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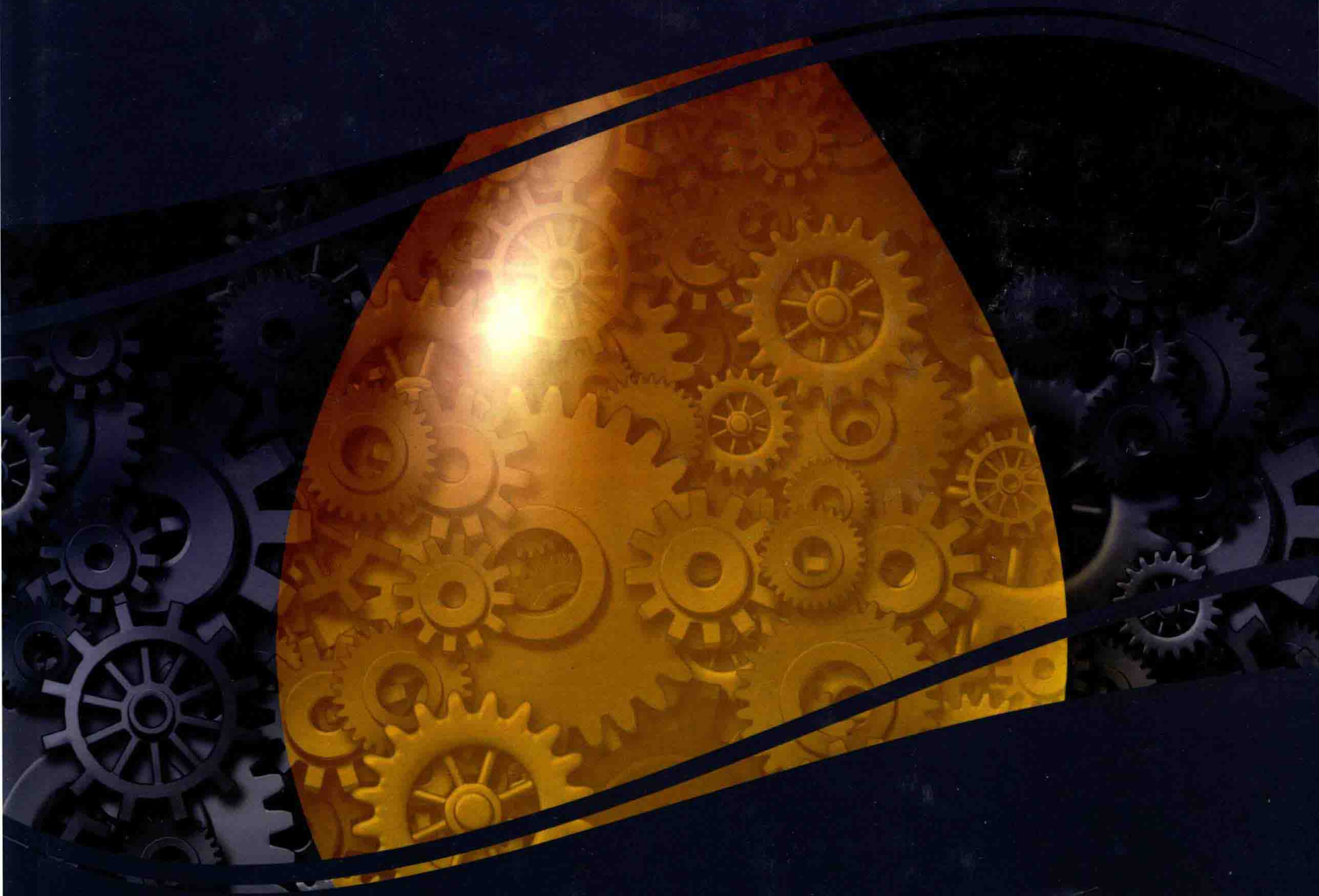

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Processing Techniques and Tribological Behavior of Composite Materials

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A volume in the Advances in Chemical and Materials Engineering (ACME) Book Series

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Foreword

Human ingenuity is continuously expanding the horizon of engineering. We moved through Paleolithic, Neolithic, Copper, Bronze, Iron, and Silicon ages, when we observed technology being pushed by human capability with materials. Polymers emerged and engineering materials were broadly classified into three non-overlapping categories – metals, ceramics, and polymers. From ancient times, there were sporadic attempts to stitch materials across categories like mud and thatch/husk to attain mechanical properties not attainable in either dried mud or thatch/husk. In our century, we have used conducting metal-metal composites in high tension transmission lines and in superconducting wires in magnets. But systematic study of combined or composite materials across the categories and even within them, started in the early sixties of twentieth century. Two materials could be combined geometrically in a number of ways. If one of them is topologically continuous, it is called matrix in which the second material is dispersed or discontinuously distributed as it happens normally in a composite. But it is also possible to combine two materials when both are topologically continuous and the composite is called interpenetrating composite. The discontinuous material may have a variety of shapes in three dimensions. The simpler shapes like needle, rod, disc etc are often characterized by aspect ratio, the ratio of length to radial dimension. One may combine more than two materials, thus offering an enormous possibility of creating combined or composite materials of different geometrical characteristics but such combination is meaningful if it offers some unique advantage in properties.

When two materials combine they create an interface and in a composite containing discontinuously distributed second material in a matrix, the second material is accessible for transmission of stress or transport of current only through this interface. Thus, status of interface is extremely important and it is broadly indicated by the energy or work of adhesion, which is difference between interface energy and the energies of the surfaces forming the interface. If the energy at the interface remains the same as the sum of surface energies, there is no interaction between the surfaces and the work of adhesion is zero. It may amount to simple stacking of materials. But if there is physical interaction in terms of local rearrangement of atoms or chemical interaction causing significant rearrangement of charged subatomic particles, there will be energy released leading to adhesion between the surfaces. In absence of this interaction, the combination will display properties given by the rules of mixtures without the benefit of synergy between the properties of the materials in combination. Even frictional interaction between the materials may provide considerable synergy in the combination under certain circumstances.

When one combines two materials, the scale of combination is a relevant consideration. In the early sixties of the last century, we started combining materials on a micrometer scale as it happens in multi-phase alloys, which are natural combination of elemental constituents and their discovery started with Bronze Age. The composite being man-made combination is distinct from multi-phase alloy. But human ingenuity could lower the scale of combination even in alloys to nanometer scale by appropriate heat treatment as in those containing GP zones. Increased focus on naomaterials in the nineties, made materials available in nanosizes for dispersion into a matrix. The resulting nanocomposites often have interesting novel properties distinct from those of the composites where the same materials have been combined in micrometer scale. The step from micro to nanocomposites may be a small step across the scale but it is fraught with challenges. Combining materials of nanosizes is very difficult because of high energy surfaces of nanoparticles giving rise to a tendency of agglomeration of particles. But when nanoparticles could be dispersed successfully, such combination has already resulted in combination of properties like enhanced strength and ductility, which could not be obtained in either microcomposites or precipitation hardened alloys.

A number of composites have been developed to attain unique tribological properties – friction and wear without and in presence of lubricants. The first patent on cast metal matrix composites is of graphite dispersed in aluminium, where graphite could overcome poor gall resistance in aluminium to make it a potential candidate for developing lightweight pistons and cylinders in automobiles replacing graphite bearing cast iron. Thereafter, both hard ceramic particles having relatively low adhesion with metals and soft solid lubricating particles with low shear strength have been dispersed in metal matrix to obtain low friction and low wear composites. Copper-graphite and silver – graphite are employed extensively in electrical contacts like relays and other components. High friction low wear composites are also important for brake pads and discs where large amount of power is to be dissipated quickly. Different kind of composites could be designed for different tribological applications. During sliding of composite surface, the debris generated often get compacted into a transfer layer on the sliding surfaces and it contains the particles of solid lubricants or oxides dispersed in the composite. This transfer layer is very important in determining the observed friction and wear behavior of the composite against a given counterface.

It is really surprising that it took us so long to focus our attention on composites while nature has evolved composite materials extensively in varieties of scales, shapes and distribution. The present book offers glimpses of processing and tribological properties of composites. In this book, the possibility to mimic ventral scales of snake by laser texturing for getting proper frictional response has been examined. Considerable attention has been given in the past to natural fibres but their variation of properties with degree of maturity poses a problem in attaining reproducible properties in a product made of it. Natural date palm fibres have been incorporated in epoxy matrix composites as described in the present book and there is significant improvement in mechanical properties of epoxy based composites. The processing of polymeric composites and manufacturing techniques like machining have also received some attention in this book.

There is significant application of tribomaterials in implants where biocompatibility is of prime concern. Generation of wear debris in joints during movement often creates medical complications necessitating replacement. This book also devotes some attention to development of coatings to reduce generation of debris so that such implants have enhanced life without needing replacement in a lifetime.

Graphite has been dispersed in aluminium/copper matrix since long to produce a low friction and low wear material having mating surfaces covered with solid lubricating layer of graphite during sliding. Some attention has been given in this book to design self lubricating composites based on copper. These composites have now been extended by changing the scale of combination to nano-dimension by incorporating MWCNT and nano-graphite in copper as the book describes one of the efforts. However, the agglomeration of nanoparticles poses a big challenge in developing satisfactory product. In addition, the book also contains some broad reviews of status of composites as tribomaterials including lightweight nanocomposites. The corrosion and degradation of the tribo-surface has also received some attention in this book.

The composite materials have become a vast subject in the last fifty years and it cannot be expected of a book to justifiably cover its entire span. Even tribo-composites by itself is so extensive that a single book is bound to prove inadequate. The present book may be judged by what it contains rather than what it fails to cover. I am very hopeful that the book will arouse interest of readers in composite tribomaterials inspiring further thought and development in this area.

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Subrata Ray, *currently Visiting Distinguished Professor in the School of Engineering at IIT Mandi, India, obtained his Bachelor's degree from Bengal Engineering College Shibpur, and Gold Medal from Calcutta University for standing first in his discipline. He was awarded M.Tech. and Ph.D. degree by IIT Kanpur. He joined a career in research and worked in National Aeronautical Laboratory, Bangalore, and National Physical Laboratory, Delhi, before joining the erstwhile University of Roorkee in 1978 as a faculty in Metallurgical and Materials Engineering. He has held visiting appointments in the University of Wisconsin – Milwaukee, USA, Institut National Polytechniq de Grenoble, France, and Technical University, Berlin, Germany. He has research interests in Materials development with special emphasis on cast Metal Matrix Composites (MMC). He has many pioneering contribution in cast MMC including introduction of stir-casting and addition of surface active elements for which he held the first patent in the world. Since then, Professor Ray has progressively decreased the size of reinforcement in stir-cast composite from hundreds of microns to nanometers. In the mean time he also developed interest on materials used in Li-ion batteries. He has supervised 29 M.Tech. dissertations and 37 dissertations leading to Ph.D. degree. He has published more than 200 technical papers, mostly in International journals and handbook, including those of ASM and ASLE. He is a fellow of the National Academy of Sciences, India, and Indian National Academy of Engineering.*

Preface

The important prerequisites of any engineering system are its reliability, efficiency, and long life. Relative sliding movement between the two components in an engineering system causes a loss of the material from the surfaces of both the components, and this loss, termed as *wear*, may affect its reliability, efficiency and long life. In most of the situations, the failure of the machines is due to the wear and not due to the breakage of component. Wear is not an intrinsic property of a material but a characteristic of an engineering system. Wear is rarely catastrophic, but it reduces the operating efficiency and increases power losses, oil consumption, and component replacement rates. It, therefore, becomes necessary that the parts having sliding motion relative to each other, be designed to minimise wear. During rubbing some fundamental changes occur in the surface of the contacting materials and these changes determine the nature of the wear process and friction force. The study of the complex phenomena occurring during rubbing and the need to minimise both energy and material losses in mechanical systems has led to an enlarged interest in the field of Tribology, the science of friction, wear, and lubrication.

Tribology finds applications in all industrial sectors including the aerospace, automotive, engineering, construction, biomedical, textile, optical, cosmetics and microelectronics industries. On average, 30 – 40% of the product cost is related to materials, hence improved materials and related technologies have a very significant impact on the economy. Losses due to wear of materials have been estimated by various sources to 1.3 – 1.6% of the GNP of an industrialized country (Jost, 1966; Czichos & Habig, 1992; Evans, 1977; Molgaard,1984). Modern materials and related technologies offer adequate solutions to friction and wear problems. Improved tribology will consequently contribute to a better environment, society, and we will be able to provide a cleaner and greener to our future generations to come. Hence, in view of the quantum of the loss due to wear, it becomes imperative for an engineer to develop better defense against wear by exploring newer wear resistant and cost effective materials for the tribological applications.

The necessity to minimize wear has given impetus to the development of the new wear resistant materials and has attracted the attention of the materials scientists worldwide. A lot of research work is going on in the direction of the development and the tribological characterization of lightweight composites based on aluminium or magnesium alloys for the last 50 years. The industries manufacturing the transport systems, be it land, air, or space, are continuing their quest to reduce weight and have a high strength/weight ratio of the components in order to increase the life and efficiency of engineering systems. The aim of the composite development is to attain a spectrum of properties, which cannot otherwise be obtained in any of the constituent materials. A wide variety of composites containing the fibres, whiskers, and ceramic particles have been developed for wear resistant applications. The underlying principle here is to utilize the mutual advantages of both the phases when the less desirable features of these phases are mitigated by the presence of the second phase. The morphology (i.e., size, shape, distribution, and volume fraction) of the second phase critically controls the mechanical properties of the two phase system which in turn influence its tribological behavior.

The development of composite materials following a wide variety of processing techniques and the design and manufacturing technologies is one of the most important advances witnessed in the history of materials. Composites are multifunctional materials having excellent mechanical and physical properties that can be tailored to meet the service requirements of a particular application. The unusual characteristics of composites equip the engineer with enormous opportunities to design the materials possessing unique properties that are not possible with conventional monolithic materials. Many manufacturing processes for composites have been commercialized for the fabrication of large, complex structures, allowing consolidation of parts, leading to reduced manufacturing costs. The uniqueness and non-conventional nature of composites do incorporate complexities in design, analysis, and fabrication due to their peculiar properties. However, the recent advancements in processing techniques coupled with advanced computational tools and numerical methods are playing a vital role in overcoming such obstacles and aiding in continued growth and application of composites.

Global concern over energy crisis that is being faced world-wide has given impetus to research related to identifying robust solutions to meet the need. Rapid depletion of oil reserves, increasing demand for fuel efficiency and regulations on emission has turned the attention towards light-weight materials. Research on these materials is in focus to achieve multiple-performance reliability, along with easier material processing, machinability/formability and high load-bearing capacity/structural strength. Energy efficiency, recyclability and sustainability are also in the focus. In this context, R&D of light weight composites, especially for weight-critical applications such as in automotive, aviation, sports, electronics and communication sectors (Gupta & Sharon, 2011; Kainer, 2006; Miracle, 2005; Rohatgi, 1996). The increasing use of Al- and Mg-based materials and polymer-based composites in the automotive industry is an excellent example of materials selection, wherein factors, such as material availability, processability, cost, properties, environmental issues, recyclability, fuel efficiency, etc., are all taken into account, together.

Tribology, the science and technology of interacting surfaces in relative motion, is primarily concerned with the friction, wear, and lubrication of moving parts in instruments, machinery, manufacturing, and technology. However, the definition must be improvised by adding that Tribology is the science of friction that aims to save energy, resources (money and materials), environment, resulting in loss minimization and improvement in quality of the product and health of the people. Keeping in view, the recent concerns related to energy, society and environment, it could be said that tribology research is the key towards a sustainable growth of society as it has an influence on our day to day life. As rightly pointed by Olander (2013), the tribology is everywhere every day; the moment you start moving tribology comes into play right from brushing teeth to charging cellphones to drinking yoghurt. Tribological phenomena are associated in every aspect of life automotive, aerospace, cosmetics, human body, and nature. Hence, better tribology practices could result in the conservation of scarce earth resources, higher energy efficiency, prolonged component lifetimes, better environment, society, and thus, helps improving the quality of life.

Tribology research contributes to the modernization of industry, and has strong impact on consumption of resources, namely, energy and materials through the development of better quality products and more efficient production system. It significantly affects the life-cycle and production-cycle issues in all industrial sectors, through the implementation of novel materials and technologies that result in products with improved performance. It is mostly concerned with improving the efficiency and reliability of machinery, production equipment, and systems for manufacturing. Through the establishment of prolonged life-times and improved production efficiency, it has a major impact on the reduction of raw materials consumption and generation of waste.

Globally, considerable effort has been and is being devoted, to tribology research. Consequently, a vast amount of know-how is available, and some new and exciting developments are still underway. With regard to transport systems in general, tribology research is concerned with improving the efficiency of engines, leading to reduced fuel consumption and reduction of emissions. In the automotive and aircraft industry, the trend towards decreased fuel consumption leads to higher utilization of lightweight materials. Thus, much of the work is concentrated on the tribology of new materials and designs, using surface engineering, improved lubrication methods, and composite materials. More efficient and cleaner production of energy is often critically dependent upon the construction material of power generation plants, and this in turn relies upon the use of adequately performing materials. Reduction of waste is obtained through the longer life-time of components, and the better efficiency of production processes. Advanced surface coatings add physical properties, such as lubricity, hardness, or corrosion resistance, to lower-valued substrates that improve the overall quality of the component. Scarce resources can thus be conserved or toxic materials substituted by application of appropriate coating systems. The reduction of friction in moving elements results in energy savings. Environmentally friendly, bio-degradable lubricants offer great potential to reduce environmental pollution. In particular cases, advanced materials can even avoid the use of lubrication, offering considerable economical savings as well as reduced environmental loading from wasted lubricants. New designs of mechanical systems enable the use of advanced composite materials such as engineering ceramics, coated surfaces, or reduced lubrication consumption in applications, which up until now remained inaccessible for these new technologies. Implants in the human body only function reliably when problems of bio-compatibility, corrosion, and wear have been overcome, and in all these areas tribology has played a crucial role. Hence, it can be seen that tribology has a significant impact on our economy, society and environment.

Energy is the driving force forall human activities. Nowadays, energy is deeply embedded in each of the economic, social, and environmental dimensions of human development. Energy services provide an essential input to economic activity while they improve living conditions and environmental quality. They also contribute to social development through education and public health, and help meet the basic human needs for food and shelter. However, extensive use of energy results in increasing carbon footprints and greenhouse gas emissions whereas mismanagement of energy resources can deteriorate existing ecosystems (Tzanakis, Hadfield, Thomas, Noya, Henshaw, & Austen, 2012).

Recently, a study has highlighted the loss of energy in passenger cars by friction only and suggested the ways to minimize the huge economic losses by utilizing improved tribological practices (Holmberg, Andersson, & Erdemir, 2012). It has been indicated that in passenger cars, one-third of the fuel energy is used to overcome friction in the engine, transmission, tires, and brakes. The direct frictional losses, with braking friction excluded, are 28% of the fuel energy. In total, 21.5% of the fuel energy is used to move the car. Holmberg et al. (2012) further suggested that by taking advantage of new technology for friction reduction in passenger cars, one can reduce the losses due to friction by 18% in the short term (5–10 years) and by 61% in the long term (15–25 years).

ORGANIZATION OF THE BOOK

The book is organized into 13 chapters and includes processing routes and tribological characteristics of composites materials like MMCs, PMCs, and biometrials apart from a chapter on biomimetics. A brief description of each of the chapters follows:

The chapter reviews the various processing/synthesizing routes of Light Metal Matrix Nanocomposites (LMMNCs), their microstructural characteristics, mechanical behaviour, and tribological properties. The authors suggest that the drawback of reduced ductility in micron sized reinforced composites can be overcome with nano-scale reinforcements. The potential of LMMNCs as advanced materials possessing superior strength and ductility along with excellent wear resistance has been emphasized.

Chapter 2 describes the fundamental issues (i.e. materials as well as tribology issues) of the self-lubricating copper matrix composite under dry sliding contact. It is suggested that for fabrication of good metal matrix composites for tribological applications, knowledge from both materials science and tribology is required. The chapter also introduces the tribological aspect of self-lubricating copper matrix composites for tribological applications.

Chapter 3 illustrates the effect of addition of solid lubricants on the high temperature friction and wear behavior of Ni-based composites. The importance of synergetic action of a combination of low and high temperature solid lubricant, nano or micro powders of two or more solid lubricants has been highlighted. A comprehensive review on the fabrication of the Ni-based self-lubricating composites containing graphite and/or MoS_2, Ag and/or rare earth, Ag and/or hBN, as solid lubricants and their friction and wear behavior at room and elevated temperatures has been included. The chapter also discusses the tribological behavior of some lubricating electro-deposited nickel-base coating containing graphite, MoS_2 or BN and graphene.

Chapter 4 explores the potential of a new class of metal matrix composites reinforced with carbon nano particles for the electrical sliding contact application. The chapter includes reinforcement of nanoparticles and innovative microwave processing technology to fabricate copper-crystalline carbon composites and examines their friction and wear characteristics.

Chapter 5 presents an overview of friction, sliding friction, and contributing factors such as adhesion, ploughing, deformation, third body, time dependence, mechanisms of friction in metallic materials. It also provides an overview of adhesive and abrasive wear and wear mechanism in mild and severe wear regime for metallic materials. Important material properties, environmental effects, and operating parameters have also been highlighted. The importance of Particle Aluminium Matrix Composites (PAMCs) with soft and hard dispersion has also been included and discussed.

Chapter 6 addresses the issues related to the tribocorrosion of metal matrix composites and provides an overview of the current knowledge of the mechanisms involved in the degradation of MMCs due to combination of electrochemical and tribological phenomena and available testing procedures.

Chapter 7 illustrates the importance of composite materials over single phase materials, and further explores the importance of natural fibre reinforced composites over synthetic fibre reinforced composites. The authors present a comprehensive review on tribological characterisation of composite materials and highlight the importance and potential of composites as TRIBO material in engineering systems.

Chapter 8 describes the advantages and disadvantages of several surface modification techniques on orthopedic implants. A critical review on the major tribological and biological outcomes of these modifications is included. Some results of recent investigations carried out by authors have been presented and explained. Futuristic trends in bio-tribological effects of orthopedic implants have been discussed.

Chapter 9 highlights the importance of surface characteristics such as microstructure, composition, mechanical properties, crystallographic texture, and surface free energy in achieving desired biocompatibility and tribological properties thereby improving the functional performance and *in vivo* life of artificial articulating implants. An overview on important surface modification techniques, their capabilities, different physical, chemical, mechanical, and biological properties of modified surfaces/implants including implant simulator tests are also presented. The clinical performance of surface modified implants and new surfaces for potential next-generation articulating implant applications is discussed.

Chapter 10 introduces the principles of designing surface texturing based on biological analogues. The chapter specifically relates to bio-mimetic and highlights the importance of deterministic structured textures that allow species to control friction and condition their tribological response for efficient function. The chapter draws a comparison between industrial surfaces and reptilian surfaces. It further highlights the feasibility an engineered surface by laser texturing based on the reptilian ornamentation constructs in controlling the friction. The author suggests that mimicking reptilian surfaces is potentially capable of generating advanced deterministic surface constructs for efficient tribological functions.

Chapter 11 addresses the issues and challenges associated with the conventional drilling of Fiber-Reinforced Plastics (FRPs) and reviews the status of the work reported in the area of conventional drilling of FRPs. A state-of-the-art research review is presented in light of the capability of advanced machining techniques for machining of FRPs. Advanced machining techniques, such as Electric Discharge Machining (EDM), Electrochemical Machining (ECM), laser beam drilling, vibration-assisted drilling, and Ultrasonic Machining (USM) for FRPs has been discussed and the limitations associated with the advanced machining of FRPs have also been highlighted.

Chapter 12 addresses the issues related fragmentation, interfacial adhesion, and strength of polymer-based composite reinforced with natural fibre that have been treated with different concentrations of NaOH and presents and an analysis of fragmentation technique using ANSYS.

Chapter 13 gives an overview of Quickstep processing, an Out-Of-Autoclave (OOA) approach, a relatively new technique for manufacturing composites. The basic principle of Quickstep processing and functionality of typical Quickstep plant are also explained. The chapter also includes a survey of different aerospace materials being investigated in Quickstep, the potential of new materials development for this process, the melding technique, in service capabilities of Quickstep cured samples, and journey of Quickstep from patent to commercialization.

In the end, we would like to thank our colleagues, the authors, who responded to our invitations and contributed to this edited book.

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Section 1

Tribology of Composite Materials

This section is devoted to tribological characteristics of composites prepared through variety of processing routes. Chapters 1 to 5 cover the issues related to synthesis and tribological characterization of Cu-based, Al-based, Ni-Based, Mg-based composites whereas Chapter 6 is devoted to the tribocorrosion studies of composite materials. Chapter 7 highlights the importance of natural fibre composites as potential tribomaterials.