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Introduction

Ceramics and Tribology

This foundational chapter introduces the readers to the multidisciplinary facets of tribology, viz. friction, wear, and lubrication. The technological significance of tribology is discussed and an overview of classification of engineering materials is provided. As this book largely discusses the tribological behavior of ceramics and their composites, typical properties and tribological applications of structural ceramic materials are emphasized. The overall structure of the book is presented toward the last part of the chapter.

1.1 Introduction

The word "tribology" originated from the Greek word "tribos" means rubbing [1, 2]. Tribology is described as "the science of interacting surfaces in relative motion and practices related there to." The science of tribology primarily embraces the study of three components: friction, wear, and lubrication, as illustrated in Figure 1.1.

While a committee of UK government coined the word "Tribology" in 1966 [3], the interest in the tribology field is much older than the documented history. It is worth finding the footprints of tribology in early human age when fire was invented by friction between stones and/or woods [4]. Archives also show the knowledge of ancestors in reducing friction during translatory motion by studded wheels of a harvest car or by lubricating the path for transporting heavy Egyptian statues. Other records on tribology concepts in Paleolithic age include drill bits for hole drilling, stone or wood wheels for grinding cereals, etc. It is to note that systematic scientific investigations of friction and lubrication date back to few centuries, whereas the concept of wear is much younger, almost five years. This delayed attention on wear concept is probably due to the unavailability of electron microscopy and other instrumentation tools in the past. However, with the recent development of

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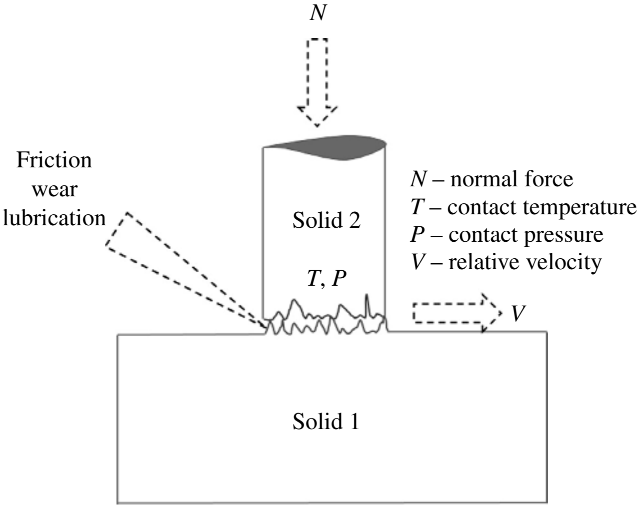

Figure 1.1 Schematic illustration of basic concept in tribology.

advanced microanalysis and spectroscopy tools, wear is now considered to be one of the potential components of tribology that helps in assessing the material loss and understanding the physics of material removal at surface and subsurface regions.

It is widely accepted in modern times that the friction and wear are major concerns in achieving sustainable growth in various industrial sectors like automotive, aerospace, construction, biomedical, optical, and microelectronics. In fact, a better understanding of tribology concepts is perceived to increase energy efficiency, reduce fossil fuels, and even improve health and lifestyle. As the performance of friction/wear components is strongly influenced by materials' behavior, novel material systems with superior properties and their processing technologies significantly influence the product efficiency and thereby cause impact on the economic sustainability.

Friction is the resistance to motion that arises from the interactions of two solid surfaces at real contact area. It should be noted that the frictionless movement is needed in some applications, whereas some applications need friction.

For example, applications like bridge supports, hinges on doors, bearings, rivets, human knee or hip joints, etc., need less friction at the contacts. However, applications like clutches, brake pads, etc., demand high and controllable friction at the contact. Nevertheless, the performance and life of engineering components for a particular application are generally based on the efficient control of friction and surface properties.

The progressive material damage from the surface due to relative velocity at the contact with other material is referred to as wear.

The phenomenon of wear can occur on surfaces of either or both mating materials, under different conditions like sliding, erosion, fretting, rolling, etc. It is important to note that mild wear in initial contact can progress rapidly during later stages to severe wear. Such transition can cause vibration and heating that may further lead to reduced product efficiency and loss. In fact, a majority of engineering disasters can be traced back to the instances of severe wear, which initiated in a mild scale. On the other hand, high and controllable wear rates are required in cases like polishing, grinding, machining, etc. Like friction, wear has to be controlled with early identification and design of suitable material systems for a better performance. In fact, the extent of friction and wear depends on the mating materials, contact conditions, and the surrounding environment. Thus, friction and wear are to be treated as system properties, not material intrinsic properties [5].

The extent of friction and material damage can be minimized by properly lubricating the contact. Several examples, where lubrication is useful, include metal cutting, gears, brakes, bearings, seals, orthopedic joints, etc. The role of the lubricant is to separate the contacting surface by forming viscous low-shear films. In fact, understanding the viscous flow characteristics of the lubricant, and interactions of solid surface and lubricant is necessary to control the friction [6–8]. Even in the absence of an external lubricant, it is quite possible that the contact is filled with a lubricating product, formed as a result of reaction between the mating materials and/or wear debris with the surrounding atmosphere. The later part of the book covers case studies where such surface interactions notably influence the wear and friction properties of ceramic composites.

While friction is the temporary and immediate response of the body in contact, wear accounts for the history of contact conditions [9].

A thorough understanding on the behavior of materials with respect to varying contact conditions in terms of contact stress, contact temperature, and environment is strictly needed to achieve desirable tribological performance.

The science of tribology is unarguably an interdisciplinary field that can be explained by synergetic interaction among concepts drawn from fundamentals of Materials Engineering, Chemical Engineering, Mechanical Engineering, Physics, and Chemistry (see Figure 1.2).

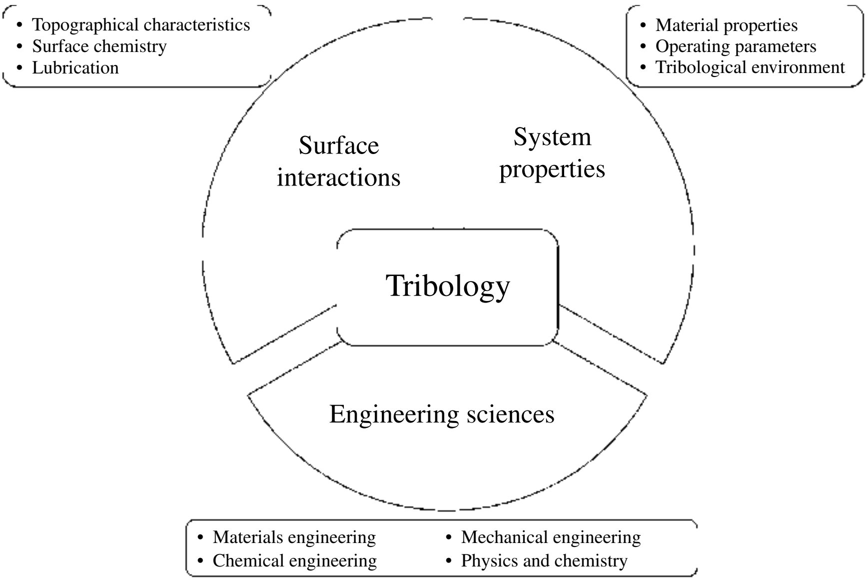

Figure 1.2 The conceptual illustration of contribution from disciplines of basic engineering and, system properties and surface interaction to tribology science.

While Mechanical Engineering concepts are greatly helpful to design the component, to understand contact mechanics and lubrication regimes; the Metallurgical Engineering concepts are useful in improving wear resistance by strengthening the bulk material or hardening the surface. On the other hand, the major aim of the material scientists is to control friction and wear by appropriately designing the process and tailoring the microstructure so that the performance in the given tribological conditions can be maximized [10]. Several technological, socioeconomic, and environmental requirements such as improved integrity, reliability, and performance of systems; higher durability of products; etc., drive the development of advanced material systems. In particular, the ever-increasing need for the development of advanced materials for extreme tribological applications necessitates comprehensive understanding on microstructure–properties–tribological performance relationship.

1.2 Classification of Engineering Materials

In general, engineering materials are classified into three primary classes: metals and alloys, ceramics and glasses, and polymers and elastomers [11–16] Among these primary classes, ceramics and glasses are widely being investigated for several engineering applications. The industrial-scale applications requiring moderate wear resistances are still dominated by steels and other metallic alloys. However, ceramics are potentially considered for use in extreme tribological environments.

While the widespread use of polymers and elastomers is driven by distinct advantages in terms of availability in different shapes or sizes, high flexibility, and low density; metallic materials have advantages of high toughness, high tensile strength, and manufacturability.

However, polymers and elastomers have a low melting point and very low elastic modulus and strength, whereas metals and alloys have much lower melting points, lower strength, hardness, and elastic modulus compared with ceramics and glasses. In particular, ceramics and glasses have superior properties: high melting points, high hardness, high compressive strength, high elastic modulus, and can withstand high temperatures without significant degradation of strength. Accordingly, ceramics are preferred for various elevated temperature structural or tribological applications.

On the other hand, another class of engineering materials, composites, is being developed to combine beneficial properties of the three primary classes of materials.

The composites are generally defined as "a class of materials that comprise of at least two intimately bonded microstructural phases aimed to tailor properties (e.g. elastic modulus, hardness, and strength) for specific applications."

The microstructure of a composite consists of three important constituents: matrix, reinforcement, and their interface. While equiaxed or an elongated grain structure is generally found in crystalline matrix phase, the reinforcement phases can have different morphology: particulates, fibers, and whiskers. The composites with fibers exhibit anisotropy in properties. Based on the major constituent type, composites are further classified as polymer matrix composites (PMCs), metal matrix composites (MMCs), and ceramic matrix composites (CMCs) [17, 18]. While several resin-bonded PMCs are largely studied for their use in aerospace applications, aluminum (Al)–silicon carbide (SiC) particulate composites and magnesium (Mg)–SiC particulate composites are widely investigated MMCs for their use as automotive and structural parts. Among CMCs, Al_2O_3–SiC whisker composites and Al_2O_3–zirconia (ZrO_2) particulate composites are largely studied for cutting tool inserts and other wear parts.

As the present book largely focuses on friction and wear behavior of ceramics and ceramic composites, a brief note on engineering ceramics followed by typical properties and important tribological applications of structural ceramics is provided in the following sections.

1.3 Engineering Ceramics

Ceramics are defined as "a class of inorganic non-metallic materials that can be either processed or used at high temperatures and have an ionic and/or a covalent bonding."

Although the major use of ceramic materials in the last few decades was focused on traditional applications such as construction materials, kitchen wares, and sanitary wares, the progress of ceramic science and technology since the early 1990s enabled this important material class to extend applications to engineering fields like aerospace, electronics, nuclear, biomedical, etc. [11–16].

It is widely agreed that ceramics can be classified as traditional ceramics and engineering ceramics. Less expensive silica-based ceramics prepared for daily-life application are named as traditional ceramics. In contrast, engineering ceramics are prepared using highly pure and expensive ceramic powders and strategic process design to tailor properties for use in advanced applications. In this regard, the present book discusses the applicability of structural ceramics for tribological applications. From application view point, engineering ceramics are broadly categorized as functional ceramics and structural ceramics.

The perfomance of functional ceramics is determined by magnetic, electric, dielectric, optical, and other properties; while the development and performance of structural ceramics is driven by the optimisation of mechanical properties, such as hardness, strength, and toughness.

Structural ceramics can be further classified as oxide ceramics (e.g. SiO_2, ZrO_2, and Al_2O_3) and non-oxide ceramics (e.g. TiN, Si_3N_4, TiC, SiC, TiB_2, and B_4C). As friction and wear properties largely influence performance of structural ceramics, it is imperative to understand the properties and tribological applications of structural ceramics.

1.4 Structural Ceramics: Typical Properties and Tribological Applications

Among advanced materials, ceramics are candidates for several wear-resistance applications owing to the unique set of their attractive properties like low density, high compressive strength, high hardness, high elastic modulus, and superior resistance against oxidation and creep [19]. The moderate fracture toughness can be improved by microstructural engineering via suitable process design.

The relevance of important properties of structural ceramics for tribological applications is presented in Figure 1.3. Table 1.1 summarizes typical properties of important metallic, polymeric, and ceramic materials. Detailed discussion on mechanical behavior of ceramics, fracture mechanics, and the assessment of different mechanical properties is provided in a later chapter. Using multiple case studies in this book, it has been emphasized that higher elastic modulus and higher hardness are, respectively, needed for superior resistance against Hertzian contact damage and abrasive wear. On the other hand, the shift of maximum Hertzian shear stress from bulk to the surface, and higher modulus-dependent contact pressures are some of the issues of concern with ceramics in tribological contacts. Further, few nitride and boride ceramics can be used for components exposed to temperatures close to 1500 °C, while Ni-based superalloys can be used only up to 1000 °C. In addition, ceramic composite (e.g. Si_3N_4-based or SiC-based composites) are demonstrated to retain high strength at temperatures as high as 1000 °C.

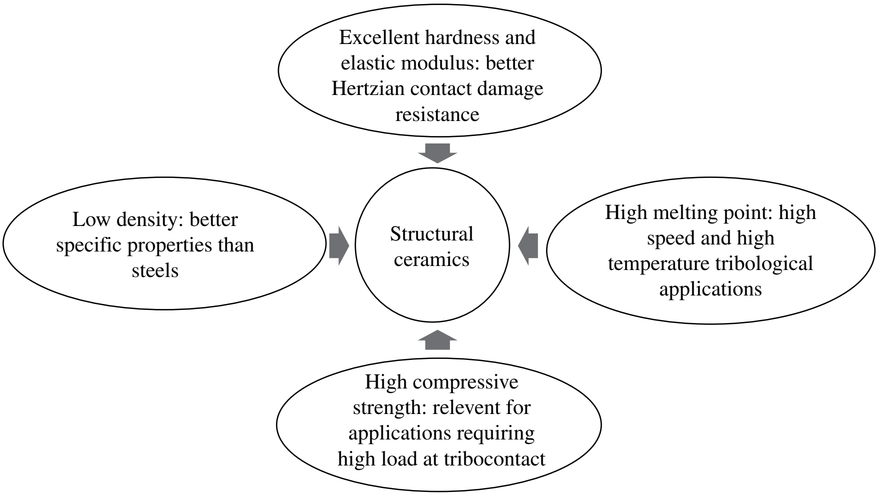

Figure 1.3 Important relevance of structural ceramics properties for tribological applications.

Table 1.1 Physical, mechanical, and thermal properties of some important metallic, polymers, and ceramic materials, which are relevant for various tribological applications [20].

Material	**Density,** ρ **(g/cm^3)**	**Elastic modulus,** E **(GPa)**	**Fracture toughness,** K_{IC} **(MPa·m$^{1/2}$)**	**Vickers hardness,** H_V **(GPa)**	**Thermal conductivity,** K **(W/m·K)**
Steel	7.8–7.9	21	5–214	1–9	3–6
Cast iron	7.1–7.4	64–181	2–6	1–8.5	3–6
Al-alloy	2.6–2.9	6–8	23–45	0.25–1.4	121–237
Al_2O_3	3.9	21–39	3–5	14–19	25–35
ZrO_2	5.6–6.25	14–21	1–8	12	2
Si_3N_4	3.2	17	4–7	16–18	5–25
SiC	3.2	45	4.5	25	9–125
Polyamide (PA)	1.1–1.14	2–4	3	0.8–1	0.25–0.35
Polyimide (PI)	1.3	3–5	—	—	0.37–0.52
Polytetrafluoroethylene (PTFE)	2.1–2.3	0.4	—	0.12	0.25
High-density polyethylene (HDPE)	0.92	0.2	1–2	0.13	0.33–0.57

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With respect to frictional heating, a large increase in friction-induced temperature is a concern with oxide ceramics having low thermal conductivity, whereas boride and carbide ceramics with relatively good thermal conductivity easily dissipate the heat from the contact. Further, density of ceramics is lower compared with many metals (see Table 1.1). This allows, high-speed machining possible with ceramic tool inserts.

The compressive strength of structural ceramics is almost eight times larger than the tensile strength and therefore, ceramics will be useful for tribological applications where contacts experience compressive loading conditions. It is to note that the compressive strength of ceramics is mostly superior to that of metals.

> Ceramics are identified as potential materials to replace existing materials for several tribological components like cutting tools, seals, valves, bearings, cylinder liners, etc.

However, the fundamental understanding of the relationship between material characteristics like microstructure, phases, etc., and wear behavior shall be understood for optimal use in tribological applications. For example, the wear behavior of non-oxide ceramics like SiC is largely reported to be influenced by test parameters, material, or environmental parameters [21]. As illustrated in Figure 1.4 [22], compared with SiC ceramics with equiaxed grains, the wear resistance was better for SiC ceramics having elongated grain morphology due to the *in situ* toughening by hard interlocking network of grains.

In general, the tribological materials development is focused mainly in two directions: ceramic coatings on metallic substrates and ceramics or ceramic composites. Coatings are mostly fabricated using nitrides, carbides, or borides with recent development of diamond or diamond-like (C–H) films at the higher end of the hardness-cost scale [23]. As the thickness of the coating is normally between 1 and 5 µm, property or performance of the relatively soft substrate is limited. In recent times, processing technology for diamond-like carbon (DLC) coatings has been improved to achieve low friction and wear for several lubricated and non-lubricated applications [24–31]. Thermal spraying can be applied for thicker coatings (in the millimeter range), but compatibility with substrate properties (thermal expansion, etc.) and cohesion are rather limited. This aspect is particularly discussed in later chapters of the book.

Monolithic ceramics, i.e. ceramics without any addition of second phase, particularly those with improved toughness and strength are being developed in several research labs and industries [32]. However, ceramic composites approach is now established to improve the overall properties of monolithic ceramics [33, 34].

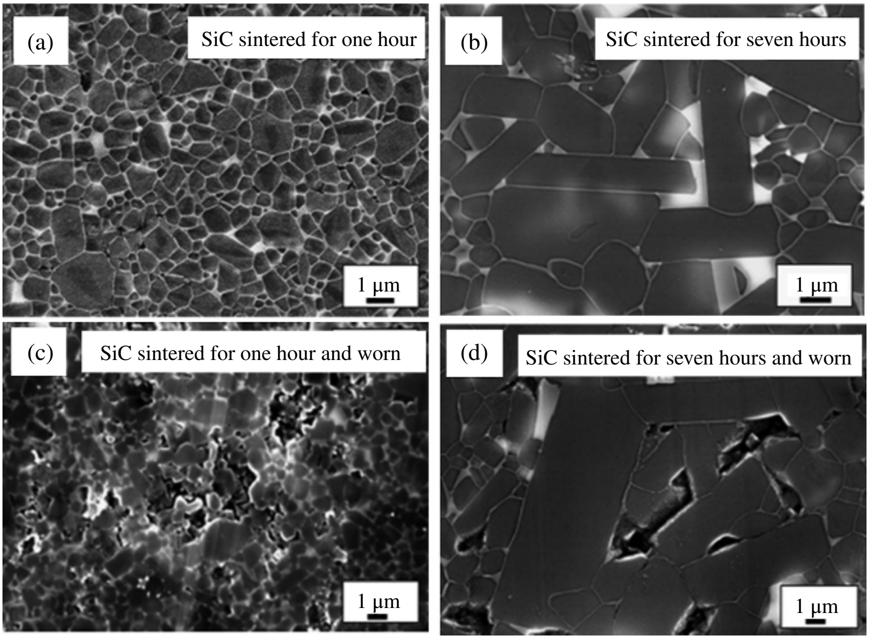

Figure 1.4 Typical SEM images of SiC ceramics (a, b) unworn and (c, d) after sliding against Si_3N_4 ball. Note the presence of elongated grains in (b) and equiaxed grains in (a), and comparatively less wear in (d) than in (c). Other conditions of sintering and sliding wear can be found in [22]. *Source:* Reproduced with permission of John Wiley & Sons.

Two major classes of ceramic composites are fiber-reinforced composites and particle/whisker-reinforced composites. Expensive ceramic fibers, composite production route, chemical compatibility between matrix and fiber, the fibers' oxidation at high temperatures are major drawbacks that restrict the widespread use of fiber-reinforced composites. To this end, particle-reinforced ceramic composites offer a feasible and a relatively cost-effective choice toward developing materials with improved properties. Tribological properties of particulate-reinforced CMCs are discussed in many case studies in this book.

The applications of wear-resistant ceramic materials range from bearings to leading edges of space shuttles, cutting tool inserts to orthopedic implants, automotive brake pads to dental crowns, and digital memory disks to turbine blades.

Few examples of engineering ceramic components, where wear resistance is of major concern are illustrated in Figure 1.5. Zirconia gears (see Figure 1.5a) are commonly used in heat engine applications. Bearings (see Figure 1.5b) with low-density silicon nitride balls are preferred in turbo pumps. Silicon carbide ceramics are used for bulletproof vest assembly units (see Figure 1.5c) because of higher hardness. Hot-pressed boron carbide nozzles (see Figure 1.5d) are preferred for nozzle applications, where abrasive resistance against silicon carbide and alumina abrasives is needed. TiCN-based cermets or their coating on steel are used for cutting tool inserts (see Figure 1.5e) in high-speed machining. In biomedical field, hydroxyapatite (HAp)-based ceramics are used for bone spacers, and Al_2O_3 or ZrO_2 ceramics are preferred for femoral ball heads (see Figure 1.5f) because of their hardness, abrasion resistance, and bicompatibility.

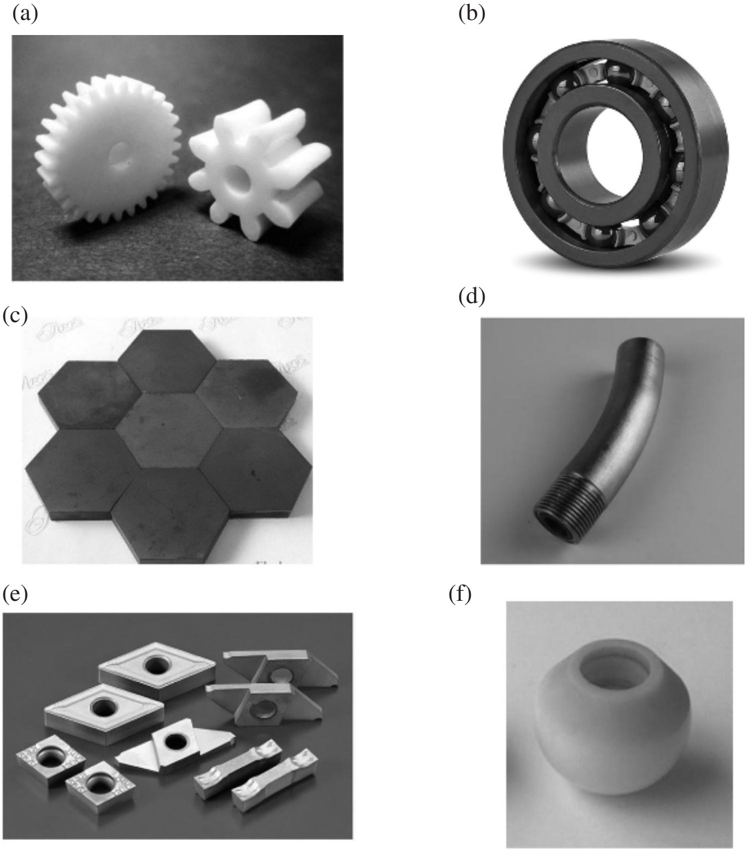

Figure 1.5 Few representative ceramic components requiring good tribological resistance: (a) zirconia gears [35], (b) Si_3N_4-based ball bearings [36], (c) SiC-based bulletproof vest assembly units [37], (d) hot-pressed boron carbide nozzle [38], (e) TiCN-coated cutting tool inserts [39], and (f) alumina femoral balls in total hip joint replacement (THR) application [40]. *Source:* Reproduced with permission of Springer Nature.

Furthermore, the use of advanced ceramics for critical transport engine components like fuel injector nozzles, needle valves, plungers, turborotors, etc., has been recently identified as a revolutionary approach for efficient and green transportation [41] in terms of reduction of carbon emissions, improved fuel efficiency, and superior vehicle performance, where material loss by sliding or erosive wear phenomenon is a serious concern.

It is important to note that despite possessing superior properties and tremendous potential, the commercialization of ceramic and ceramic composites for tribological applications is rather limited, due to difficulties in processing and machining, and limited understanding on wear behavior.

For given conditions of design, environment, and lubrication, engineers and scientists involved in preparing tribological components prefer possible ceramic materials with required set of physical, mechanical, and thermal properties. Nevertheless, the tribological behavior of the ceramic component is not controlled unless microstructural features like grain size, phase assemblage, defect distribution, etc., are tailored and micromechanisms of material removal in different wear contacts like abrasion, adhesion, erosion, etc., are thoroughly understood. It shall be noted that innovative process design can be adopted to achieve engineered microstructures and a combination of superior properties, whereas a thorough understanding on the wear behavior is extremely essential to enhance the applicability of advanced ceramic materials for tribological contacts.

1.5 Structure of the Book

The present book covers basic issues of processing and properties of ceramics and ceramic coatings, and major concepts of friction, wear, and lubrication. In order to understand possible correlations among the microstructure, properties, and wear behavior, a collection of recent research on wear studies of important ceramic and ceramic coatings is presented in the later part of the book. The content of the book is organized in six thematic sections spanning over 18 chapters.

The first section of this book, Section I: “Fundamentals of Ceramics,” is very important as this has been designed to facilitate readers who do not have a background in the area of ceramics. Considering the impact of processing or manufacturing approaches on the microstructural-development and resultant properties/performance of ceramics in tribological conditions, Chapter 2 is dedicated to explain fundamentals in ceramics processing wherein salient techniques for processing bulk ceramic materials via conventional and advanced sintering techniques. As ceramic coatings are preferred for several wear-resistant applications, a conceptual understanding on thermal spray-based ceramic coating techniques is also provided. Considering the particular preference of ceramics over steels or WC-Co hard materials in high-speed machining applications, basic concepts of conventional and advanced machining techniques are explained in Chapter 3. The advanced technique of electro-discharge machining is emphasized.

The mechanical behavior of ceramic materials is distinctly different than that of metallic and polymeric materials. It is widely reported that the elastic modulus, fracture toughness, and hardness strongly influence the wear behavior of ceramics in contact loading conditions. Therefore, brief discussion on stress and strain response, and details of fracture mechanics and toughening mechanisms are provided in Chapter 4. This chapter also discusses the experimental assessment for various mechanical properties of ceramics.

In addition to mechanical properties, wear test parameters (like load, speed, lubrication, etc., in sliding contacts; erodent type, size, velocity, angle of impingement, etc., in erosion contacts; depth of cut, speed, workpiece type, etc., in machining contacts) and environmental parameters (like temperature, relative humidity, inertness, etc.) also influence overall tribological behavior of the material. In fact, the interaction of mating materials with surrounding environment may influence contact conditions by forming a third body in contact. The friction and wear are largely influenced by the nature and stability of the third body. The application of lubricants can reduce the wear and friction by establishing a viscous and low shear strength film in contact. In the aforementioned perspective, Section II: "Fundamentals of Tribology" is dedicated to enlighten the reader with the fundamental concepts of tribology. The physical characteristics of contacting surfaces are explained in Chapter 5 and fundamentals of friction are provided in Chapter 6. As friction at the contact induces heat, basic understanding on the dissipation of frictional heating and contact temperatures is necessary in order to protect mating material surfaces from degradation. Therefore, key concepts of frictional heating and flash temperatures and the implications of important analytical models in flash temperature calculations are also provided in Chapter 6. Furthermore, as understanding on degradation behavior in wear contact provides a strong background to the readers as how to design and develop new tribological ceramic material systems, detailed explanation of wear mechanisms in terms of physicochemical changes at tribocontacts, leading to tribomechanical wear and tribochemical wear, is provided in Chapter 7. The importance of lubrication in reducing the friction *and* wear, and basics of lubrication regimes are also discussed in Chapter 7.

The later part of the book is important in realizing the implications of tribology concepts and material properties on friction/wear resistance of ceramic systems. For this, salient results obtained from studies of the author's own research groups on friction and wear behavior of ceramic or ceramics coatings subjected to sliding wear/erosive wear/machining induced wear are described. The selection of these wear contacts is justified in view of increasing contribution of ceramic systems toward energy and product efficiency and manufacturing ability. Based on the strong influence of materials on tribological behavior of systems in unlubricated (dry) operating conditions, majority of the results obtained in dry sliding wear studies on SiC ceramics, SiC–WC composites, ZrO_2–Al_2O_3 composites, and WC-Co coatings are discussed in detail in Chapters 8–11 (Section III: "Sliding Wear of Ceramics"). In addition, a comparative study on steels, coatings, polymers, and ceramics in lubricated sliding contacts is provided as Chapter 12 to explain the role of interface of solid surface with lubricant in controlling the friction.

Section IV: "Erosive Wear of Ceramics" deals with the solid particle erosive wear behavior of selected ceramic composites and ceramic coatings. The influence of material and operating parameters on erosive wear behavior of SiC–WC composites are discussed in Chapter 13, whereas the necessity and role of computational analysis in understanding the experimental erosive wear results for ZrB_2–SiC-based multiphase composites are highlighted in Chapter 14. The correlation of erosive wear performance with mechanical properties and erodent type for WC-Co coating is discussed in Chapter 15.

Further, considering the growing demand for light weight, hard, wear resistant, and chemically inert materials for cutting tool inserts, the performance and wear behavior of advanced cermets in machining of steel workpiece are discussed in Section V: "Machining-Induced Wear of Cermets." The results obtained in conventional machining and nonconventional electro-discharge machining conditions are elaborately explained in Chapters 16 and 17. It is to state that emphasis is given in each case study to explain dominant material removal mechanisms in selected sliding, erosive, or machining-induced wear conditions.

In the concluding section, Section VI: "Future Scope," authors' perspective for designing and developing next-generation ceramic materials with superior tribological properties is discussed in Chapter 18. The directions for the progress of tribology field are provided with an emphasis on the immediate need for developing advanced ceramics for self-lubricating films, robust testing equipment and in situ tribological interaction diagnostics facility, and simulation and modeling tools for improved understanding of experimental results. The necessity for data science and data mining concepts for better predictive capability of wear resistance of advanced materials is also highlighted. Also, a new conceptual approach "Tribomaterialomics" is suggested toward developing new generation wear-resistant materials.

Last but not the least, the most distinguishing part of this book is the Appendix: "Appraisal," wherein a rich collection of several types of questions is provided.

One can assess the understanding on fundamental concepts of tribology by attempting the numerous questions in ‘appraisal’ section. As per the knowledge of authors, such a large collection of qualitative and quantitative questions along with model answers is not available in any other tribology-related book, and this makes the present book unique. It is further expected that the ‘appraisal’ section serves as quick-reference and makes the book student-friendly and text-book type.

1.6 Closure

The influence of materials on tribological performance shall be considered in a larger context as these materials are components of “tribological systems.”

Materials for tribological applications include all major classes of materials like polymers, metals, ceramics, and their respective composites. Moreover, interfacial properties are affected by environment and tribochemical reactions. Being system dependent, these properties, including both mating materials, influence the tribological properties of any contact and component considerably.

Ceramics and ceramic composites are preferred for many components in friction and wear-resistant applications, because of the unique combination of their superior properties such as low mass forces, better abrasion resistance, and moderate tribochemical behavior. However, a better understanding on the assessment and mechanisms of material loss in friction and wear contacts is essential to increase the applicability of advanced structural ceramics for tribological components. In particular, the relationship among processing, microstructure, properties, and tribological performance is to be thoroughly understood.

In this regard, the present book is structured to enrich the fundamental knowledge on processing, microstructure, and mechanical properties of bulk ceramics and ceramic coatings, and friction, contact temperature, wear, wear mechanisms, and lubrication. In order to realize the implications of ceramic and tribology concepts, state-of-the-art research findings of tribological behavior of selected ceramic systems is presented in later part of the book. Further, a rich collection of conceptual, numerical, and analytical-type questions and model answers is provided in appraisal section to help readers in assessing their knowledge on the subject of tribology of ceramics.

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