a Ti6Al4V alloy disc. Another study also was performed by Conradi et al. (2023). They investigated circular dimple shapes with the size of the dimple 50-100 μm, distance of 100 - 400 μm and 0.5–2μm depth. The texture density ranged from 10-40%. Based on tribological analysis, the surfaces with the highest texture density demonstrated the greatest friction coefficient reduction. COF found between 0.36-0.45.

The additive texturing method has been applied by Dwivedi et al. (2022). The SUS316 protrusion dimples and linear groove fabrication were done using the laser-based powder bed fusion (PBF). The study found that the bio-tribology test indicated a coefficient of friction of 0.11 for groove-textured samples in dry conditions and 0.38 for dimple-textured samples in lubricated conditions. The geometry of the protrusion circular dimple was 150 dia. μm and 96 μm height. The other geometry was 145 μm width and 75 μm height. A significant improvement in COF was observed on the textured surfaces: dimple 0.54, groove 0.11, as compared to the untextured specimen 0.55.

A similar technique was performed by Li et al. (2022). The result shows that the dimple-textured surface's lubrication performance was optimal at 10 mm depth, 8% area density, and 100mm diameter, with a 32.6% decrease in friction coefficient compared to the untextured surface. The COF was between 0.04 - 0.15. The work of Long et al. (2022) extends the idea of them by investigating the rolling element of bearing with a circular shape. The result shows the dimples on bearing raceways are excellent in minimizing friction and wear losses when the dimple diameter configuration is at 250 μm diameter and 8 μm depth. Lu et al. (2021) investigated the textured plasma electrolytic oxidation (PEO) coating with various dimple densities using a laser surface texturing approach. Surface texturing with circular dimples on the bearing surface reduces the friction coefficient by 0.11 and improves the load-bearing capacity on PEO/PTFE coating. Constant compensation is required to lubricate the PTFE film on the wear track. There were three types of dimples investigated by Mawignon et al. (2023): circular, rectangular, and hexagonal, which are fabricated by laser surface texturing. The laser configuration was set to a frequency range of 10-80 kHz, scanning speed of 500 mm/s, wavelength of 1064 nm, focal length of 78 mm, to produce maximum output power of 12 W. The dimples were fabricated in various shapes, circular (450 μm dia.), rectangular (450 x 425 μm) and hexagonal (circumradius of 420 μm). The result indicated that the transformer oil significantly reduces COF and wear in LST, with up to 73.8% reduction due to its excellent shielding and coolant properties, and its dimple shapes also contribute. The COF recorded was between 0.065-0.216. Niu et al. (2022) used a nanosecond pulsed laser to produce round-shaped micro-dimples with diameters of 100 μm and 10 μm depth. An area density of 10% was created on thermally oxidized samples. The result shows that the Ti-Zr alloy's tribological characteristics are improved by thermal oxidation treatment, which produces a ZrTiO4 layer that is harder and more wettable when combined with PAO4 oil. The COF during the study was between 0.15-0.3. Qin et al. (2023) improvised the tribological characteristic with dimple-filled MoS2 and modified MoS2 with dopamine. The dimples were fabricated by a laser welding machine. The average diameter and depth of dimples were 333.5 μm and 305.8μm respectively, and distances between dimples of 800μm and 967μm. The results indicated that the COF of the dimpled specimen surface of modified MoS2 was 11.9% lower than that of the sample filled with MoS2. The COF recorded ranges between 0.375-0.475.

More recent work by Rathmann and Radel (2022) on micro-dimple of tool surface by laser-induced periodic surface structure (LIPSS). The laser-based process chain successfully hardens tool surfaces while retaining the hydrophilic properties of LIPSS. Distortion of the tools is kept within a tolerable range where the COF recorded was 0.15. The improvement of COF obtained by Phun et al. (2023) during their study on SKH51 Tool steel surface. At a sliding speed of 15 cm/s, the coefficient of friction of the laser-textured tool steel surface, which had a 35% dimple density, was 0.087, 12.6% lower than that of the untextured surface. Wu et al. (2023) studied the tribological effect on various dimple shapes, circular, groove and mesh dimple shapes on micro-arc oxidation (MAO) coated hard ceramic bearings. The finding of this study shows that laser texturing dimples combined with MAO improve titanium alloy's wear resistance. The results of COF were Dimple ≈ 0.6, groove ≈ 0.65, mesh ≈ 0.75. whereas for COF/MAO were Dimple ≈ 0.275, groove ≈ 0.225, mesh ≈ 0.21. Yuan et al. (2022) also applied laser surface texturing in their study. Laser settings used were a 1064 nm wavelength, 20 kHz repetition rate, 16 W power, 24.9 mm focal length, and processing speed of 5 mm/s. Circular dimples were fabricated with 800, 1000, and 1200 μm pitch and 5-11% texturing density. Texture density, material type, counterpart type, and applied force were significant factors for mass loss. The COF ranges from 0.05 to 0.4. (Zhang et al. 2022). Another study used a laser setting with 4W to 20W of power. The shape of the dimple was circular. It was 120 μm across the dimple, and the texture density ranged from 20% to 50%. They used a scratch test to look at laser texture (LTC), laser carburized (LCC), and combination laser textured and carburized (LTCC) DLC coatings. The LTCC samples had better tribological qualities because they were laser-textured and then carburized. The surface roughness was between 0.0575 and 0.225 μm.

SIMULATION

Gangadia and Sheth (2023) investigated sliding performance of textured surface using a CFD simulation approach. They examined three dimple geometries; circular, bowtie, oriented bowtie dimple shapes were the design of dimple shapes. The depth was set between 10-30 μm and dimple density of 30%. Bowtie-shaped dimples enhance fluid stability and are influenced by geometrical and operational factors such as dimple depth and sliding speed, resulting in higher net hydrodynamic pressure. The COF reported was between 0.02-0.5. Similar work was also carried out by Abril et al. (2022). The simulation results showed that friction losses from piston rings to cylinder liners contribute 4-15% of engine fuel consumption. Doubled dimple radius and depth increase lubrication film thickness. The simulation model was validated with an average error of 14% affirming the predictive accuracy of the computational approach. Alternative approaches have similarly been proposed by Masmoudi et al. (2023) and Vignesh et al. (2023). The texturing geometry and location enhance the operational performance of hydrodynamic journal bearings.

ELECTRICAL DISCHARGE MACHINING (EDM)

Electrical discharge machining is also being used for dimple fabrication. Kango et al. (2022) studied the cylindrical dimples shape with average diameter of 3.2 mm and 70 μm depth. Experimental results showed that bearings with converging zones (0^o to 180^o) reduce the coefficient of friction and temperature rise more effectively than conventional and other textured cases with COF ranging between 0.016-0.03. Similar work has also been pursued by Sharma et al. (2023) in modification of the steel surface with rectangular and circular shapes. The circular pattern was found to have better tribological properties than the rectangular pattern. The COF was reduced by 7–12% ranging between 0.04–0.14. Singh et al. (2022) also did similar work with the setting for EDM was 3A of current, a 20μs pulse-on time, a 40% duty ratio, and a 25V gap voltage. The average result of the COF microchannel was 0.19, dimple 0.15, pillar 0.13, and untextured 0.35.

TURNING

Khanali et al. (2021) altered the contour of the dimple by employing vibration-assisted face turning to form a stretched dimple shape. The dimples were manufactured with a maximum length of 2.5 mm and a space between each dimple ranging from 0.72 to 1.6 mm. The researchers discovered that reducing the rotational turning speed from 90 to 31.5 RPM substantially impacts the dimple characteristics. Specifically, the dimple length decreases by 73% while the number of dimples increases by 68%. The COF was between 0.2-0.6. The dimples on the cylinder surface were done by Mohd Nasir et al. (2021) to create a similar stretched profile. Ellipse dimples of different sizes and forms were produced by the turning process to create the surface's surface roughness, Ra less than 1 μm.

MILLING

The study conducted by Bhaumik et al. (2022) examined the friction reduction of both grooves and circular formations. The dimple configuration includes a distance between 2-8 mm textures and a depth of cut ranging from 0.05-0.3 mm. This macro-size dimple was fabricated by a milling machine. A pin-on-disc tribometer was utilized to investigate wear. The dimpled texture exhibited superior friction reduction capabilities compared to the grooved texture. The disk with a textured groove pattern exhibits evident damage on the pin surfaces and deep furrows. The COF recorded between 0.02-0.085.

ABRASIVE JET

Pawlus et al. (2022) used an abrasive jet machining process and burnishing to modify the texturing surface. The process involved a work pressure of 0.6 MPa, an 8 mm nozzle diameter, and a 100 mm distance between the nozzle and the processed surface. The texturing shapes were spherical, oval, triangular, and chevron. Aluminium oxide with grain dimensions between 75 and 106 um was used as the abrasive material for machining the surfaces.

TRIBOLOGICAL PERFORMANCE ENHANCEMENT

Studies have shown that surface texturing significantly impacts tribological characteristics. Techniques such as laser texturing, CNC milling, EDM, and abrasive jet machining can modify surface parameters such as dimple shape, size, density, and depth. Optimizing these parameters can reduce friction coefficient and wear rates, improving mechanical component performance. Laser texturing improves lubrication film thickness and COF reduction, while CNC milling creates specific dimple textures, influencing wear behaviour under different lubrication conditions. Numerous studies have explored techniques and materials to improve tribological performance. Among these, hierarchical micro-dimples, a structured dimple with multiple levels pattern, usually micro scale and sometimes nano scale small, round or elliptical indentations on machined surface. Combined with laser texture, surface coatings, and additive combinations, these structures show promise in further improving friction, wear, and lubrication efficiency. These techniques have shown lower coefficients of friction under high contact-pressure regions, improved friction in water and oil lubrication, and enhanced friction states between moving parts. Surface texturing, particularly with spherical dimples, significantly reduces frictional coefficient and wear rate. Concave-type textures on graphite surfaces enhance the tribological performance of water-lubricated graphite materials. The synergistic effect of surface textures and DLC coatings has shown promising results in reducing friction, adhesion, and wear on Si3N4/TiC ceramic surfaces. Star-shaped micro-dimples produce higher hydrodynamic pressure than circular-shaped dimples, affecting tribological behavior. Surface texturing has also improved the adhesion of diamond-like carbon coatings on medical titanium alloy substrates. These findings highlight the effectiveness of surface texturing, additive integration, and material selection in elevating tribological performance across various applications and conditions.

Ali et al. (2022) investigated the tribological performance of micro-dimple surface texture on an aluminum alloy cylindrical surface during starved lubrication. They found that the length of the micro dimples is the main factor influencing friction response, and hierarchical micro dimples have a reduced friction coefficient at high contact-pressure zones. The minimum COF recorded was 0.4. Another study conducted by Bo et al. (2022). The study indicated that the methanol diluting oil significantly enhances corrosion, increasing the friction coefficient of ball-on-plate pairs with a dilution rate exceeding 15%, negatively impacting lubrication performance. This value could be used as a maximum limitation index for changing new lubrication oil in a methanol engine. The COF measured was 0.08-0.3. The effect of surface texture on polymer transfer film growth was studied by Cao et al. (2022). They reported that the CCF-PEEK composites show lower friction and wear loss than neat PEEK due to the lubricating effect of added carbon fiberes. The minimum COF measured was around 0.8. Conradi et al. (2022) studied the water application versus oil lubrication of Titanium Allow. They concluded that the MoS2 nanotubes enhanced friction in water and oil lubrication, with laser texturing demonstrating a comparable tribological response to oil. The lowest COF obtained was 0.35.

Investigation by Conradi et al. (2023) were done on the functionalization of AISI 316L. In their finding, MoS2 nanotubes do not significantly affect friction. The COF was 0.25 and 0.1 for untextured and textured surfaces, respectively. Further investigation by Fu et al. (2023) on the influence of stress concentration caused by surface dimples. Even though the presence of surface dimples leads to surface stress concentration. They proved that surface dimples and solid lubricants enhance friction between moving parts, with dimples causing surface stress at edges, which decreases as the dimple diameter increases. The correlation between dimple diameter and COF values was not significant. Gangadia and Sheth (2023) investigated the effect of star-shaped dimples on sliding surfaces. The star-shaped dimples produce a larger net hydrodynamic pressure and provide better stability between the sliding surfaces than a circular-shaped dimple.

Na et al. (2022) did the numerical simulation and experimental of SiC with squamous micro-texture. Based on their study, the friction coefficients of micro-textured samples increased initially and then decreased with increased rotational speed. In addition, the heat dissipation area was improved simultaneously, increasing the wear debris region. Hence, the lubrication temperature and wear morphology were modified effectively. Qiao et al. (2022) reported that the textured coating's wear scar was thinner, and the volume wear track was reduced because of the role of micro dimple textured coating as oil reservoir and debris entrapment, a low friction coefficient can be maintained for a long period after lubricant oil cutoff. The COF for textured coating was 0.13. The correlation between energy used and texturing surface was reported by Segu et al. (2023). The average COF of the dimple-textured surface is better than the cross groove and untextured textures by 24–28% and 57–60%, respectively. Srivyas et al. (2023) studied surface texturing with three different patterns: dimple, square and triangular. The study found that surface texturing of a square shape significantly reduced friction coefficient (50-70%) and wear volume (44-84%), enhancing friction efficiency and reducing the running-in period.

Tomar et al. (2023) examined the effect of texturing on journal-bearing surfaces using magnetorheological (MR) fluid. The combination of textured surfaces and MR fluid significantly improved tribological systems' performance by maintaining the bearing's minimum fluid film thickness and stability. Vignesh and Barik (2022) investigated the dimple texture by comparing the tribology performance of honeycomb shape and spherical dimple type. The study found that the spherical-shaped dimple-textured pattern significantly reduced the coefficient of frictional and wear rate compared to honeycomb and non-textured smooth surfaces, reducing them by 45% and 51%, respectively. Based on their result, increasing RPM speed will reduce COF and wear rate in both dry and solid lubrication conditions. Wang et al. (2023) looked at how different types of lubricants interact with different types of surface roughness. It was discovered that surface texture makes three types of lubricants work better: white oil with a low viscosity, silicone oil with a high viscosity, and castor oil with a high viscosity. Wei et al. (2022) mentioned that even though the ground ZrO2-C/SiC and Si3N4 with micro dimples-C/SiC demonstrated superior tribological qualities. The surface texture may not always have an effect on tribological capabilities. The formation and the trapped wear debris inside micro dimples result in a worse result.

In contrast, the investigation on diamond-like carbon (DLC) coatings and surface textures on Si3N4TiC ceramic surfaces done by Xing et al. (2022) found that the debris capture of dimpled textures increases surface hardness and mechanical interlocking effect and reduces contact area. Xu et al. (2022) investigated the frictional behaviours of the fused deposition modelling (FDM) printed components under oil lubrication. The test results indicate that the frictional performance of a small groove of a linear-printed component is much better than that of a large groove depth with a minimum average friction coefficient of approximately 0.07. Xu et al. (2023) studied the frictional performance between graphite material and cemented carbide. Friction coefficients, surface micrographs, and friction micrographs of cemented carbide plates and sample graphite all showed that the tribological performance of water-lubricated graphite materials was enhanced by concave-type patterns on graphite surfaces. Yang et al. (2023) reported the effect of copper surface textured by a laser machine. The surface was lubricated with Micron-TiO2 and Nano-TiO2. The research focused on applying TiO2 nanoparticles as an additive in insulating grease to enhance its insulation and tribological properties in electrical equipment. The result shows that nano grease lowers the COF value and wear width than micro grease. Zhang et al. (2022) used laser texturing and carburizing to improve diamond-like carbon film coating (DLC) adhesion and tribological behaviour on titanium alloy. The coefficient of friction of the sample shows an overall trend of rising and falling. It shows the sample with 30% density-textured had the lowest COF with 0.105.

FUTURE TREND OF DIMPLE PROFILE

The future of tribological dimple profiles is promising in applying mechanical moving parts due to improving the surface friction, retaining lubrication capability, and wear rate between two mating surfaces in motion. A vast number of experiments, together with advanced CAE simulations, could be performed to investigate further and fine-tune the current designs. There are a lot of possibilities to explore micro and nanoscale dimple sizes and patterns using nanotechnology and microfabrication techniques using advanced removal machines. Self-lubrication material properties could also be explored with dimple profiles to extend the lifespan of mechanical parts. Various intricate dimple patterns of varied arrangements and dimensions can be investigated on surfaces that experience friction and wear. Applying specific lubrication treatments or additives has the potential to enhance dimple profiles. This can be achieved by introducing solid lubricants through injection or by coating the dimples with lubricating materials. These developments would enhance nanotechnology, materials science, and surface engineering, resulting in increased reliability, strength, and efficiency of mechanical components.

TABLE 2 Table for dimple profile modification studies

Author	Process	Parameter Range	Dimple Profile	Size	COF
Cao et al. 2023	Laser	N/A	Round	Depth: 8.82-36.34 µm, Dia.: 2 mm, Density: 8.7-78.5%	0.011
Chen & Wu, 2022	Laser	N/A	Round	Depth: 50 µm, Dia.: 40 µm, Distance: 150-250 µm	0.3-0.8
Conradi, Kocijan et al. 2023	Laser	N/A	Circular	Distance: 100-400 µm, Depth: 0.5-2 µm, Density: 10-40%	0.36-0.45
Dwivedi et al. 2022	Laser	N/A	Protrusion/Groove	Depth: 96 µm, Dia.: 150 µm, Width: 145 µm, Height: 75 µm	0.11 (groove), 0.38 (dimple)
Li et al. 2022	Laser	The wavelength: 1064 nm, the scanning speed: 100 mm/s, pulse frequency: 40 kHz.	Round	Depth: 5-25 µm, Dia.: 50-150 µm, Density: 8-12%	0.04-0.15
Long, Shang et al. 2022	Laser	N/A	Circular	Dia.: 200-300 µm, Depth: 0.4-12 µm	-
Niu et al. 2022	Laser	N/A	Round	Dia.: 100 µm, Depth: 10 µm, Density: 10%	0.15-0.3
Phun et al. 2023	Laser	Output Power: 10-5 W, Wavelength: 1064 nm, Pulse Duration: 100 ns, Focal Length: 100 mm, Density: 5-15%	Circular	Density 5-15%	0.087
Qin et al. 2023	Laser	N/A	Round	Dia.: 333.5 µm, Depth: 305.8 µm, Distance: 800-967 µm	0.375-0.475
Mawignon et al. 2023	Laser	Frequency range: 10 - 80 kHz, scanning speed: 500 mm/s, wavelength: 1064 nm, focal length: 78 mm, output power: 12 W.	Circular/ Rectangular/ Hexagonal	Dia.: 450 µm, Rectangular 450x425 µm, Hexagonal Radius 420 µm	0.065-0.216
Rathmann & Radel, 2022	Laser	N/A	Rectangular	Length: 522 µm, Width: 500 µm, Density: 25%	0.15
Wu et al. 2023	Laser	N/A	Circular/Groove/ Mesh	Dia.: 80 µm, Depth: 0.4 µm, Width: 50 µm	Dimple ≈ 0.6, Groove ≈ 0.65, Mesh ≈ 0.75; COF/ MAO: Dimple ≈ 0.275, Groove ≈ 0.225, Mesh ≈ 0.21

continue...

...cont.

Yuan et al. 2022	Laser	Wavelength: 1064 nm, repetition rate: 20 kHz, power: 16 W, focal length: 24.9 mm , processing speed: 5 mm/s	Circular	Pitch: 800-1200 μm, Density: 5-11%	0.05-0.4
Zhang et al. 2022	Laser	Power: 4-20 W, Diameter: 120 μm, Density: 20-50%	Circular		-
Lu et al. 2022	Laser	N/A	Circular	Density: 10-40%	0.11
Kango et al. 2022	EDM	N/A	Cylindrical	Dia.: 3.2 mm, Depth: 70 μm	0.016-0.03
Sharma et al. 2023	EDM	N/A	Circular/ Rectangular	Length: 208, Width: 234, Depth: 85 μm	0.04-0.14
Singh et al. 2022	EDM	Current: 3A, Pulse-on Time: 20 μs	Square/Circular		Micro-channel 0.19, Dimple 0.15, Pillar 0.13
Bhaumik et al. 2022	Milling	N/A	Grooves/Circular	Distance: 2-8 mm, Depth: 0.05-0.3 mm	0.02-0.085
Mohd Nasir et al. 2022	Turning	N/A	Stretched	Length: 517-3928 μm, Width: 565-1040 μm, Depth: 14.5-124.9 μm	-
Khanali et al. 2022	Turning	Rotational speed : 90 to 31.5 RPM	Stretched	Length: 2.5 mm, Distance: 0.72-1.6 mm	0.2-0.6
Pawlus et al. 2023	Abrasive Jet	Pressure: 0.6 MPa, Nozzle: 8 mm diameter	Protrusion/ Grooves		-
Abril et al. 2022	Simulation	N/A	Spherical	Depth: 2-4 μm, Dia.: 50-100 μm	-
Vignesh et al. 2023	Simulation	N/A	Circular	Density: 30-50%, Aspect Ratio: 0.025-0.030	-
Masmoudi et al. 2023	Simulation	N/A	Protrusion Rectangular	Depth: 8-22 μm	-
Gangadia & Sheth, 2023b	Simulation	N/A	Circular/Bowtie/ Oriented Bowtie	Depth: 10-30 μm, Density: 30%	0.02-0.5

Empirical evidence has demonstrated that the application of surface texturing can effectively decrease friction and enhance overall performance in various applications, including engines, bearings, and mechanical seals. Techniques such as chevron micro-textures in engine components and laser-textured surfaces on piston rings have been employed to modify surface properties for improved tribological performance. Different techniques, such as simulation-based approaches, CNC milling, laser texturing, EDM, turning, abrasive jet, and modelling, provide insights into tailoring surface characteristics to enhance tribological behaviour across various applications. Studies have also explored the effects of surface texturing, lubrication conditions, and material compositions on friction and wear performance. Hierarchical micro-dimples show lower friction coefficients in high-pressure regions, while methanol dilution negatively affects lubrication performance. MoS_2 nanotubes enhance tribological performance in both water and oil lubrication.

CONCLUSION

This systematic review examines various approaches to dimple profile configuration to reduce friction and improve tribology performance across various applications. The effectiveness of a textured surface is influenced by crucial factors such as the shape, density, arrangement, and surface material. The research also clarifies the fabrication methodology with various machining parameters, dimple shapes and sizes. The review emphasizes the need to consider the additional needs to be met in operating conditions. The coefficients of friction (COF) recorded associated with dimple profiles and motion speeds are specified.

While the positive effects of surface dimples are well documented, recent literature lacks detailed discussion on their adverse effects or potential failure mechanisms. Issues such as material incompatibility between two mating parts, improper dimple geometry and density, loading condition due to reduce contact area, manufacturing complexity, and the potential for contamination or debris entrapment which may lead to abrasive wear, warrant further investigation. These overlooked aspects highlight an important research gap and open opportunities for more comprehensive studies to optimize surface texturing for reliable and consistent tribological performance.

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DECLARATION OF COMPETING INTEREST

None.

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