

# Knowledge mapping analysis of the track and hotspot of water lubrication: A scientometrics review

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**Abstract:** With the enhancement of environmental protection awareness of the international community and the continuous promotion of green and sustainable development of manufacturing industry, water lubrication instead of mineral oil has become the future development trend due to its green, pollution-free, clean, safe, and sustainable advantages especially in ships, marine, coal mining, and other fields. In recent years, with the rapid development of water lubrication research, significant progress has been made in related research knowledge domain and discipline. A systematic and extensive assessment of water lubrication research has become increasingly important. The objective of this research is to reveal the research status, research hotspots, and development trends in the field of water lubrication. Therefore, CiteSpace was used to conduct a systematic bibliometric and scientometrical analysis of 1,792 publications from Web of Science core collection database (1997–2021). The results show that China and USA are the most productive countries in the field of water lubrication and have made outstanding contributions. Through the analysis of hot key words and co-citation references, this paper reviews the research status of water lubrication in three aspects: (1) lubricating medium modification; (2) material preparation; (3) surface optimization. It has become a research hotspot to promote the superlubricity contact interface and the application of nanotechnology. The results of this study can make a significant contribution to the development of water lubrication by providing a comprehensive understanding of the research status and research hotspots in this field. Personal understanding and discussion of research hotspots and research status are expected to provide insights into future research trends. In addition, this study will provide valuable references and guidelines for researchers who are interested in this field.

**Keywords:** water lubrication; friction; scientometrics; CiteSpace

## 1 Introduction

Tribology is a science that studies the friction, wear, and lubrication of contact surfaces in parts with relative motion, and it is related to our daily life and almost all industries, such as the protective coating/film for touch panel of cellphone screens, articulation in human body, bearings in the motor, and compressor. Friction consumes about 1/3 of the world's primary energy, wear causes about 80% of machine parts to

fail, and more than 50% of mechanical equipment malignant accidents are caused by excessive wear of parts. According to the differences in economic models of different countries, the annual economic losses caused by friction and wear account for about 2%–7% of their gross domestic product (GDP). The friction interface of mechanical parts plays an important or even decisive role in the efficiency, noise, accuracy, corrosion, reliability, and life of the equipment. Therefore, improving the friction state between

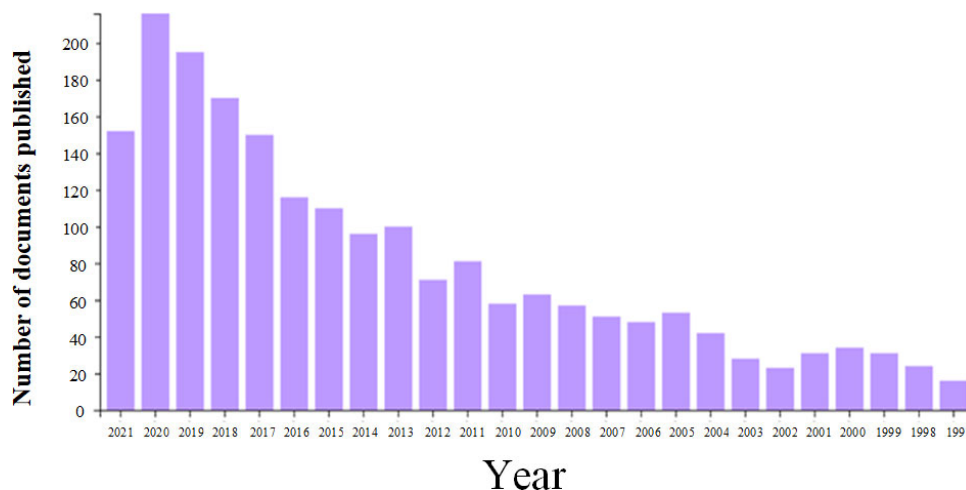
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mechanical parts and effectively reducing the friction coefficient is of great significance to solve energy shortage, resource depletion, environmental pollution, and health problems.

Lubrication to reduce the friction and wear of contact interface has been used as early as thousands of years before Christ (B.C.). In 1886, Reynolds proposed the hydrodynamic lubrication equation, referred as the Reynolds equation, which established the theoretical basis of lubrication. Lubricating oil is easy to form the lubricating film due to its high viscosity. It has been widely used in lubricating media in the past few decades. However, because the traditional mineral lubricating oil is difficult to degrade, its extensive use has seriously damaged the natural environment [1]. Water has attracted extensive attention because of its advantages such as flame retardant, high thermal conductivity, non-toxic, easy access, biodegradation, and environmental friendliness [2]. Due to the simple structure of the friction pair system with water as the medium, its maintenance time are less, and the cleaning and maintenance cost is lower than that of the oil medium system. All of these advantages make water lubrication have a wide range of applications in many industrial fields, especially in ships, marine, coal mining, and other fields. From 1997 to 2021, water lubrication research has experienced three stages: slow growth—fluctuating growth—rapid growth, as shown in Fig. 1. Since 2016, more than 100 articles have been published annually, indicating that the field of water lubrication research has attracted widespread attention from international researchers.

Due to the polarity of water molecules, water lubrication at the contact interface is more complicated than oil lubrication. According to the characteristics and mechanisms of water lubrication at the contact interface, researchers have made extensive and in-depth studies including the effects of different contact conditions, the evolution of the contact surface morphology, the microscopic mechanism of action, etc. Based on this, different improvement and optimization methods have been proposed. Despite the tremendous efforts of researchers, the study of water lubrication still faces huge challenges. Although water lubrication reduces the shear force of the friction interface due to low viscosity, it is difficult to form a water film during the wear process, resulting in insufficient lubrication of the contact interface and aggravating wear. The corrosive wear of friction pairs caused by the corrosivity of water is also a major challenge. In order to avoid these shortcomings, researchers have made extensive and in-depth research on improving the water lubrication performance of friction pairs. Therefore, the research on water lubrication is complex and diverse. A comprehensive and accurate tracking and summary of the current status and hotspots of research in the field of water lubrication through scientometric methods will play a very positive role in promoting the further development of water lubrication-related research.

As a branch of informatics, scientometrics can understand the research status and knowledge structure of a field through quantitative analysis of scientific literature. In scientometrics analysis, the method of



**Fig. 1** Change of the numbers of publications on water lubrication during 1997–2021.

information visualization, namely knowledge map, is used to reveal the structure, development trend, and the relationship between various research contents in this field. CiteSpace, as the most widely used knowledge mapping tool at present, is used to analyze and visualize the co-citation network, that is, two units, including literature, authors, keywords, etc., are cited by the same object [3], including co-citation references, co-authors, and co-occurring keywords [4], which facilitates to identify the fields of a research front and important disciplines and detect new research hotspots in a timely manner by analyzing the relationship between research objects [5]. The visual analysis software CiteSpace is of great value for analyzing the frontier and hotspots of discipline research and the evolution trend of topics, and exploring the relationship between knowledge base.

This article systematically reviews water lubrication based on statistical data obtained from CiteSpace. The current research status of water lubrication from a personal and global perspective is analyzed, and also the research hotspots and development trends in the field of water lubrication are discussed. The most influential organizations, countries, and documents have been explored within the scope of this research. In addition, the challenges and shortcomings faced by existing research fields are discussed. The results of this review are expected to provide researchers with a clearer perspective on the development of this field of knowledge.

## 2 Characteristics of water lubrication

According to the theory of hydrodynamic pressure and boundary lubrication, reducing the viscosity of the lubricating medium can effectively reduce friction. However, as the viscosity decreases, it is difficult to form a lubricating film, which causes the load-carrying capacity of the friction pair to decrease and ultimately leads to lubrication failure and friction increase. The viscosity of water is very low compared with that of lubricating oil, and the corresponding carrying capacity is much lower than that of oil film. Therefore, water lubrication is often difficult to form an effective fluid lubricating film.

As water is a corrosive medium, when materials

conduct friction behavior in water environment, the material surface is easy to be corroded by water, which aggravated the wear of materials under water lubrication [6, 7]. The contact surface of the friction pair is more prone to chemical reaction with water, which is due to the activation of the chemical reaction by the heat generated by friction. Because the shear strength of the tribochemical reaction layer formed by the tribochemical reaction between water and the friction pair material is often lower than the shear strength of the material matrix, it has a better boundary lubrication effect. Although the reaction layer is easy to shear, the wear of materials is often exacerbated because the reaction layer is often easy to dissolve. When  $\text{Si}_3\text{N}_4$  and stainless steel (Japanese standard SUS 630) wear in a water environment, the wear of  $\text{Si}_3\text{N}_4$  in water is intensified, which is mainly due to the dissolution of  $\text{Si}(\text{OH})_4$  produced by tribochemical reaction in water [8]. On the other hand, the reaction layer is continuously sheared or dissolved to make the friction surface gradually smooth, which leads to the hydrodynamic lubrication of water. Guo et al. [9] found that under the condition of water lubrication, the matching pair of cemented carbide and graphite obtained an ultra-low friction coefficient after three-stage running in.

When the material is running in a water environment, the water molecules on the surface of the material diffused into the matrix, which plasticized the material. This plasticization has two effects: One is to reduce the strength, hardness, and elastic modulus of the material; the other is to cause regional expansion and stress concentration. This plasticization has a very obvious impact on polymers, and it also has a certain impact on ceramics. Plasticization causes a decrease in the strength and hardness of the material, which aggravated the wear of the material. In addition, for composite materials that are used in water environments, the interface between the reinforcing phase and the matrix will be destroyed to a certain extent after the water infiltrates the material, thereby increasing friction and wear [10].

The generation and growth of cracks will aggravate the wear of materials, and in the water environment, water accelerated the growth of cracks. The reasons why water accelerates crack growth mainly include the following two explanations:

1) Chemical effects of water. For example, in the study of metal pitting corrosion, the atomic hydrogen produced by the reaction of water with oxygen, metal, and other substances infiltrates into the interior of the material, resulting in the embrittlement of the high stress surface, further leading to cracks and further growth.

2) Hydraulic action. The hydrostatic pressure of water produces wedge action, resulting in crack growth.

The effect of water accelerating crack growth is particularly obvious in ceramic wear. When ceramic materials operate in water environment, crack growth leads to grain fragmentation or spalling. Therefore, water accelerates the growth of cracks and aggravates the wear of materials [11, 12].

In summary, the friction pair exhibits complex characteristics under water lubrication conditions. In order to improve the friction and wear performance of the friction pair under water lubrication and reduce the friction coefficient and wear rate of the contact interface, researchers have made various attempts and efforts to address the problems of low viscosity of water medium, corrosion of wear-resistant friction pair materials in water-carrying environment, plasticization, and evolution of the contact interface of friction pairs.

### 3 Data source and method

In order to ensure the comprehensive, accurate, and highly credible of original data, Web of Science, the largest global academic journal network, was selected as the data source in this article. “Water lubrication” is retrieved as a dataset, with the year period ranges from 1997 to 2021. In addition, the data type is set to articles, and therefore nonacademic papers (such as reports and proceeding papers) are not included. Finally, 1,792 articles were selected for research.

CiteSpace is an analysis software developed by Professor Chaomei CHEN of Drexel University, which is used to mine, analyze, and visualize scientific research documents [13, 14]. This article used CiteSpace V software, and the version is 5.8.R2 (64-bit) to draw various knowledge maps through the original data obtained in Web of Science. Firstly, the most active countries, institutions, and literature have been

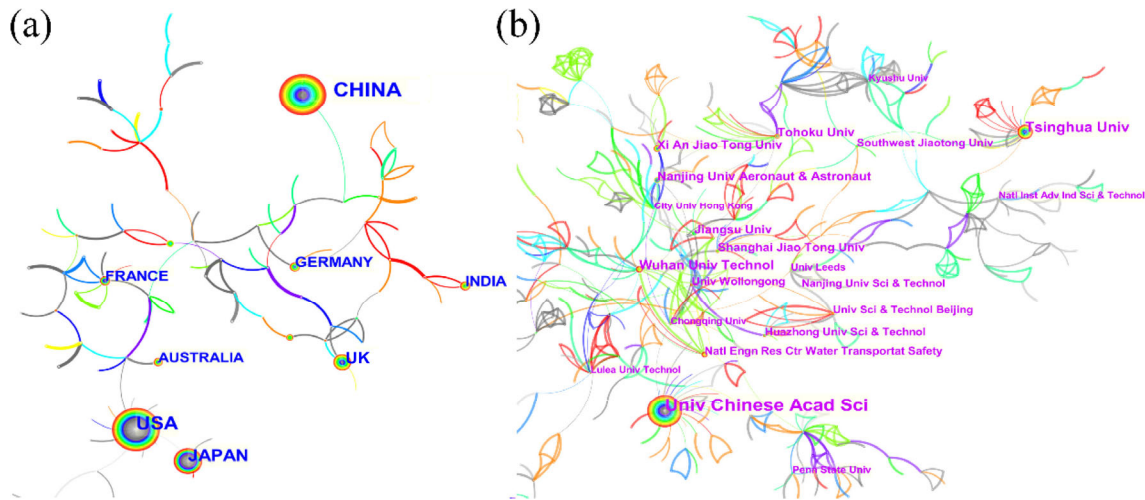
analyzed. Secondly, the knowledge structure and research status in the field of water lubrication are displayed by co-citation analysis and cluster analysis. Finally, the research trend is analyzed by keyword burst detection and timeline visualization.

## 4 Analysis on research status of water lubrication

### 4.1 Analysis of contributing countries/institutions

Figure 2 shows a network of cooperating international institutions and countries, as well as international organizations and countries with a high frequency of research. Each node represents different countries and institutions. The larger the node, the higher the frequency of publications. This indirectly reflects that the institution/organization has made outstanding contributions in this field and is more authoritative. Color represents the year that the article was published. The darker the color, the earlier the article was published. The node link represents the cooperative relationship between countries and organizations. The number of the node link reflects the centrality, and the greater the number, the higher the importance of the node in the cooperative network. Figure 2 shows a large number of countries and institutions that have different degrees of joint research. According to the number of articles published, the top five countries are China, USA, Japan, UK, and Germany. Although the numbers of published papers in USA, Japan, and Germany are smaller than that in China, the centrality values of their research nodes are greater. This may be because these countries have carried out research in this field earlier and have made many achievements, which makes their influence and cohesion very large. Most of the top 10 institutions are Chinese, with the Chinese Academy of Sciences ranking first and Tsinghua University ranking second, which shows that the institutions of China have excellent influence in the field of water lubrication. From the network of international institutions displayed in CiteSpace, it can be concluded that the cooperation between institutions is relatively close, and cross-unit and national cooperation is the norm. Most representative institutions/organizations have formed a cooperative





**Fig. 2** Collaboration network in water lubrication: (a) country; (b) institution.

network similar to the diamond structure as the center.

#### 4.2 Reference co-citation analysis

When two papers are cited by the third paper at the same time, the two papers are considered to have established a co-citation relationship [15]. Reference co-citation analysis is a key technology to evaluate the evolution of research fields and analyze the structure of research fields [16, 17]. Reference co-citation analysis is an analysis method based on citation network. It is different from the citation quantity analysis method, which evaluates the quality of journals, authors, countries, and documents through the number of citations. Reference co-citation analysis uses network analysis method to cluster the documents in a specific field, which can show the structure and characteristics of the specific field. Therefore, the co-citation analysis of references is helpful to understand the knowledge structure and evolution process in the field of water lubrication. Figure 3 shows a visual network of the co-citation of references, which has 1,085 nodes and 2,417 links. Each node contains information about the first author, year of publication, and DOI. The larger the node, the more important the literature is. The importance of nodes does not show a large number of citations, but illustrates research topics closely related to water lubrication research. The links between nodes represent the co-citation relationship of literatures, and the closer they are, the higher the co-citation frequency is.

From the time distribution in the reference co-citation network, it can be seen that from 1997 to 2021, the research field and knowledge base of water lubrication have changed significantly, that is, from Black area (Chen M (2002)) above to Orange area (Liang S S (2016) and Wu H (2018)) below.

Through reference co-citation clustering analysis, the evolution of research topics in the field of water lubrication can be reflected, so as to reveal the potential knowledge structure in the field of water lubrication. Through the log likelihood ratio (LLR) test algorithm provided by CiteSpace, 9 clusters are extracted from the literature co-citation network, as shown in Fig. 4. The cluster module value ( $Q$ ) is 0.937, indicating that the cluster structure is significant. The average contour value ( $S$ ) of clustering is 0.9676, indicating that the clustering result is credible. As we mentioned above, the research topic of water lubrication has shifted in the past 20 years. It can be seen from the clustering map in Fig. 4 that the field of water lubrication has gradually developed from focusing on ceramics (Clusters #6, #7) to nanomaterials (Clusters #0, #4, and #5). On the one hand, the research topics in the field of water lubrication are closely related, intersected, and integrated with each other. On the other hand, the field of water lubrication has gradually gained attention and development, that is, related topics are gradually increasing. The main clustering information of the co-citation reference are shown in Table 1. As can be seen in Table 1, “graphene oxide” is the most obvious cluster, containing 60 papers, whose main

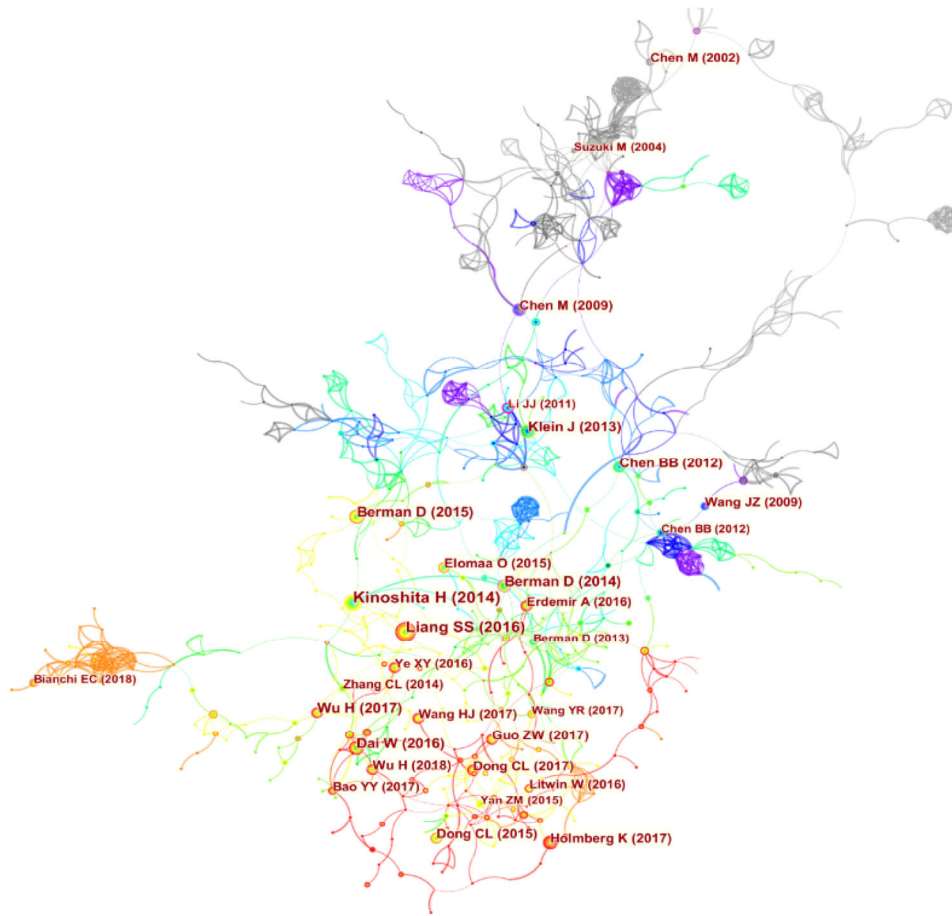


Fig. 3 Reference co-citation network in water lubrication.

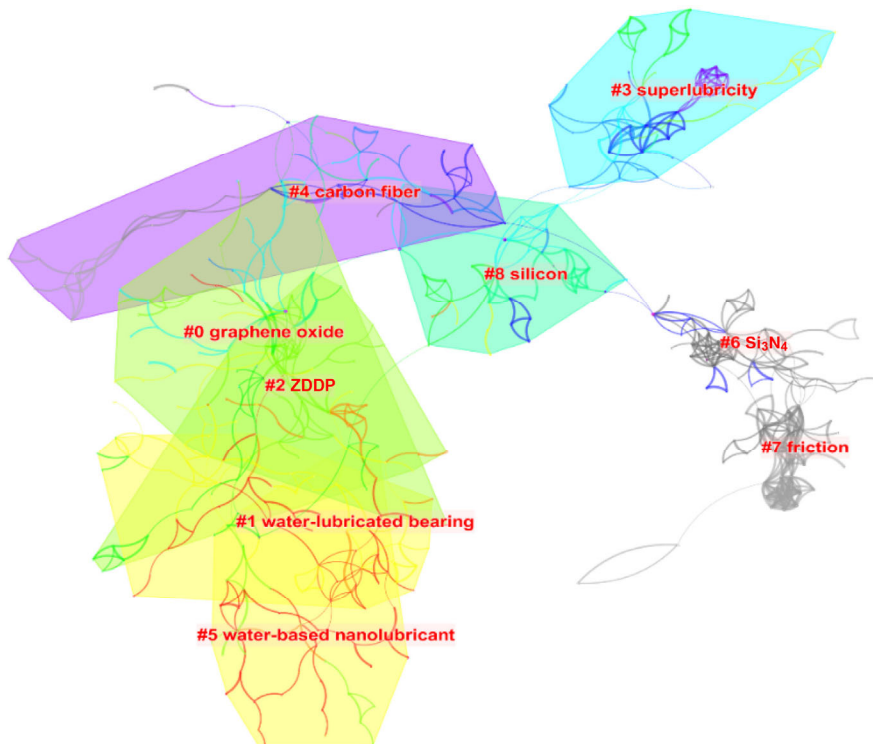


Fig. 4 Clustering map of co-citation network.

studies include graphene oxide, water-based lubricant additives, etc. The clusters related to nanomaterials are also Clusters #2, #4, and #5. It can be seen that nanocomposites and nanomaterials as water lubrication additives are the main research directions at present. Kinoshita et al. [18] improved the water lubrication performance of friction pairs by adding graphene oxide to water. Liang et al. [19] reduced the friction coefficient of self-mated GCr15 by 81.3% by adding surfactants and *in-situ* exfoliated graphene in water. The TiO<sub>2</sub> nanoparticles added by Wu et al. [20] in the water acted as a solid lubricant at the contact interface of the friction pair, which reduced the friction coefficient by 49.5%. Elomaa et al. [21] improved the water lubrication properties of diamond-like carbon (DLC) and stainless steel by adding graphene oxide to water. Ren et al. [22] promoted the superlubricity of the contact interface between Si<sub>3</sub>N<sub>4</sub> and sapphire by adding oxidized black phosphorus (oBP) nanosheets in water. Han et al. [23] achieved superlubricity on the ceramic surface after running-in in acid solution in water with alkali metal ions. Adding additives such as nanomaterials and acids to water to alleviate the problem of insufficient lubrication caused by low viscosity of water medium is an important method,

which we call “lubricating medium modification”. It can be found that in the field of water lubrication, “lubricating medium modification” is now the focus of attention [24–28]. Another focus of attention is superlubricity, as shown in Clusters #1 and #3, which is a technology that fundamentally solves the friction and wear problems of friction pairs. Different ways of superlubricity have been explored. On the other hand, as a low-viscosity lubricating medium, water has the potential to achieve superlubricity. Ceramics are also a hot research topic as the first material to achieve superlubricity conditions under water lubrication [29], from Cluster #6 to Cluster #8. It can be found that the application of nanomaterials in the field of water lubrication promotes the significant improvement of the water lubrication performance of friction pairs. Polymers and their nanocomposites [30–35] and polymer brushes [36] have also been widely used in water lubrication.

### 4.3 Keywords map

As a high generalization of the research hotspots of academic papers, keywords are the core and essence of papers, indicating the research hotspots in the subject field. Through the summary and analysis of

**Table 1** Details of cluster of co-citation references.

Cluster ID	Size	Silhouette	Label (LLR)	Representative reference
0	60	0.982	Graphene oxide; friction coefficient; water-soluble g-C <sub>3</sub> N <sub>4</sub> ; lubricant additives	Berman et al. [27]
1	57	0.961	Water-lubricated bearing; stern tube bearing; marine bearing; stick-slip phenomenon; bearing material; hydrophilic fibers; hydrodynamic lubrication; superlubricity; polyurethane	Dong et al. [33]
2	52	0.961	Graphene oxide; hybrid material; nanodiamond (ND); short carbon fiber; TiO <sub>2</sub> nanoparticles; molecular dynamics simulations; zinc dialkyl dithiophosphate (ZDDP)	Zhou and Qu [28]
3	49	0.927	Amorphous carbon film; transfer film; hydrogen content; wear mechanism; annealing treatment; hydrogen content; superlubricity	Klein [37]
4	47	0.932	Water lubrication; nanoparticle; transfer film; carbon fiber (CF); polyetheretherketone (PEEK) composite; fiber-reinforced PEEK	Chen et al. [30]
5	44	0.988	Water lubrication; lubricant additive; water-based nanolubricant; water-based nanolubricant	Wu et al. [20]
6	44	0.979	Water lubrication; surface polishing; superlow friction coefficient; Si film; carbon-based coatings; Si <sub>3</sub> N <sub>4</sub> ; SiC; graphite-like carbon film	Chen et al. [38]
7	38	0.974	Water lubrication; carbon nitride coatings; ion implantation; Si <sub>3</sub> N <sub>4</sub> balls; amorphous CN <sub>x</sub> coatings; friction	Zhou et al. [39]
8	37	0.896	Atomic force microscopy; water environment; organic residues; hydrodynamic effect; surface characterization; boundary lubrication; silane treatment; silicon	Matsuda et al. [40]

keywords in relevant publications, the theme of a field can be described [13, 41]. Table 2 lists the 30 keywords that appear most frequently in publications. Except the top six general academic terms (“wear”, “friction”, “behavior”, “water”, “lubrication”, and “performance”), the main concepts closely related to water lubrication are widely distributed. The “surface” of workpiece surface evolution, “film” of contact interface chemical film and water film change, “boundary lubrication” of contact interface behavior, and “temperature” of the material surface change caused by the change in temperature at the friction interface appear more frequently, which indicates that the wear evolution of the contact interface of materials under water lubrication conditions is a hotspot for researchers to focus on, which is conducive to revealing the research mechanism of water lubrication for its further development. Ways to improve the friction and wear behavior of frictional subsets under water lubrication is another major category of interest for researchers, such as self-lubricating materials “polymers” and “surface modification coatings”, ceramic materials “silicon nitride” and “ceramics”, and the application of nano-lubrication technology “composite”, “nanoparticle”, “nanocomposite”, and “carbon”. Studies related to the

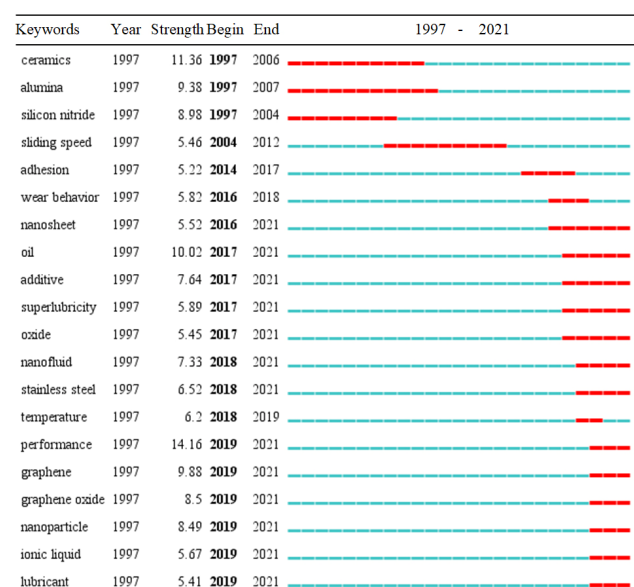
**Table 2** Top 30 keywords in water lubrication.

Keyword	Frequency	Keyword	Frequency
Wear	696	Mechanical property	88
Friction	616	Oil	84
Behavior	318	Tribological behavior	75
Water	303	Silicon nitride	73
Lubrication	277	Microstructure	69
Performance	242	Ceramics	68
Surface	164	Temperature	67
Tribological property	163	Nanoparticle	67
Film	134	Dry	59
Composite	118	Si <sub>3</sub> N <sub>4</sub>	54
Steel	116	Nanocomposite	53
Mechanism	115	Additive	52
Coating	103	Carbon	50
Contact	101	Boundary lubrication	47
Wear behavior	95	Polymer	45

mechanical properties of materials are also essential, such as “mechanical property” and “microstructure”. The “contact” of contact conditions has an important influence on the water lubricating performance, which has also attracted the attention of researchers.

Figure 5 shows the burst keywords in publications in the field of water lubrication, that is, the frequency of keywords has increased sharply over a period of time. Red segment on White baseline indicates a sudden increase in the frequency of the keyword, and the position of Red line segment indicates the time period of the burst. The burst keywords indicate that the relevant topics are the most active, or the publications grow the fastest in this time period, which is focused and studied by researchers. As a result, burst keywords are an important symbol to guide the further development of this field and point out the direction for the further development of this field. Keywords of articles in the dataset “water lubrication” (1997–2021) were analyzed for their burstiness. A total of 1,097 unique keywords were detected. The top 20 burst keywords with the most strength was extracted.

Based on the analysis of the burst keywords in Fig. 5, the research trends in water lubrication obviously presents three periods: 1997–2007, 2004–2012, and 2017–2021. “Ceramic” (with a strength score of 11.36) is the keyword with the strongest burst in the first period, which is an important direction in the field of



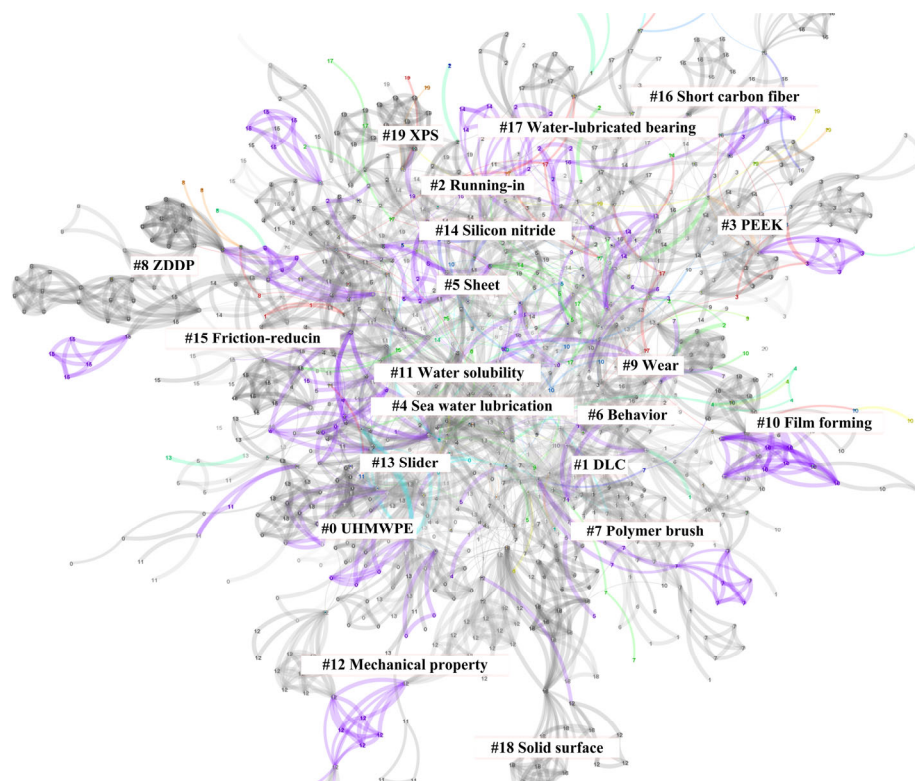
**Fig. 5** Burst keywords in water lubrication.



water lubrication. Ceramic materials have been widely studied for their ultra-low friction coefficient and excellent wear resistance under water lubrication, such as “alumina” of  $\text{Al}_2\text{O}_3$  and “silicon nitride” of  $\text{Si}_3\text{N}_4$ . In the second stage, on the one hand, due to the limitation of contact conditions (sliding speed and load), the water lubrication performance of ceramic materials shows different trends, which has attracted the attention of the majority of researchers. On the other hand, the influence of contact conditions on the friction properties of contact interface has always been a key point that cannot be ignored. In the third period, the development of micro-nano technology is widely used in the field of water lubrication. The first is that the development of observation and interference based on the molecular and atomic has led to a surge in “superlubricity” research. The purpose of superlubricity performance research is to solve the problem of contact interface friction and wear caused by insufficient lubrication caused by low water viscosity under water lubrication. Secondly, with the development of micro-nano manufacturing, the application of nanoparticles with unique properties in the field of water lubrication has surged. Composites

with nanoparticles are widely studied, and the modification of water medium by nanomaterials is also the focus of research, such as “graphene”, “graphene oxide”, and “nanoparticle”. Nano-lubrication technology has broad application prospects.

Keyword clustering can exhibit the hotspots in different research directions in this field. Clusters of co-occurrence of keywords are obtained by CiteSpace with the LLR test algorithm, which are firmly attached internally, but weakly attached between them. The research contents, research directions, and research trends in specific fields can be found from the results of clusters. Figure 6 is the keyword clustering map, in which there are 1,097 nodes and 6,250 connections, and the topological network density is 0.0058. The number of links between nodes is greater than the number of their own, which indicates that the keywords in this field are closely related, that is, different research directions and research contents have different degrees of intersection and integration. The mean silhouette is usually used for evaluating the clusters. The results showed that the modularity  $Q = 0.8108$ , which indicated that the clustering effect was very significant. The mean silhouette = 0.9191,



**Fig. 6** Cluster analysis view. Cluster are labeled in black text.



which indicated that the clustering results are highly reliable. Eventually, we obtained 20 clusters. The cluster size is inversely proportional to the cluster number, and the node size is directly proportional to the frequency of citations. The relevant research broadly covered polymer (e.g., #0 ultra-high molecular weight polyethylene (UHMWPE) and #3 PEEK), material superlubricity research (e.g., #1 DLC, #7 polymer brush, and #14 silicon nitride), and nano-lubrication technology (e.g., #5 sheet and #16 short carbon fiber). It can be seen that improving the water lubrication performance of friction pairs by improving contact materials is still the focus of research. The formation of water film and the improvement of water film carrying capacity are promoted by improving surface wettability and preparing surface texture (e.g., #10 film forming and #18 solid surface), so as to improve the insufficient lubrication caused by boundary lubrication and mixed lubrication under water lubrication. These indicate that the researchers have made various efforts to improve the water lubrication performance of the friction pair. The evolution of

contact interface of friction pair under water lubrication is also the focus of research, such as the change of chemical film produced by chemical reaction at friction interface and water film at contact interface (e.g., #10 film forming and #19 X-ray photoelectron spectroscopy (XPS)). The modification of water by the dissolution of wear products at the friction interface and additives such as nanomaterials under water lubrication is also a problem worthy of attention (e.g., #11 water solubility). The contact condition of the friction pair has an important influence on the water lubrication performance. For example, at high speeds, hydrodynamic lubrication of the contact interface can be caused to reduce the friction coefficient. Therefore, the influence of the contact condition has been extensively studied (e.g., #2 running-in and #13 slider).

The next analysis performed was to observe the clusters on a timeline, as shown in Fig. 7. The timeline is arranged by its size from the largest downwards. The legend of the keyword time is shown on top of the view. The colored curves represent co-citation links added in the year of the corresponding color.

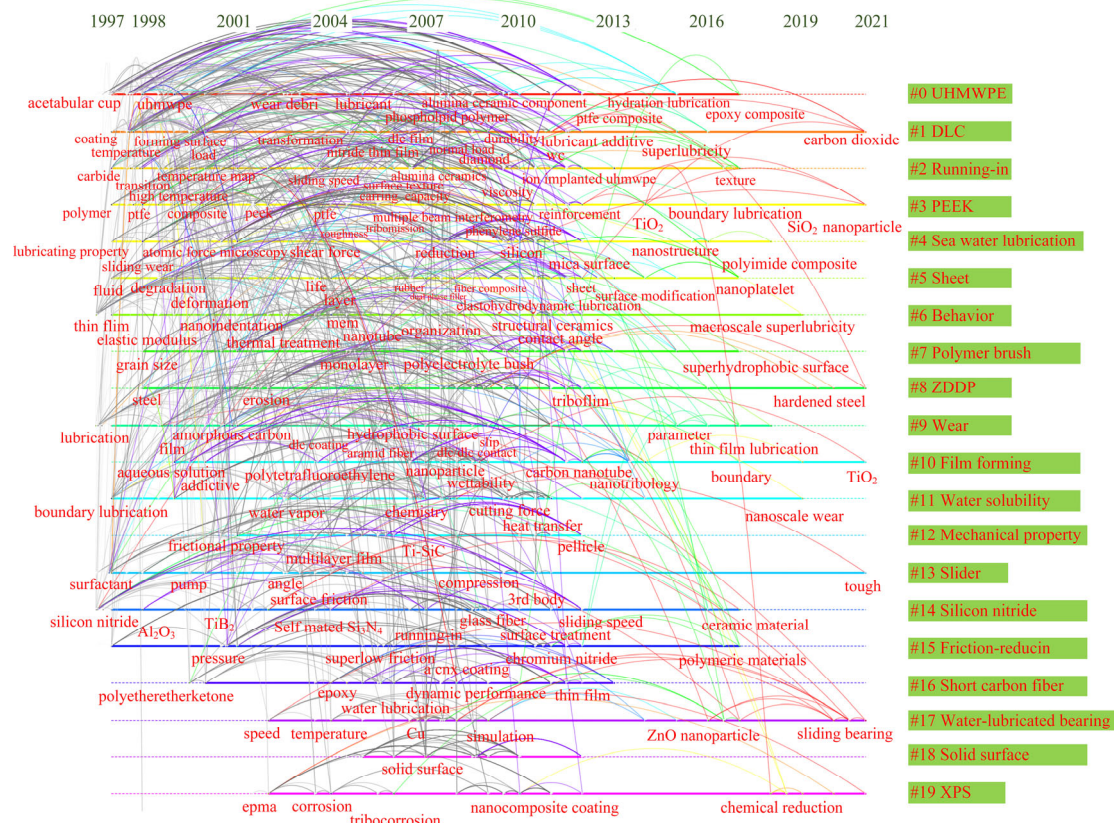


Fig. 7 Timeline view for keywords of water lubrication: 1997–2021.

The solid line on the dashed line represents the duration of research on this topic, which helps to analyze the evolution and research hotspots in the field of water lubrication. The key words between different clusters are closely connected, which indicates that the research topics of water lubrication are more concentrated. It is worth noting that polymer materials (e.g., #3 PEEK) with corrosion resistance and self-lubricating properties are still widely used and studied today. The evolution law of the corresponding contact interface in the wear process has been continuously studied in depth. DLC coating is an important way to achieving superlubricity under water lubrication condition. Its high hardness and ultra-low friction still have broad prospects under water lubrication. In fact, the selection, preparation, and optimization of friction pair materials are still the focus of researchers in the field of water lubrication. Media modification has gradually attracted the attention of researchers (e.g., #5 sheet and #8 ZDDP). Promoting the formation of a water film at the contact interface of the friction pair and improving the bearing capacity of the water film can be directly used to improve boundary lubrication or mixed lubrication under water lubrication, which has always been the focus of researchers (e.g., #10 film forming). Researchers have also made different attempts, such as changing the wettability of the surface, preparing the surface texture, etc. The influence of contact conditions on the friction pair has been concerned (e.g., #13 slider).

Through keyword clustering and bust detection, this article will review the development and evolution of the water lubrication field through three aspects, namely material preparation (e.g., #0 UHMWPE, #1 DLC, #3 PEEK, #5 sheet, #7 polymer brush, #14 silicon nitride, #16 short carbon fiber, and coating), surface optimization (e.g., #10 film forming and #18 solid surface), and lubricating medium modification (e.g., #8 ZDDP and #11 water solubility). Other related contents are also included here.

#### 4.3.1 Material preparation

##### 4.3.1.1 Superlubricity materials

Superlubricity technology is an important means to solving the problem of water-lubricated friction and wear. Superlubricity refers to the wear state, in which the friction coefficient between contact interfaces is

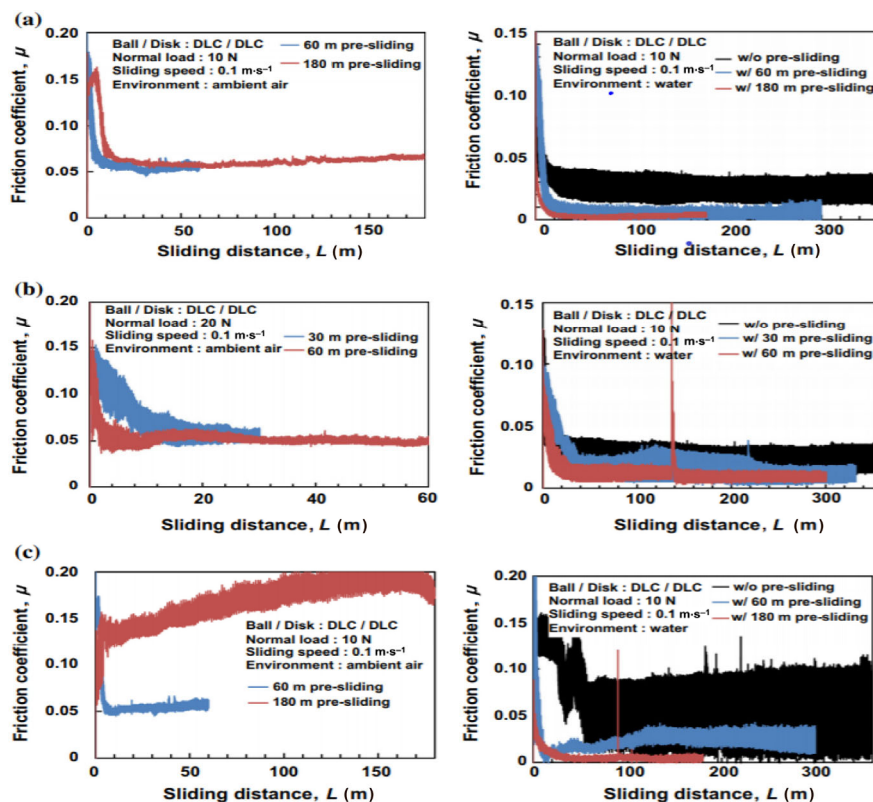
close to zero. It was first proposed by Hirano and Shinjo [42]. Therefore, theoretically, superlubricity can achieve near zero friction and near zero wear. Superlubricity by preparing different contact pair materials has been widely studied.

##### 1) DLC (Cluster #1)

Hirano and Shinjo [42] first proposed the concept of solid superlubricity in the early 1990s. According to the Frenkel–Kontorova–Tomlinson model, they theoretically predicted that when the two crystal planes slide relatively in an incommensurate state, the friction will disappear completely. Erdemir [43] found for the first time that the DLC films can achieve superlubricity under dry and inert conditions due to the high hardness and the saturation of surface hydrogen suspension bonds. Based on the high hardness and low friction coefficients of DLC film, the majority of researchers have studied the friction and wear properties of DLC film under water lubrication conditions. Niiyama et al. [44] realized the superlubricity state of the DLC coating in the water environment by pre-sliding in the air, as shown in Fig. 8. The results show that this is related to the enhancement of the hydrophilicity of the DLC surface. The pre-slip in the air leads to the intensification of the chemical reaction between the DLC surface and water in the water environment, as shown in Fig. 9. The rapid generation of OH groups and CO groups enhances the adsorption of water on the DLC surface. Zhang et al. [45] studied the tribochemical changes of the DLC film contact interface in an aqueous environment. In vacuum, the graphitization is induced by the removal of terminal –H atoms during friction. The results show that the dissociation adsorption of water on the surface of DLC produces terminals –H and –OH, which finally inhibits the graphitization of DLC and further reduces the wear of the DLC. On the one hand, although DLC has a low friction coefficient under water lubrication, it is still difficult to achieve superlubricity under water as a solid superlubricity material. On the other hand, despite the high hardness of DLC, its wear resistance needs to be further improved due to its graphitization and delamination under water. In response to these problems, researchers have conducted extensive research by changing the material structure, matching materials, and contact conditions. Wang et al. [46] improved the friction and wear properties of DLC

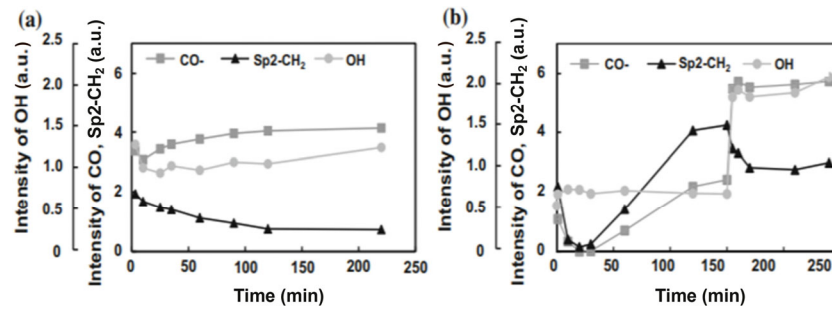
under water lubrication by adding Ti. The results show that Ti exists in the C–C bond of Ti–DLC coating through displacement or solid solution to promote the formation of Ti–C bond, which deforms the carbon network in the DLC coating. Ti–C bond improves the hardness and bearing capacity of the coating by limiting the grain boundary spacing and hindering the grain boundary sliding, which has a positive effect on reducing the friction coefficient and wear rate of Ti–DLC coating. Ohana et al. [47] compared the friction and wear properties of Si–DLC and DLC under water lubrication conditions. Observed by the transmission electron microscope, it is found that the Si–DLC wear surface has a double-layer lubricating film structure, which is the main reason why it is more wear-resistant than DLC film, as shown in Fig. 10. The results show that analyzing the structure of DLC surface lubricating film plays an important role in analyzing its friction behavior in water environment, optimizing the composition of DLC, and reducing its friction coefficient. Yamamoto and Matsukado [48] studied the tribological properties of hydrogenated DLC coatings with different hardness

and different metals (stainless steel and brass) and UHMWPE under water lubrication. The results show that the wear behavior of the friction pair is related to the hardness of DLC and the carbon-rich thin layer produced by the contact surface. Tokoro et al. [49] improved the hydrophilicity of DLC surface by diamond polishing, thereby improving the wear resistance of DLC under water lubrication conditions. Uchidate et al. [50] found that the higher the water temperature under water lubrication, the worse the wear resistance of DLC. Zhang et al. [51] studied the friction and wear behavior of DLC and  $\text{Al}_2\text{O}_3$  in water environment by a ball–disk tribometer. The results show that hydrogen in hydrogenated DLC films in aqueous environment terminates the chemical reaction between the carbon dangling bonds on the DLC surface and water, hinders the generation of oxygen-containing groups, and reduces its hydrogen bond with water molecules, so as to reduce the shear force at the contact interface and finally reduce the friction coefficient. Ohana et al. [52] found that the greater the surface roughness of DLC, the lower the friction coefficient of DLC and stainless steel friction pairs.

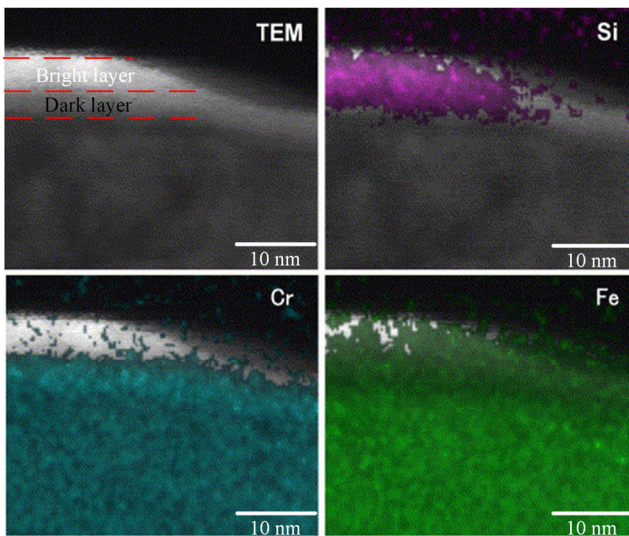


**Fig. 8** Variations of friction coefficients of pre-sliding process and tribotest in water. Reproduced with permission from Ref. [44], © Springer Science+Business Media New York 2017.





**Fig. 9** IR spectra: (a) without pre-sliding process; (b) with pre-sliding process. Reproduced with permission from Ref. [53], © Springer Science+Business Media New York 2017.



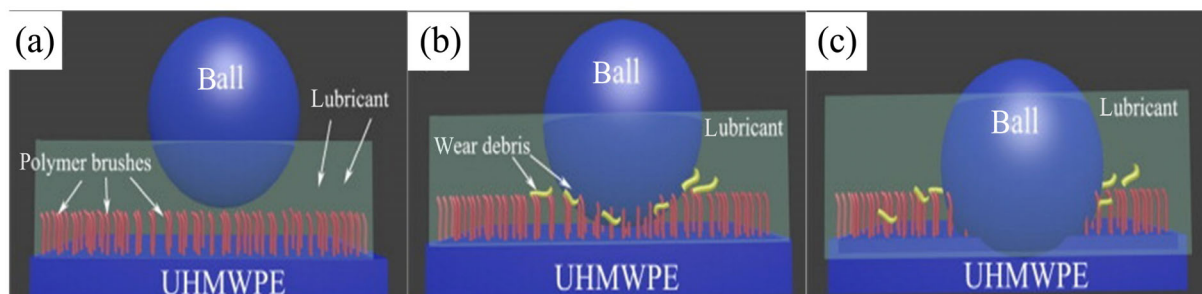
**Fig. 10** Transmission electron microscope micrograph of lubrication film of mating ball against Si-DLC film and the element distributions of Si, Cr and Fe. Reproduced with permission from Ref. [47], © Elsevier B.V. 2005.

Exploring the forming process and optimizing the material structure of DLC film is an important way to improving its wear resistance under water lubrication, which is being widely studied [53]. However, as a protective film, the bonding strength between DLC

and the substrate in water is an important issue, which should be emphatically considered in order to improve its application value. The mating material has an important influence on the water lubrication performance of DLC, which needs more in-depth research. It is still a great challenge to explore the mechanism of superlubricity under appropriate contact conditions. This is still a direction worth paying attention to.

## 2) Polymer brush (Cluster #7)

By preparing polymer molecular brushes on the contact surface, the superlubricity friction coefficient of 0.001 can be achieved, which is due to the high osmotic pressure between polymer molecules and the separation of the contact surface under the action of electric double-layer repulsive force and dispersive force. In 2016, Røn et al. [54] reported a new grafting method to obtain hydrophilic polydimethylsiloxane (PDMS) molecular brush on PDMS. The method is based on the selective separation of hydrophilic polymer chains of amphiphilic block copolymers from the PDMS matrix membranes. Through this method, the hydrophilic polymer brush obtained by the material's excellent grafting stability and recovery ability (even in a harsh friction environment) can



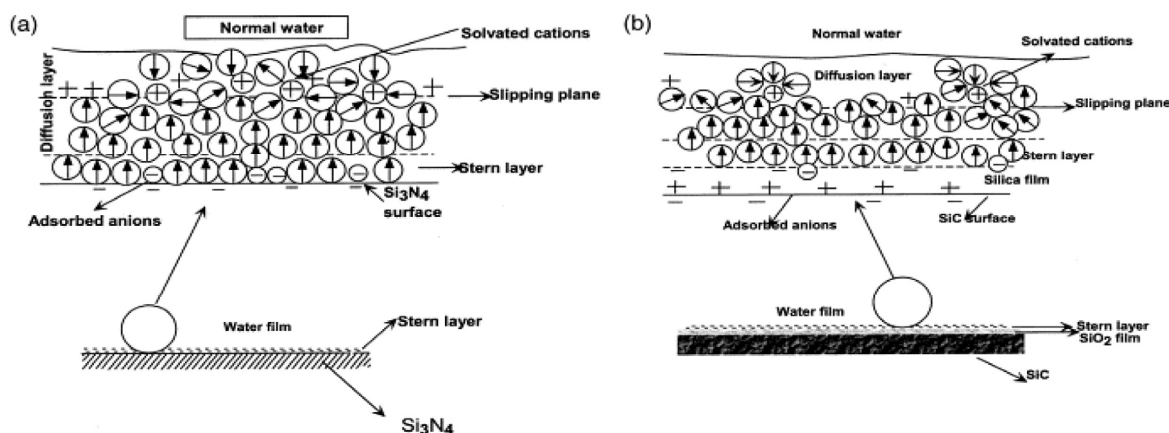
**Fig. 11** Schematic of lubrication mechanism: (a) before the test; (b) during the test; and (c) after the test. Reproduced with permission from Ref. [55], © Elsevier B.V. 2014.

obtain a minimum friction coefficient of 0.001 on the ceramic substrate. Xiong et al. [55] self-polymerized to form the brush-like structure on the surface of UHMWPE after grafting 2-methacryloyl phospholcholine (MPC). The results show that the hydrophilic polymer brush will adsorb water molecules and form a hydration layer at the contact interface to separate the contact pairs, so as to reduce the friction coefficient by 37%, as shown in Fig. 11. Deng et al. [56] grafted MPDSA polymer molecular chains on the surface of UHMWPE to improve its water lubrication properties. The MPDSA polymer chain absorbs water molecules under water lubrication conditions to form a polymer brush, which can separate friction pairs and provide lubrication. Chen et al. [36] achieved superlubricity (friction coefficient of 0.00043) by preparing brushes of the polymer poly(2-(methacryloyloxy) ethyl phosphorylcholine) (pMPC) under water-lubricated conditions with a contact stress of 7.5 MPa. The superlubricity mechanism is mainly attributed to the hydration layer with lubricating film formed by the highly hydrated phosphorylcholine (PC) group on pMPCs and water molecules.

It is still difficult to achieve superlubricity by polymer brushes in water, which has specific requirements for contact materials and contact conditions. At the same time, polymer or molecular brushes have poor bearing capacity, so it is not suitable for high-load conditions. Therefore, the preparation process and material selection of polymer brush need to be further studied. The theoretical model and mechanism of polymer brush water lubrication still need to be further studied to promote its long-term application.

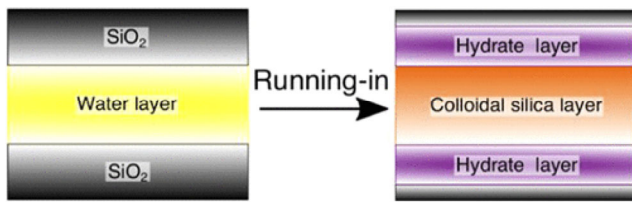
### 3) Ceramics (Clusters #2 and #14)

Chen et al. [38] found that the electric double layer produced by self-mated  $\text{Si}_3\text{N}_4$  and SiC interface emitting electrons under water lubrication conditions promotes hydrodynamic lubrication. Different chemical reactions of  $\text{Si}_3\text{N}_4$  and SiC under water lubrication (whether the reaction product  $\text{SiO}_2$  is soluble in water or not) lead to different structures of electric double layers, which leads to different bearing capacities of electric double layers, as shown in Fig. 12. Ootani et al. [57] explored the superlubricity mechanism of silicon-based ceramics under water lubrication conditions through experiments and molecular dynamics simulations. The double-layer lubricating film formed on the ceramic surface under water lubrication conditions is the outer colloidal silica friction layer, which is produced by dissolving the wear debris generated by the hydrolysis of the  $\text{SiO}_2$  surface in water and the inner hydrophilic hydrate layer, which is formed by the reaction of water molecules penetrating into the wear surface, resulting in an ultra-low friction coefficient at the friction interface, as shown in Fig. 13. Matsuda et al. [40] found that the silica gel formed on the SiC surface in the water environment is the main factor, leading to the super sliding state of the friction interface. The low wear rates of ceramic friction pairs are affected by the Na, Cl, Mg, and K elements in the seawater. Existing studies have shown that under the condition of water lubrication, the surface of self-made ceramics will undergo tribochemical reaction to form a negatively charged silicon sol layer. The lubrication of the electric



**Fig. 12** Schematic diagram of friction mechanism of (a)  $\text{Si}_3\text{N}_4$  tribopairs and (b) SiC tribopairs in water. Reproduced with permission from Ref. [38], © Elsevier Science Ltd. 2002.

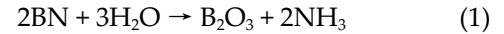




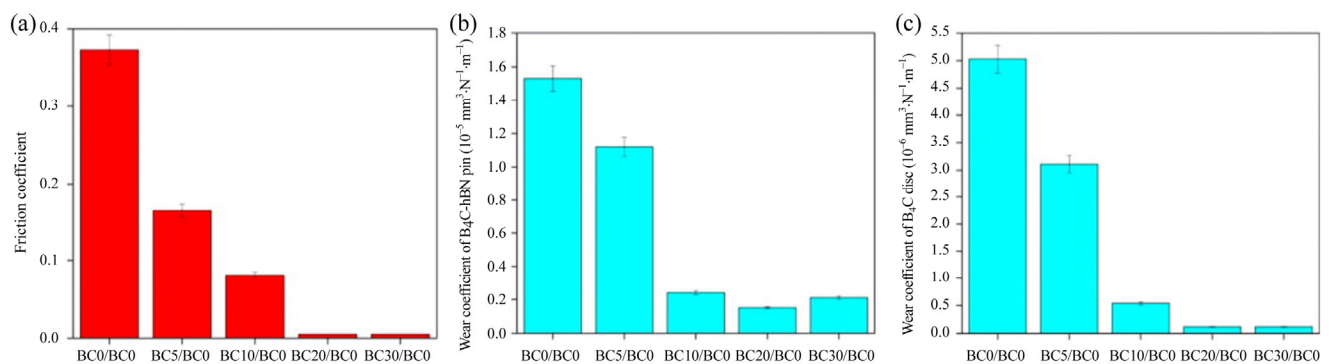
**Fig. 13** Surface evolution model of friction pair. Reproduced with permission from Ref. [57], © American Chemical Society 2020.

double layer formed by its further combination with hydrogen ions in water is an important reason to promote the ceramics to reach the superlubricity state under water lubrication [58, 59]. On the other hand, when silica sols are in contact with each other, their shear strength is very low, resulting in a small friction coefficient of boundary lubrication. In fact, the superlubricity of ceramics under water lubrication is closely related to load and sliding speed. It is difficult to achieve superlubricity under high load and low speed. At the same time, it takes a period of running-in time for self-matching ceramics to appear ultra-low lubrication. Researchers have made various efforts to solve these problems. Ootani et al. [60] revealed the molecular motion and tribochemical experience of the contact interface of  $\text{Si}_3\text{N}_4$  and  $\text{SiC}$  when achieving ultra-low friction coefficients, which is conducive to the selection of friction pairs and contact conditions, so as to reduce the running-in time and friction coefficient. Li et al. [61] realized the ultra-low friction coefficient under water lubrication by adding hexagonal boron nitride (hBN) to the  $\text{B}_4\text{C}$ -based ceramic composite material, which resulted in a significant decrease of the friction coefficient to 0.005 for  $\text{B}_4\text{C}$  20 wt% hBN/ $\text{B}_4\text{C}$  sliding pair, as shown

in Fig. 14.  $\text{B}_2\text{O}_3$  film is produced by tribochemical reaction between hBN and water molecules at  $\text{B}_4\text{C}$ -hBN friction interface according to Reaction (1), which, on the one hand, protects the wearing surfaces from further wear, and on the other hand, facilitates the wearing surfaces to smooth so that the sliding pair may enter a state of fluid lubrication.

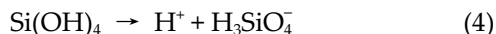


Chen et al. [62] studied the friction and wear behavior of  $\text{Si}_3\text{N}_4$ -hBN through pin-on-disk test. The results show that the lubrication of  $\text{SiO}_2$  and  $\text{B}_2\text{O}_3$  lubricating films produced by tribochemistry at the friction interface leads to the friction coefficient of lower than 0.001. On the other hand,  $\text{SiO}_2$  and  $\text{B}_2\text{O}_3$  can spontaneously react with water molecules to form water-soluble hydrolysis products, which increase the viscosity of water and form dynamic pressure lubrication at the contact interface. Liu et al. [63] studied the friction and wear behavior of  $\text{Si}_3\text{N}_4$  and 316 stainless steel under seawater lubrication. Under the action of the high flash temperatures of the friction interface, the silicon nitride ceramics tribochemically react with water to form  $\text{SiO}_2$  colloidal particles. In seawater, colloidal particles easily aggregate to form a silica gel layer attached to the sliding surface of silicon nitride, which greatly reduces the friction coefficient. Chen et al. [64] improved the friction and wear properties of  $\text{Si}_3\text{N}_4$  and Ti6Al4V under water lubrication by adding hBN to  $\text{Si}_3\text{N}_4$ . Wu et al. [65] studied the friction and wear behavior of WC-10Co-4Cr and  $\text{Si}_3\text{N}_4$  through face-to-face contact. The shear mode produced by the tribochemical reaction



**Fig. 14** Variations of friction coefficients and wear coefficients of  $\text{B}_4\text{C}$ -hBN/ $\text{B}_4\text{C}$  sliding pairs in water. Reproduced with permission from Ref. [61], © Elsevier Ltd and Techna Group S.r.l. 2015.

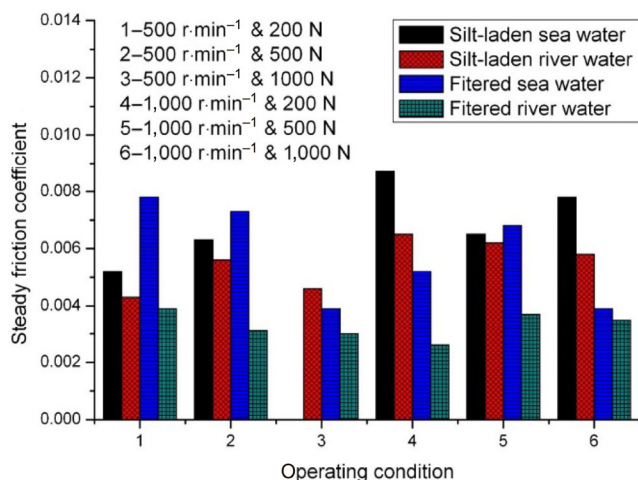
between  $\text{Si}_3\text{N}_4$  and water leads to the superlubricity state of the friction interface, as shown in Fig. 15. The related experiments show that the tribochemical reactions between the ceramic surface and water molecules under water lubrication conditions are as Reactions (2)–(4):



Ceramics still have great potential for application as water-lubricated materials. The friction mechanism of ceramics under water lubrication still needs to be explored in depth in order to reduce the running-in time and promote the realization of superlubricity. The friction and wear properties of ceramics differ significantly for different wear materials, and optimising the ceramic pairing and exploring its mechanism of action is a key point for its application.

#### 4.3.1.2 Self-lubricating materials

Due to their excellent self-lubricating and chemical stability, high-performance polymers and their composites are an important means to solving the problems of friction and wear caused by insufficient water lubrication at the contact interface and corrosion in water environment. It has been widely and deeply studied for many years. Table 3 lists the friction



**Fig. 15** Variations of friction coefficients under different natural waters. Reproduced with permission from Ref. [65], © Elsevier Ltd. 2015.

coefficients of specific materials in Section 4.3.1.2 under water lubrication and different contact conditions.

#### 1) UHMWPE (Cluster #0)

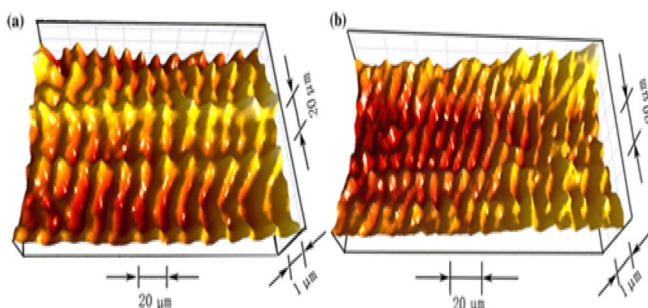
Xiong and Ge [66] found that under water lubrication, the water absorption and swelling of UHMWPE led to the reduction of surface strength, thus reducing friction and wear. Wang et al. [67] found that the wettability of GCr15 and Ni–P coatings to seawater is higher than those of other aqueous solutions, which enhances the lubrication of seawater with UHMWPE and reduces friction and wear. The research results show that the surface of the UHMWPE will form periodic ripple patterns due to the large plowing effect of asperities on the mating material surface, as shown in Fig. 16. Liu et al. [68] improved its wear resistance by adding UHMWPE to glass fabric/phenolic laminate composites. The results show that UHMWPE absorbs and dissipates wear energy through plastic deformation, which forms regular ripple-like abrasion patterns on the surface, to effectively reduce friction and wear, as shown in Fig. 17. Wang et al. [69] improved the water lubrication performance of UHMWPE by filling glass fiber (GF)/carbon fiber (CF). The research results show that the supporting effect of the filled fibers on the matrix reduces the contact stress and contact area, thereby reducing friction and wear. Baena and Peng [70] studied the effect of temperature on the friction properties of UHMWPE under water lubrication. Pang et al. [71] improved the wear resistance of UHMWPE by adding graphene oxide. The results show that graphene oxide can improve the crystallinity of UHMWPE, which reduces the water absorption of UHMWPE and improves the mechanical strength of UHMWPE, and improve the hydrophilicity of UHMWPE, which can promote the formation of water film at the contact interface. Dong et al. [32] found the friction and wear behavior of UHMWPE, synthetic rubber (SR), and fiber resin composite (FRC) under water lubrication conditions. Vadivel et al. [72] improved the friction and wear properties of UHMWPE under water lubrication by filling graphene oxide (GO), ND, and short carbon fibers (SCF). The research results show that GO can be used as a lubricating medium to improve the lubrication performance, ND can increase the hardness, SCF can improve the strength of the matrix, and the

**Table 3** Contact conditions and friction coefficients under dry conditions.

Reference	Material	Contact type	Motion	Load (N)	Speed (or frequency)	Friction coefficient (minimum)
Xiong and Ge [66]	UHMWPE/Al <sub>2</sub> O <sub>3</sub>	Point	Sliding	38	20 mm·s <sup>-1</sup>	0.04 (water)
Wang et al. [67]	UHMWPE/GCr15, Ni-P	Line	Sliding	100	0.5 m·s <sup>-1</sup>	0.031 (Ni-P water) 0.018 (Ni-P seawater)
Liu et al. [68]	Glass fabric-phenolic laminate-UHMWPE/316 stainless steel	Line	Sliding	200	0.5 m·s <sup>-1</sup>	0.02 (5 wt% UHMWPE)
Wang et al. [69]	UHMWPE-GF, CF/GCr15	Point	Sliding	28–141	0.2–1.0 m·s <sup>-1</sup>	0.05 ( <i>Ra</i> = 0.1 μm water) 0.1 ( <i>Ra</i> = 0.3 μm water)
Baena and Peng [70]	UHMWPE/316 stainless steel	Point	Sliding	6.5	60 mm·s <sup>-1</sup>	0.15 (30 °C water) 0.17 (40 °C water) 0.18 (50 °C water)
Pang et al. [71]	UHMWPE-GO/GCr15	Line	Sliding	100	0.5 m·s <sup>-1</sup>	0.08 (1% GO seawater) 0.07 (1% GO deionized water)
Dong et al. [32]	UHMWPE, SR, FRC/ZCuSn <sub>10</sub> Zn <sub>2</sub>	Point	Sliding	77	1.26/12.56/ 75.36/150.72/ 226.08/301.44/ 376 mm·s <sup>-1</sup>	0.075 (UHMWPE 376 mm·s <sup>-1</sup> water)
Vadivel et al. [72]	UHMWPE-GO, ND, SCF/Al <sub>2</sub> O <sub>3</sub>	Point	Sliding	251	0.13 m·s <sup>-1</sup>	0.103 (1% GO water) 0.104 (1% ND water) 0.096 (GO+ND+SCF water)
Bin Ali et al. [73]	UHMWPE-CNT, C15A/440C	Point	Sliding	30	0.13 m·s <sup>-1</sup>	0.087 (1.5 wt% C15A water)
Chang et al. [74]	UHMWPE/ZCuSn <sub>10</sub> Zn <sub>2</sub>	Point	Sliding	56	0.55 m·s <sup>-1</sup>	0.25–0.35 (aged 240 h water) 0.17–0.28 (aged 720 h water)
Wang et al. [75]	UHMWPE-PAAm-GO/QSn4-3	Point	Sliding	5/10/30/50	60 mm·s <sup>-1</sup>	0.08 (P-GO 0.5% 18.7 MPa water) 0.057 (P-GO 0.5% 23.5 MPa water) 0.043 (P-GO 0.5% 33.9 MPa water) 0.048 (P-GO 0.5% 40.2 MPa water)
Yamanmoto and Takashima [76]	PEEK, polyphenylene-sulphide (PPS)/steel	Surface	Sliding	100	1–5 m·s <sup>-1</sup>	0.09 (PPS)
Sumer et al. [77]	PEEK-GFR/AISI D2	Point	Sliding	50/100/150	0.8/1.6 m·s <sup>-1</sup>	0.125 (30 wt% GFR)
Zhong et al. [78]	PEEK-SCFs, ZrO <sub>2</sub> /4Cr13	Point	Sliding	18–145	2 m·s <sup>-1</sup>	0.04 (PEEK/10CF/20ZrO <sub>2</sub> 8 MPa water) 0.05 (PEEK/20CF/10ZrO <sub>2</sub> 8 MPa water)
Chen et al. [79]	PEEK-CF, polyimide (PI)/316 stainless steel	Point	Sliding	100/400	0.5/1 m·s <sup>-1</sup>	0.022 (PTFE-5% PI-15% CF seawater)
Guan and Wang [80]	PEEK, PI, PTFEF/Cr, CrN, GLC	Line	Sliding	80–160	0.2–0.6 m·s <sup>-1</sup>	0.075 (PEEK 120 N) 0.15 (PEEK 120 N) 0.04 (PEEK 120 N)
Song et al. [81]	PEEK-GO/stainless steel	Point	Sliding	2.94	0.0628 m·s <sup>-1</sup>	0.357 (2 N water)
Gao et al. [82]	PEEK-FeOOH/SUS 316	Line	Sliding	50–400	0.2 m·s <sup>-1</sup>	0.9 (PEEK-20 vol% α-FeOOH water)
Liu et al. [83]	PEEK-CF, GF/316 stainless steel	Surface	Sliding	326	0.5 m·s <sup>-1</sup>	—
Gao et al. [84]	PEEK-Cu/SUS 316	Line	Sliding	100/400	0.2 m·s <sup>-1</sup>	0.18 (PEEK-3 wt% Cu 100 N water) 0.09 (C-PEEK-3 wt% Cu 100N water)
Zhao et al. [85]	Polyvinyl alcohol (PVA)/AA-g-PEEK/stainless steel	Point	Sliding	2–10	2.5–25 mm·s <sup>-1</sup>	0.021 (75 μm sands in water)

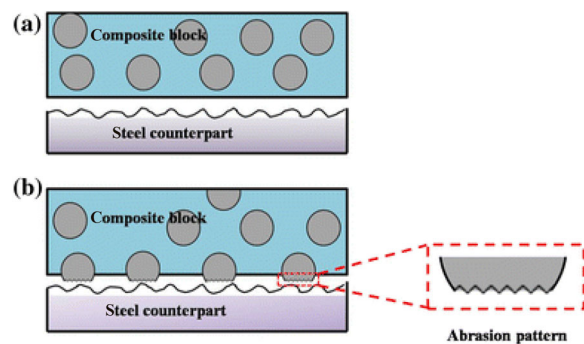
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Reference	Material	Contact type	Motion	Load (N)	Speed (or frequency)	Friction coefficient (minimum)
Shen et al. [86]	PTFE–SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	Point	Sliding	60	2 cm·s <sup>-1</sup>	0.068 (water)
Lu et al. [87]	Polytrifluorochloroethylene (PCTFE)/Cu–C	Point	Sliding	5	24 mm·s <sup>-1</sup>	0.436 (water)
Li et al. [88]	CFRPEEK/AISI-431	Surface	Sliding	200/400/600	0.68/1.36 m·s <sup>-1</sup>	0.09 (1.83 MPa, 11.36 ms <sup>-1</sup> , 1–5 °C)
Yan et al. [89]	EP–aligned carbon nanotube (ACNT)/stainless steel	Point	Sliding	9–47	0.47/0.69 m·s <sup>-1</sup>	0.04 (1.2 MPa water)
Gao et al. [90]	EP-composites (Coms)/SUS 316	Line	Sliding	100	0.1–3.0 m·s <sup>-1</sup>	0.04 (EP/SCF/Gr/Si water)
Nie et al. [91]	PI–MWCNT–COOH/316 stainless steel	Point	Sliding	1–5	0.05–0.26 m·s <sup>-1</sup>	0.18 (0.7 wt% MWCNT–COOH seawater)
Qi et al. [92]	PI–SCF, AP, PTFE/QSn6.5–0.4Cu	Point	Sliding	16/48/96	0.5/1 m·s <sup>-1</sup>	0.05 (PI/SCF/PTFE seawater)
Jiang et al. [93]	PU–Coms/QSn4–3	Point	Sliding	181	250 r·min <sup>-1</sup>	0.06 (3 wt% LG)
Wu et al. [94]	PU–polyethylene wax (PEW)/tin bronze	Surface	Sliding	136/226/317/407	50 r·min <sup>-1</sup>	0.24 (0.7 MPa 10 wt% PEW)
Yu et al. [95]	PU–EP–SCF, SiC/SUS 304	Line	Sliding	100/200	0.05–1.8 m·s <sup>-1</sup>	0.125 (5 wt% SCF 25 wt% SiC, deionized water)
Dong et al. [96]	Nitrile butadiene rubber (NBR)–MoS <sub>2</sub> /ZCuSn <sub>10</sub> Zn <sub>2</sub>	Surface	Sliding	2–10	0–3.3 m·s <sup>-1</sup>	0.05 (flaky MoS <sub>2</sub> )
Yuan et al. [97]	NBR/ZCuSn <sub>10</sub> Zn <sub>2</sub>	Line	Sliding	100	0.11–1.1 m·s <sup>-1</sup>	0.08 (75 μm sand in water, 0.7 MPa, 0.11 m·s <sup>-1</sup> )



**Fig. 16** Three-dimensional (3D) profiles of the worn surfaces of UHMWPE: (a) under 3.5 wt% NaCl solution lubrication; (b) under seawater lubrication. Reproduced with permission from Ref. [67], © Springer Science+Business Media, LLC 2009.

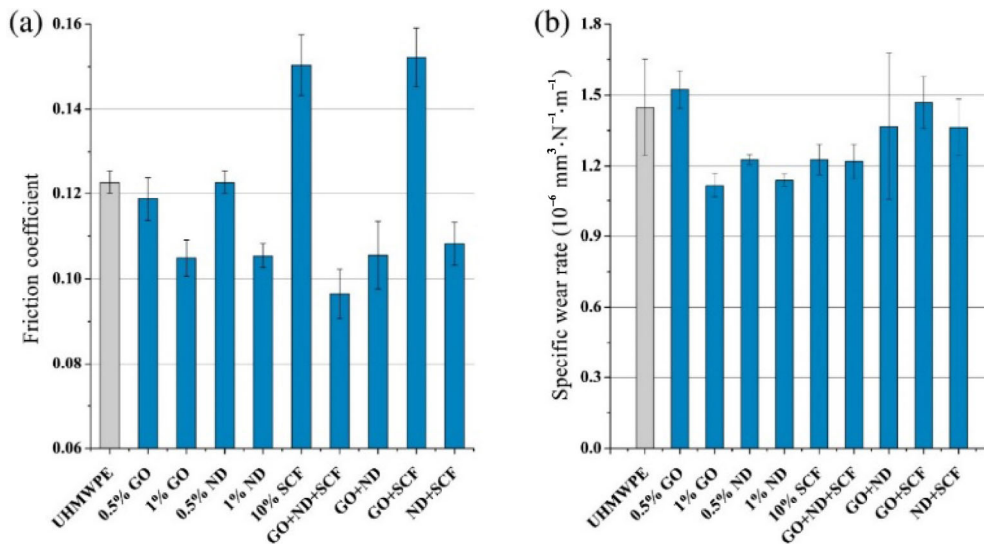
synergy of the three kinds of nano and microparticles can further reduce friction and wear, as shown in Fig. 18. Bin Ali et al. [73] studied the friction and wear properties of nanoclay (C15A) and carbon nanotube (CNT)-reinforced UHMWPE in an aqueous environment. The research results show that C15A can hinder the water absorption and softening of the polymer surface, and CNTs can improve the bearing capacity of the matrix. The synergistic effect of the



**Fig. 17** Schematic diagram of contact interface wear mechanism: (a) static; (b) dynamic (Gray balls represent the UHMWPE microparticles). Reproduced with permission from Ref. [68], © Springer Science+Business Media New York 2014.

two kinds of nanoparticles can avoid the rupture of polymer molecular chains, thereby reducing friction and wear. Chang et al. [74] studied the effect of aging time on the friction performance of UHMWPE under water lubrication. The aging of UHMWPE aggravates the chemical oxidation of the surface and promotes the transformation of the surface wear mechanism. Wang et al. [75] improved the bearing capacity and





**Fig. 18** Variations of (a) friction coefficients and (b) wear rates of the various polymer composites. Reproduced with permission from Ref. [72], © Elsevier Ltd. 2018.

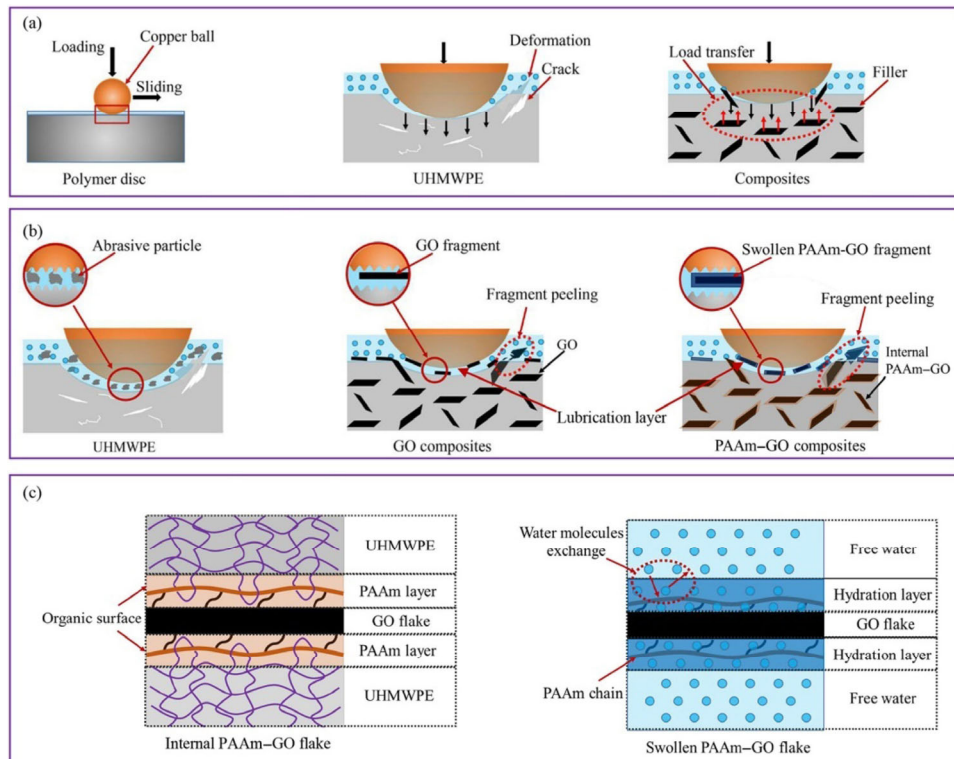
tribological properties of UHMWPE under water lubrication by integrating hard graphene oxide (GO) flakes and soft polyacrylamide (PAAm) hydrogel layers. GO can effectively improve the mechanical properties of the matrix, improve its bearing capacity, and reduce its wear. PAAm can not only adsorb water molecules on the polymer surface through electrostatic adsorption to form a hydration layer, which has good overall fluidity and low shear force, but also enhance the bonding strength between go and matrix, further enhancing the mechanical strength of composites, so as to reduce the friction resistance caused by plastic deformation, as shown in Fig. 19. At the same time, PAAm–GO with a high surface area will form a lubricating layer on the contact surface through physical adsorption to reduce wear.

## 2) PEEK (Cluster #3)

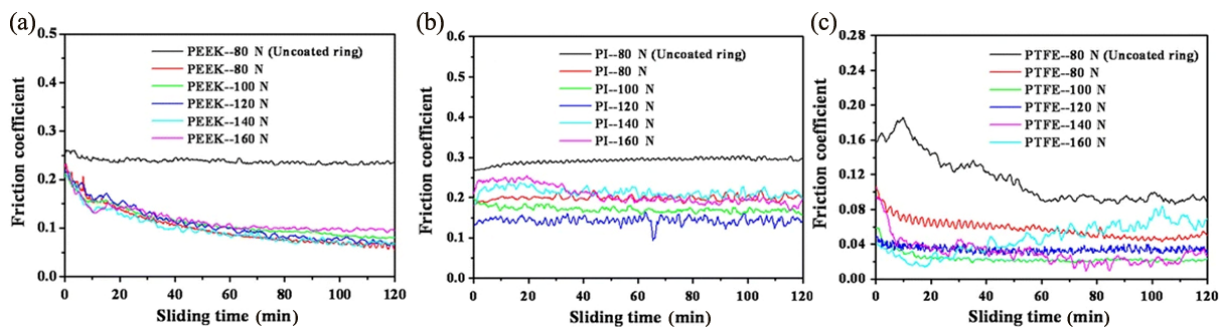
Yamanmoto and Takashima [76] compared the friction and wear properties of PEEK and PPS under water lubrication. The results show that FeS formed by the reaction of sulfur contained in PPS with steel promotes the transfer and adhesion of PPS to the steel surface, thus promoting the formation of transfer film, which effectively reduces friction and wear. Sumer et al. [77] studied the friction and wear behavior of PEEK–GF composites under water lubrication. Zhong et al. [78] studied the wear behavior of PEEK reinforced by short carbon fibers (SCFs) and nanoscale zirconium dioxide ( $\text{ZrO}_2$ ) under water lubrication. The results

show that SCFs bear the stress, and  $\text{ZrO}_2$  reduces the interface stress between the fiber and the matrix and inhibits the debonding of the fiber during abrasion. Chen et al. [79] added carbon fiber (CF) and PI to PEEK to enhance the wear resistance under seawater conditions. The synergy of CF and PI improves the density and carrying capacity of the matrix. Guan and Wang [80] found that the water lubrication performance of polymers increased with the increase of sliding speed, as shown in Fig. 20. Song et al. [81] studied the friction and wear properties of PEEK with graphene oxide added under water lubrication conditions. The research results show that PEEK swelling with water absorption has an adverse effect on its wear resistance. Gao et al. [82] added nano  $\alpha$ -FeOOH particles to PEEK to enhance its abrasion resistance in water environments, as shown in Fig. 21. The research results show that the addition of  $\alpha$ -FeOOH promotes the formation of high load-bearing and easy-to-shear transfer films at the contact interface, which effectively improves the friction and wear properties of PEEK materials. Liu et al. [83] improved the wear resistance of peek under high hydrostatic pressure in seawater by adding carbon fiber (CF) and GF. The research results show that GF and CF can improve the bearing capacity of the matrix to resist plasticization and swelling caused by PEEK absorbing seawater under high pressure. Gao et al. [84] added copper nanowires (Cu NWs) to PEEK to enhance

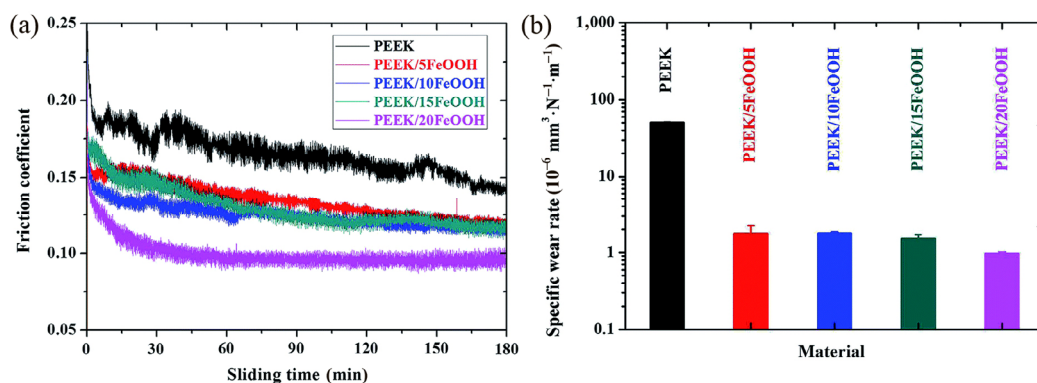




**Fig. 19** Model of tribological mechanisms: (a) bearing statuses of contact interface; (b) lubricating characteristics of the composites; (c) influence of two states of PAAm-GO flakes. Reproduced with permission from Ref. [75], © Elsevier Ltd. 2020.



**Fig. 20** Variations of friction coefficients for different applied loads. Reproduced with permission from Ref. [80], © Springer Science+Business Media, LLC 2012.



**Fig. 21** (a) Friction coefficients and (b) specific wear rates of different PEEKs. Reproduced with permission from Ref. [82], © The Royal Society of Chemistry 2016.

its wear resistance. The research results show that Cu NWs can bear part of the load and promote the formation of friction film on the contact surface, thereby reducing friction and wear. The synergistic effect of Cu NWs, short carbon fiber, and graphene can further promote the formation of friction film. Zhao et al. [85] combined PVA hydrogel layer and a 3D porous layer with PEEK substrates to prepare PVA/AA-g-SPEEK. The results show that the water absorption of hydrogel provides lubrication to the contact interface, which effectively reduces friction and wear. Li et al. [88] studied the friction and wear properties of carbon fiber-reinforced polyetheretherketone (CFRPEEK) at different water temperatures (1–52 °C). The results show that temperature had an adverse effect on the water lubrication properties of CFRPEEK.

### 3) PTFE and rubber (Clusters #10 and #16)

Shen et al. [86] studied the friction and wear behavior of PTFE–SiO<sub>2</sub> under water lubrication. In the wear process of PTFE, transfer film and metal–F bonds are produced at the contact interface, which effectively reduces the friction and wear. The results show that water molecules at the contact interface can inhibit the generation of transfer film and metal–F bonds, which has an adverse effect on wear. Lu et al. [87] studied the friction and wear properties of PCTFE and Cu–C under water lubrication. Song and Zhao [98] studied the friction and wear mechanism of PTFE/Cu under water lubrication by molecular dynamics. The interaction between H<sub>2</sub>O as a polar molecule and PTFE molecules is stronger than the interaction between Cu and PTFE molecules, which indicates that the water layer formed at the contact interface under water lubrication separates most of the PTFE molecules from the Cu layer, reducing the interaction between Cu atoms and C atoms in PTFE. Yan et al. [89] enhanced the friction and wear performance of epoxy composites under water lubrication by adding ACNTs. The research results show that ACNTs have a strong interaction with polymer molecular chains, which can hinder the movement of polymer molecular chains, improve the mechanical properties of the matrix, and reduce friction and wear. Gao et al. [90] improved the water lubrication performance of EP by adding different

nanoparticles (short carbon fiber (SCF), short glass fiber (SGF), graphite (Gr), and SiO<sub>2</sub>(Si)). The results show that the mechanical properties of nanoparticle-reinforced Coms (EP-Coms) have been significantly improved. Due to the high abrasiveness of SGF, it will scratch the surface of the grinding pair and hinder the formation of transfer film. The transfer film containing SiO<sub>2</sub>, Fe<sub>2</sub>O<sub>3</sub>, and C formed by EP/SCF/Gr/Si under water lubrication significantly reduces the wear and has the lowest friction coefficient. Nie et al. [91] improved its wear resistance by adding carboxyl-functionalized multiwalled carbon nanotube (MWCNT–COOH) to PI. The results show that the lubrication performance of MWCNT–COOH greatly reduces the wear. The results show that the transfer film formed by PTFE under water lubrication provides lubrication. Qi et al. [92] doped reinforcing particles (short carbon fibers (SCF) and aramid particles (APs)) with different hardness and moduli into PI–PTFE composites to enhance their wear resistance in seawater environment. The results show that seawater weakens the strong interface interaction between SCF and Cu, promotes the formation of boundary film, and reduces friction and wear. Jiang et al. [93] improved the wear resistance of polyurethane (PU) by adding lubricating grease (LG) under water lubrication. Wu et al. [94] improved the water lubrication performance of polyurethane (PU) by adding PEW. The results show that PEW will melt in the wear process and form a lubricating film at the contact interface to reduce wear. Yu et al. [95] improved the water lubrication performance of polyurethane/epoxy interpenetrating network (PU/EP IPN) composites by adding short carbon fibers and SiC nanoparticles. The results show that the hydrolysate of SiC under water lubrication promotes the formation of transfer film, which can improve boundary lubrication and reduce friction and wear. Dong et al. [96] improved the water lubrication performance of NBR by adding flake and spherical MoS<sub>2</sub>. The results show that the self-lubricating performance of MoS<sub>2</sub> nanoparticles can form a lubricating film at the contact interface, so as to reduce friction and wear. Yuan et al. [97] studied the friction and wear properties of NBR in the water environment containing sand particles with different particle sizes. The results show that under low

speeds and low loads, the larger the sand particle, the greater the influence on the water lubrication performance of the contact interface, while under high speeds and high loads, the particle size of the sand particle has little effect on the friction and wear performance.

The results show that the addition of nanoparticles can significantly improve the friction and wear properties of polymer materials. Although polymer materials are widely used in water environments, further improving the lubricating properties of polymer materials under water conditions is still an important direction. The addition of nanoparticles can effectively improve the mechanical properties of polymer materials, but the improvement of lubrication performance in water needs further research and improvement. Further reducing the friction coefficient of polymers under water lubrication conditions is still a major challenge and demand.

#### 4.3.2 Surface optimization

Directly optimizing the material surface of the contact pair can effectively combine the excellent mechanical properties of the matrix and improve the friction and wear properties of the contact pair under water lubrication at low cost.

##### 4.3.2.1 Wear-resistant coatings (Cluster #1)

The preparation of lubricating and wear-resistant coatings on the substrate is an important means to solving the friction and wear problems of materials under water lubrication, which has also been widely studied. Amorphous graphite carbon coating (GLC) has excellent tribological properties due to its unique microstructure, high hardness, low stress, high bonding strength, and high bearing capacity. It is proved to have application prospects under water lubrication. Wang et al. [99] improved the friction and wear properties of WC and silicon nitride under water lubrication by preparing GLC coating on WC surface. The results show that dangling  $\sigma$  bonds on the surface of GLC might be passivated by reacting with the polar radicals in water ( $-\text{OH}$ , etc.), so as to promote the separation of the contact interface. At the same time, the aqueous solution containing graphite particles promotes the lubrication, which leads to the

improvement of the wear resistance of the matrix. Wang et al. [100] found that the proportion and distribution of  $\text{sp}^2$  carbon bonds in GLC films have an important impact on their water lubrication properties. Wang et al. [101] added a Si interlayer between GLC coating and the substrate to improve the bonding force between the coating and the substrate and hinder the erosion of the bonding interface by water under water lubrication conditions, which enhance the wear resistance of the coating. Ye et al. [102] studied the friction and wear behavior of Cr-doped GLC, which formed the CrC strengthening phase and nanocrystallite/amorphous structure, and different metal materials (Al, Ti, H62, and GCr15) under seawater conditions. Gao et al. [103] reduced its friction coefficient and wear rate under water lubrication by preparing TiSiC coating, which has high hardness on Ti6Al4V substrate. Ye et al. [104] improved the friction and wear properties of 316 stainless steel substrate under water lubrication by doping WC into NiCrBSi coating. Wu et al. [105] paired the WC–10Co–4Cr coating with  $\text{Si}_3\text{N}_4$  to reduce the friction coefficient of the friction pair to 0.0043 under water. Zhou et al. [106] found that amorphous hydrate  $\text{Si}(\text{OH})_4$  and  $\text{Cr}_2\text{O}_3$  were produced at the friction interface between CrN coating and  $\text{Si}_3\text{N}_4$  under water lubrication, so as to reduce friction and wear. Zhou et al. [107] improved the friction and wear behavior of  $\text{Si}_3\text{N}_4$  under water lubrication by depositing amorphous carbon nitride ( $\text{a-CN}_x$ ) coating on the surface. The results show that the wear surface forms a  $\text{sp}^2$  bonding-rich structural surface with low shear strength due to the removal of nitrogen atoms from the  $\text{a-CN}_x$  coating, which contributes to ultra-low friction of the friction pair. Niu et al. [108] improved its wear resistance under water lubrication by preparing  $\text{Ni}_3\text{Si-Cr}_7\text{C}_3$  composite coating on AISI 1020. Wang et al. [109] studied the friction and wear properties of multilayer Cr/CrN/GLC coatings under water lubrication. Wu et al. [110, 111] found that the lubricating effect of the Si and Cr amorphous phases in the CrSiCN coating reduces wear under water lubrication conditions. Huang et al. [112] studied the effect of processing technology on the water lubrication properties of Ni/ $\text{Al}_2\text{O}_3$  composite coatings.

The bonding between coating and substrate and

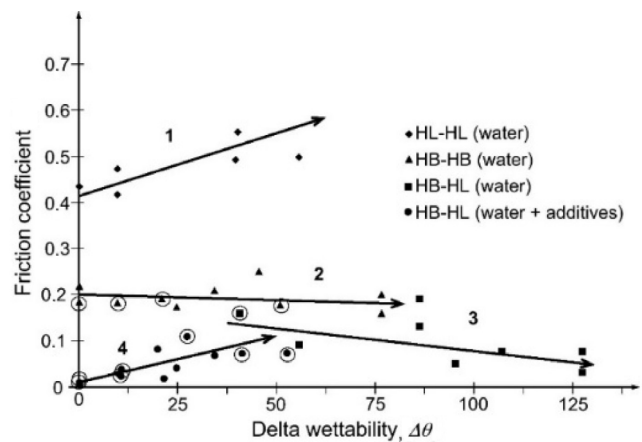


the evolution of contact interface between coating and substrate in the process of friction and wear need to be paid attention to, in addition to the properties of the coating material itself. Coatings with long service life are still a difficult area of research.

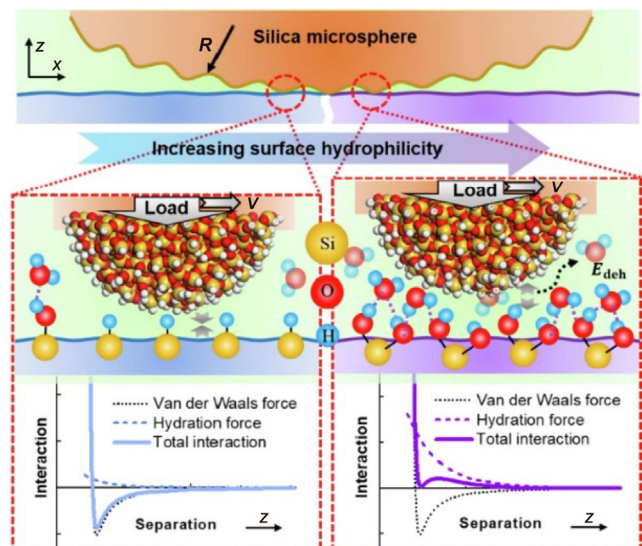
#### 4.3.2.2 Wettability improvement (Cluster #10)

Wettability refers to the ability or tendency of a liquid to spread on a solid surface. The improvement of wetting contributes to the formation of water film in the wear process, which can bear the load and separate the contact surface. The friction and wear of the material is affected by the wettability of the material surface [113, 114]. Lee and Spencer [115] found that improving the hydrophilicity of the material surface is conducive to improving the boundary lubrication state of the friction pair under water lubrication, promoting the contact interface to enter the full fluid lubrication state and reducing the friction and wear of the friction pair. Pawlak et al. [116] found that the friction coefficients of hydrophobic surfaces are lower than those of hydrophilic surfaces. Because the surface tension of water creates a repulsive force between the water and the hydrophobic surface, the water plays a bearing role at the contact interface. The friction coefficient is low due to the low energy loss during the adhesion hysteresis of water on the hydrophobic surface during wear. The different wettability of the surface of the friction pair leads to different friction behavior, as shown in Fig. 22. The effect of surface wettability on friction and wear behavior needs to be further studied. Dai et al. [117] found that the polarity of Ag leads to the improvement of hydrophilicity of  $\text{Mo}_2\text{N}/\text{Ag}$  coating, which leads to the reduction of friction coefficient. Li et al. [118] quantitatively studied the influence of material surface wettability and friction and wear properties. The lubrication performance under water lubrication is affected by the adhesion of surface water molecules, which is related to the wettability of the surface. Water molecules are tightly adsorbed on the hydrophilic surface, that is, the polar interaction between the interface and water. When the friction interfaces are in contact with each other, the large energy to remove the adsorbed water molecules leads to the repulsion of the adsorbed water molecules, that is,

hydration force, as shown in Fig. 23. The enhancement of surface hydrophilic properties promotes a reduction of the friction coefficient of the contact interface by an order of magnitude. Yang et al. [119, 120] found that the hydrophobic surface has a lower friction coefficient and wear resistance. Because the low surface energy of the hydrophobic surface reduces the adhesion of water molecules, the water flows more easily on the hydrophobic surface, so the shear strength between the two sliding solid surfaces is reduced, resulting in a relatively low friction coefficient.



**Fig. 22** Variation of friction coefficients ( $f$ ) with delta wettability. Reproduced with permission from Ref. [116], © Elsevier B.V. 2011.



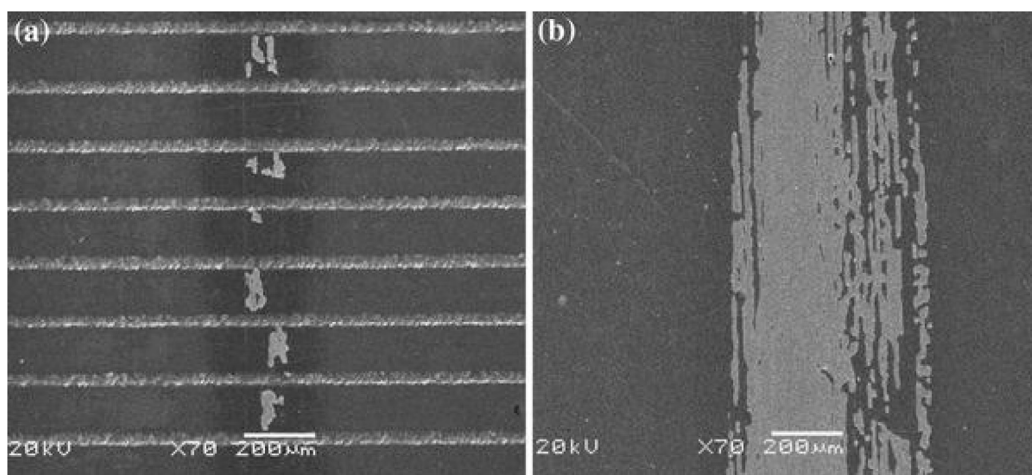
**Fig. 23** Schematic illustration of the interaction between silica ball and the silicon surface with different wettability ( $E_{\text{deh}}$  indicates the dehydration energy). Reproduced with permission from Ref. [121], © Elsevier Inc. 2021.

Improving the friction and wear properties of parts by improving the wettability of material surface has been widely studied. There are different explanations for the action mechanism of hydrophilic/hydrophobic surfaces on water lubrication. However, the mechanism of surface wettability on water lubrication needs to be further studied to further analyze the formation process and lubrication mechanism of the water film at the contact interface. The action mechanism of hydrophilic/hydrophobic surface on water molecules at the friction interface needs quantitative and qualitative analysis.

#### 4.3.2.3 Surface texture (Clusters #2 and #18)

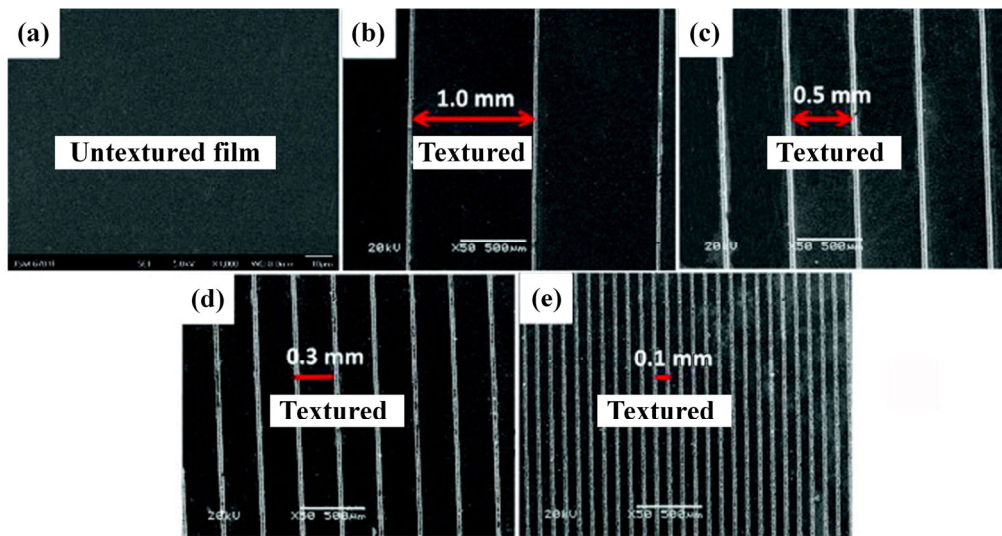
Surface texture is a new technique used to improve the surface properties of a friction pair, which has the effect of increasing the load-bearing capacity of water film, improving secondary lubrication, reducing frictional wear, and capturing micro-abrasive particles. He et al. [122] improved the water lubricity of the substrate by preparing a uniformly distributed surface texture of circular pits on the surface. The number, diameter, and depth of circular pits on the study surface have an important influence on hydrodynamic lubrication and cavitation during water lubrication. Ding et al. [123] studied the water lubrication properties of DLC coatings with surface texture. The results show that the surface texture with 15% groove area density ( $R$ ) can significantly reduce friction. The experimental results show that a transverse phase gradient film structure is formed in the textured DLC

film, which relieves the shear stress and dissipates the crack energy during friction to impede the cracks and suppress the enlargement of delamination, as shown in Fig. 24. Finally, the grooves can capture wear debris to reduce wear. Song et al. [124] improved the friction and wear properties of a-C:H films with different textures under water lubrication, as shown in Fig. 25. The results show that the textured a-C:H films can capture wear debris and inhibit abrasive wear and phase transformation. On the other hand, the textured surface can effectively promote hydrodynamic lubrication to reduce wear. Huang et al. [125] prepared dimple patterns with a dimple depth of 5  $\mu\text{m}$ , diameters of 50, 100, and 200  $\mu\text{m}$ , and area densities from 2.6% to 40.1% on the surface of PDMS to improve its water lubrication properties. The research results show that the dimple hinders the removal of water from the contact surface and has the effect of storing water. Yang et al. [126] effectively suppressed friction, wear, and vibration noise by preparing surface textures in water-lubricated bearings. Wang et al. [127] prepared surface texture on SiC surface to reduce its friction and wear under water lubrication, as shown in Fig. 26. The results show that the surface-textured SiC can maintain the superlubricity in a long load range, because the dimple on the surface promote the generation of complete hydrodynamic lubrication. Cui et al. [128] improved its friction and wear performance under water lubrication by preparing rhombic texture on the surface of thermoplastic polyurethane (TPU).

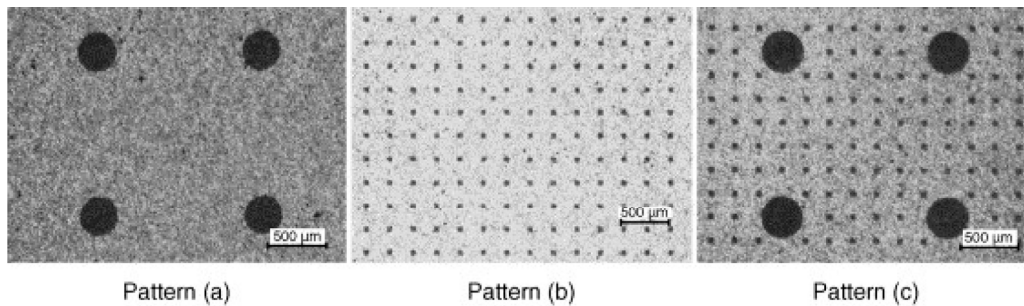


**Fig. 24** SEM images of wear tracks on deposited films: (a) textured sample; (b) untextured sample. Reproduced with permission from Ref. [123], © Springer Science+Business Media, LLC 2010.





**Fig. 25** SEM morphologies of (a) untextured film and (b–e) textured films. Reproduced with permission from Ref. [124], © Society of Tribologists and Lubrication Engineers 2015.



**Fig. 26** SEM morphologies of surface texture: (a) large dimples only; (b) small dimples only; and (c) large dimples mixed with small dimples. Reproduced with permission from Ref. [127], © Elsevier B.V 2006.

The results show that on the one hand, the rhombic texture produces cavitation, resulting in uneven fluid flow and positive pressure; on the other hand, the texture produces wedge gap and positive pressure in the process of fluid flow, which will contribute to the generation of hydrodynamic lubrication. Guo et al. [129] prepared a surface texture with superhydrophobic properties on the surface of aluminum alloy, which reduces friction by reducing the adhesion of the contact interface.

The preparation of surface texture can promote the generation of hydrodynamic lubrication at the contact interface, so as to improve the insufficient lubrication caused by boundary lubrication and mixed lubrication under water lubrication. On the other hand, surface texture can store lubricating medium and produce secondary lubrication. However, surface texture is limited in improving the friction

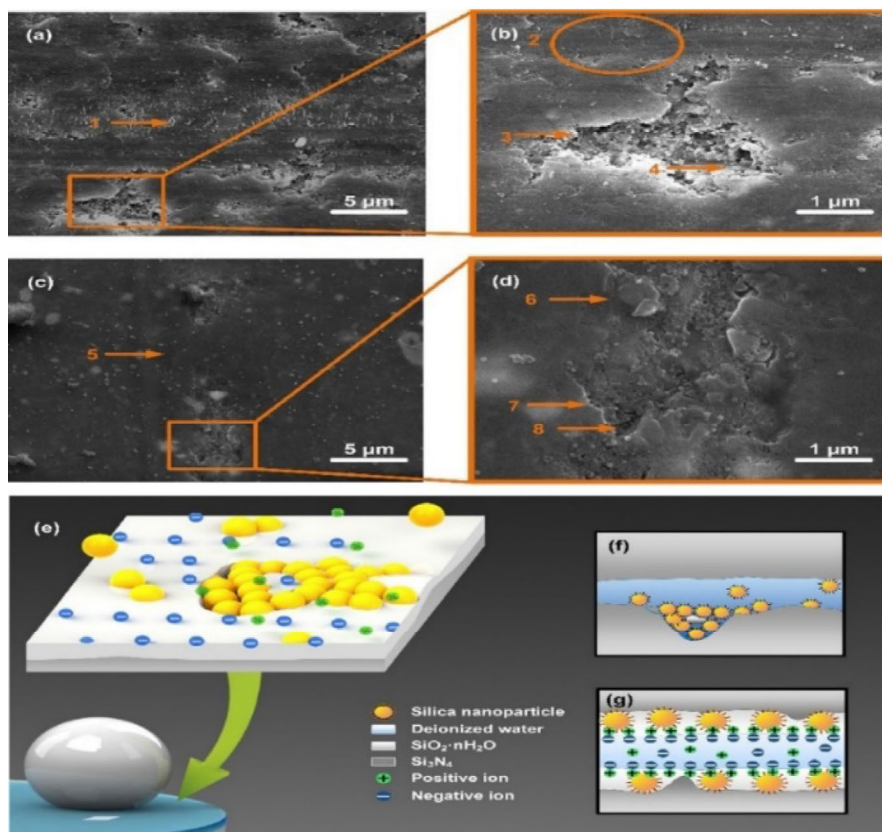
and wear performance under water lubrication. On the one hand, the research on the mechanism of surface texture is not deep enough, which specific role and function of surface texture under non-contact conditions need to be further studied. It is necessary to establish a model of the surface texture and analyze the dynamic characteristics of the surface texture during friction. Biomimetic texture has important research and application prospects, but its theoretical and practical application research needs further development. On the other hand, the wear resistance of surface texture under long-term action needs to be further improved. The experimental tests of the existing surface textures are all carried out in a short period of time, and the evaluation of the wear resistance of the surface textures under long-term action is the difficulty of its research and the hotspot of its application.

#### 4.3.3 Lubricating medium modification (Clusters #5 and #8)

Improving the poor water-lubricating load-carrying capacity and promoting water-lubricating performance by adding additives such as nanoparticles, polyols, and acid solutions, ionic liquids in water is the frontier of research.

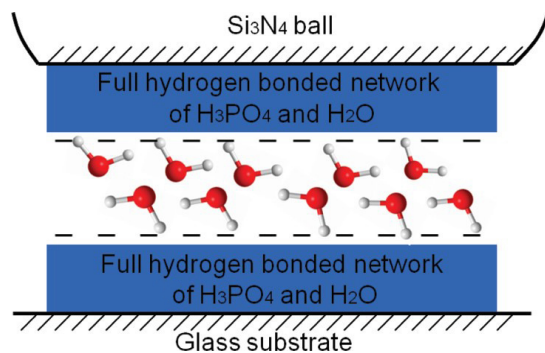
Lin et al. [130] improved the water lubrication performance of self-made  $\text{Si}_3\text{N}_4$  ceramics by adding modified  $\text{SiO}_2$  particles (amino-modified silica nanoparticles, carboxyl-modified silica nanoparticles, phenyl-modified silica nanoparticles, and octyl-modified silica nanoparticles) in water. The results show that  $\text{SiO}_2$  particles added in water can fill the surface wear pits and cooperate with silicon nitride to form silica gel chemical film on the surface, so as to make the contact surface smooth and promote surface hydrodynamic lubrication. The ionization of the modified  $\text{SiO}_2$  particles promotes the increase of the hydrogen ion concentration in the water.

Therefore, the repulsive force and electric-viscosity of the double electric layer formed by the adsorption of hydrogen ions on the  $\text{Si}_3\text{N}_4$  surface promote the stability of hydrodynamic lubrication. The lubrication mechanism is shown in Fig. 27. Phillips and Zabinski [131] reduced the running-in period of self-made  $\text{Si}_3\text{N}_4$  under water lubrication by adding ionic liquid in water. The formation of a double electric layer on the surface of the silicon carbide promoted by the ionic liquid increases the carrying capacity of the water film. Tomala et al. [132] reduced the friction coefficient of AISI 52100 steel by 30% under water lubrication by adding ethanolamine and ethylene glycol to water. Zhang et al. [133] achieved superlubricity of the contact interface by using a mixed aqueous solution of glycerol and boric acid. Li et al. [134] achieved the superlubricity of sapphire and ruby under water lubrication by adding phosphoric acid solution for the first time. The stern layer formed by the adsorption of hydrogen ions on the surface and the hydrogen

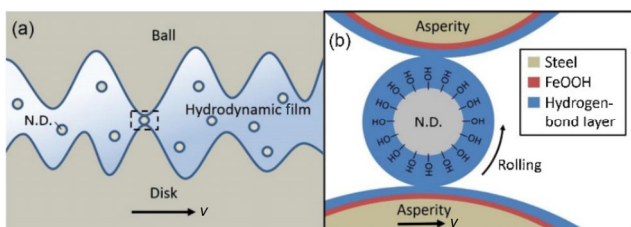


**Fig. 27** Illustration of lubrication mechanism of silica nanoparticles in water: (a, b) SEM images of worn surface in deionized water under a 60 N load; (c, d) SEM images of worn surface in  $\text{SiO}_2$  aqueous lubricant under a 60 N load; and (e, f, and g) schematic diagram of synergistic lubricating effect of silica nanoparticles. Reproduced with permission from Ref. [130], © American Chemical Society 2019.

bond network formed by the phosphoric acid solution and water on the surface promoted the formation of superlubricity. On this basis, Li et al. [135–138] proposed a water-based superlubricity theory based on hydrogen bonding effects, as shown in Fig. 28. Wang et al. [139] achieved an ultra-low friction coefficient (0.002) at the contact interface by dissolving polyalkylene glycol (PAG) in water. The results suggest that the low-shear hydration layer formed by the combination of PAG chains and water molecules plays an important role. Chen et al. [140] reduced the friction coefficient of the steel-to-steel (AISI 52100) to 0.006 by adding glycerol and nanodiamonds (N.D.) in water. The synergistic effect of the hydrogen bond layer with bearing capacity formed by glycerol and water and the solid lubrication of NDs promoted the superlubricity of the contact interface, as shown in Fig. 29. Zheng et al. [141] have promoted the achievement of a superlubricity, i.e., a friction coefficient of 0.006 in a steel-to-steel (GCr 15) pair by adding propanediol and ionic liquids to the deionized water. The results show that the low-shear lubricating film formed by the ionic liquid adsorbed onto the steel



**Fig. 28** Illustration of the superlubricity mechanism of hydrogen bonding. Reproduced with permission from Ref. [135], © American Chemical Society 2011.



**Fig. 29** Illustration of the lubrication model: (a) separation of water films at the contact interface; (b) synergy of hydrogen-bonded layers and nanoparticles. Reproduced with permission from Ref. [140], © Elsevier B.V. 2015.

surface and the hydrogen bonding network with load-bearing capacity generated by the combination of propylene glycol and water facilitate the achievement of the superlubricity.

Modification of water by additives to improve its lubricating properties is an important means, and even superlubricity can occur under certain conditions. But how to maintain the lubricating effect of modified water over a wide range of speeds, high loads, and long cycles is still a difficult area of research and application. The effect of additives on water and lubrication needs to be further studied, and the more essential lubrication mechanism needs to be further explored to promote its wider application. The use of modified water as a lubrication and working medium requires significant attention in terms of its corrosiveness and contamination. Nanomaterials with a layered structure, weak van der Waals forces between the layers, and good dispersion in water are now a hot research topic for water lubrication additives, but the mechanism of their action under water lubrication needs theoretical and practical in-depth study. The modeling and dynamic characterization of nanoparticles in water are necessary. Not all nanoparticles are suitable for water lubrication additives, and exploring nanoparticle additives suitable for water lubrication still requires intensive research.

## 5 Discussion and conclusions

It can be seen from the above literature review that the researchers have made various efforts to improve the water lubrication performance of friction pairs. Therefore, the friction, wear, and corrosion problems of materials in water environments have been improved to varying degrees. However, the friction and wear problems of friction pairs under water lubrication still have great room for improvement. How the superlubricity material maintains a long-term superlubricity state in a wide range of speed and load is still the focus of attention. It is still difficult to achieve ultra-low lubrication by combining nanoparticles with materials. The effect of media modification to improve the water lubrication performance is effective, and more in-depth research is needed to further improve its performance to improve



its applicability and stability. The environmental protection of modified water is an important problem. It is effective to improve the friction and wear problem under water lubrication by optimizing the material surface, but its lubrication under long-term action needs to be further studied. In addition, considering how to be applied in actual working conditions should gradually get the attention of researchers. The contact problem under high speed and high pressure needs further research. The problem of sediment doping under actual working conditions needs to be considered in the research process. Considering the life problem in practical application, the wear resistance of contact pair should be considered emphatically.

The friction and wear of friction pairs under water lubrication still has broad research space. The pursuit of ultra-lubrication or even zero friction of the contact interface is the highest goal of researchers. Reducing its friction coefficient and wear amount has important application values and significance to various industries, and has an important contribution to protecting the environment. This study presents the results of a detailed scientific mapping analysis in the field of water lubrication. 1,792 articles published between 1997 and 2021 (end of October) were analyzed by CiteSpace, highlighting the highly active research areas. This study identifies the countries and institutions that have made outstanding contributions, influential articles, popular keywords and topics, widely-cited journals and literature, and the research status and development trend in the field of water lubrication. In this review, the research field of water lubrication can be divided into three categories: lubricating medium modification, material preparation, and surface optimization. These three types of research are currently active. Emerging developments in water lubrication has been revealed by identifying the most robust burst up to 2021. The field of superlubricity and nano-lubrication technology has gradually gained attention and development. It has become a research hotspot to explore ways to achieving superlubricity of water-lubricated contact interfaces. The analysis of the research status and development trend of water lubrication provides future scholars with an overall and personal understanding of the whole field.

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## Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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