CHAPTER 1

INTRODUCTION

Tribology, the science and technology of bodies in relative motion, involves the interaction of moving elements in natural as well as artificial systems and includes three major aspects, namely, friction, wear, and lubrication. Friction is the resistance to relative motion, wear is the loss of material due to that motion, and lubrication is the use of a fluid (or in some cases a solid) to minimise friction and wear. The field is essentially complex, fascinating and interdisciplinary, which encompasses the cooperative efforts from mechanical engineering, manufacturing, materials science and engineering, chemistry, chemical engineering, physics, mathematics, bio-medical science and engineering, computer science, and many more as indicated by Dašić et al. (2003), who have graphically depicted the interdisciplinary nature of tribology given in Fig. 1.1.

Tribology is particularly essential for any industrialised nation because a vast amount of energy is lost in overcoming the friction in mechanical systems and results in enormous economic losses. In 1966, Peter Jost emphasised the economical significance of tribology by reporting that the economy of U.K. could save approximately £515 million per annum at 1965 values by the application of the basic principles of tribology (Jost, 1966). A similar report published in West Germany in 1976 pegged the economic losses caused by friction and wear at about 1% of the Gross National Product. According to an estimate, about 11% of total annual energy could be saved in the four major areas of transportation, turbo-machinery, power generation and industrial processes through progress in tribology in U.S.A (Pinkus and Wilcock, 1977). Dake et al. (1986) reported that tribological improvements in cars alone could save about 18.6% of total annual energy consumed by cars in the U.S.A., which is equivalent to about 14.3 billion US$ per annum. In the U.K., the possible national energy savings achieved by the application of tribological principles and practices have been estimated to be between £468 to £700 million per annum (Jost and Schofield, 1981). In a recent study, Holmberg and Erdemir (2017) have pointed out that approximately 23% (119 EJ) of the world's total energy consumption originates from tribological contacts, out of which 20% (103 EJ) is used to overcome friction, whereas the remaining 3% (16 EJ) is used to remanufacture the worn parts and spare equipment due to wear and wear-related failures. Hence, tribology is critically important to address some of the world's key issues related to energy efficiency and the economic and societal implications of energy usage.

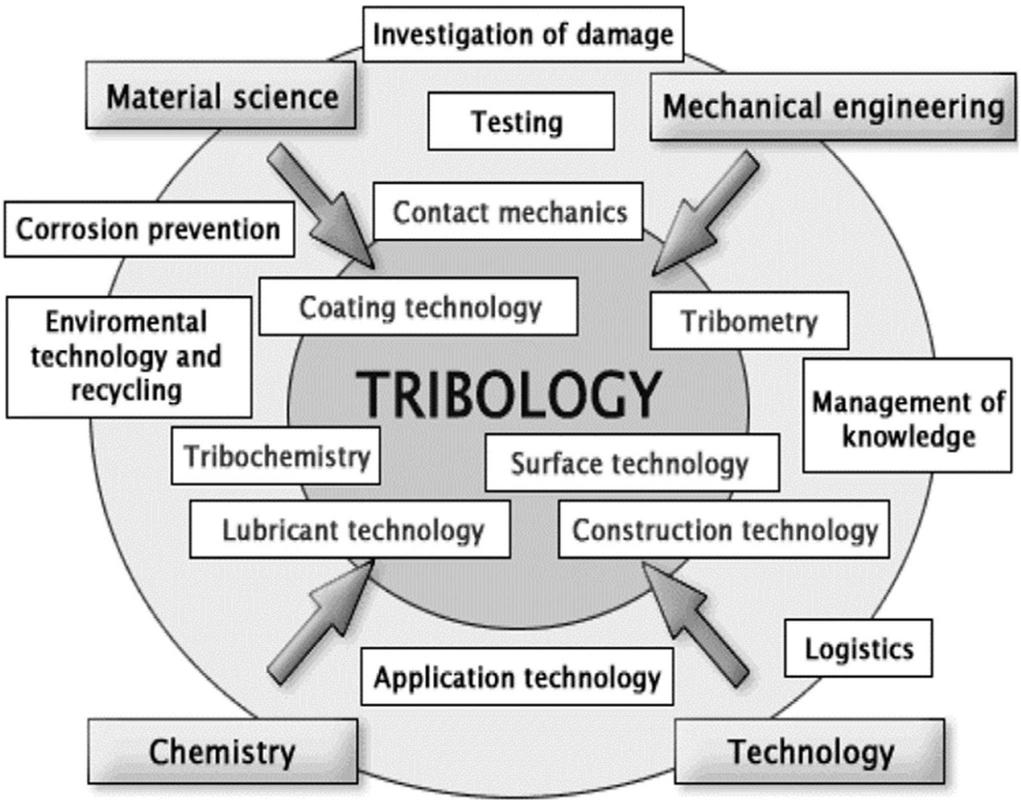

Fig. 1.1 Graphical representation of the multidisciplinary concept of tribology with other sciences. (Dašić et al., 2003)

In view of the quantum of the losses due to friction and wear, it becomes imperative for an engineer to develop a better defence against wear by exploring newer methods or techniques. Out of the several techniques, the most traditional way of controlling friction and wear, i.e., lubrication (liquid and solid), continues to be one of the favourite choices for reducing friction and wear-related mechanical failures for moving mechanical assemblies. Hence, there is always a craving for finding or developing a lubricant, which is not only cost-competitive but also environmental friendly.

Steel is the most widely used material in various industries like construction, automobile, aerospace, manufacturing, and many others, due to its low cost, design flexibility, recyclability, sustainability and durability, and high strength. The friction and wear response are also the main criteria for selecting steel in various applications. Many researchers have demonstrated the improvement in tribological characteristics of steel using various techniques such as lubrication, surface treatments, alteration of microstructure etc. The use of carbonaceous materials, either in the form of coatings or in the form of additives in the lubrication system, has also been reported to work well in improving the tribological response of a system. The advent of carbon-based nano-materials (graphene, nano-diamonds, fullerenes, carbon nano-tubes, carbon nano-horns, graphite nano-sheets) as potential friction and wear reducing agents has also opened new vistas for modern tribological practices.

Two dimensional (2D) materials such as graphene, MoS_2, hBN, and black phosphorus, have a sheet-like structure consisting of one to few atomic layers and exhibit a low coefficient of friction and outstanding wear behaviour due to weak interlayer shear stress. The ultra-thin structure of 2D materials facilitates their entry between interacting surfaces very easily. Among all these 2D materials, the excellent mechanical strength, chemical inertness, thermal stability along with the outstanding tribological response, render graphene as an ideal candidate to be used in numerous applications as a solid lubricant. Graphene having the layered structure comprises mono, few, or multi-layer with ultra-low shear strength.

Out of the various methods used to synthesise or isolate graphene, the chemical vapour deposition (CVD) is the most effective way to synthesise relatively high-quality graphene over a large area through the control of various factors such as substrate material, type of precursor, carrier gas, precursor flow rate, growth temperature, reaction time and cooling rate. Graphene growth by CVD involves the pyrolysis of precursors on the substrate surface to form carbon atoms, their dissolution into the surface followed by precipitation over the surface during cooling and thus, forming graphene structure. Copper and nickel are the two most widely used substrates for growing graphene.

A large number of studies conducted in the past decade have demonstrated the potential of graphene as a promising material for friction and wear reduction at nano-, micro- and macro-scale. Despite having a thickness of atomic level, the graphene has been shown to possess excellent lubricating potential with a very low coefficient of friction and wear. The lubrication potential of graphene is extensively being investigated both as a solid lubricating coating and as an additive to lubricants. The tribological performance of graphene has been found to be affected by various factors such as the number of graphene layer, quality of graphene, substrate material including the methods of coating preparation. Lamellar structure and low interlayer shear stress favour the solid lubrication effect of graphene. Along with astonishing dry lubrication behaviour, graphene, as an additive in industrial lubricants, has also demonstrated its worth in improving friction and wear performance. To date, graphene has been used as an additive in many conventional lubricants (oils, water, and other fluids), and an improvement in lubricious properties of lubricants has been reported by addition of even a small amount of graphene. Chemical modifications such as functionalisation and hydrophilic treatment have been utilised to solve the problem of aggregation and precipitation arising due to poor dispersibility of graphene in base lubricants. It has been indicated that the graphene forms a smooth and protective tribo-layer on sliding bodies due to the adsorbtion of graphene, which causes improved anti-friction and anti-wear properties.

In light of the above, the present study has been carried out to explore the potential of graphene as a solid lubricant, either in the form of coating over nickel catalysed steel or as an additive in water. The tribological behaviour of graphene as a solid lubricating coating has been examined by synthesising graphene films via chemical vapour deposition under different growth conditions (temperatures, acetylene gas flow rates, and reaction times) and carrying out friction and wear tests under unidirectional as well as reciprocating sliding. Whereas, the lubrication potential of graphene as an additive has been examined by dispersing different amounts of graphene oxide nano-sheets in water, and performing reciprocating tribo-tests at different normal loads and sliding speeds. The knowledge base generated through this study is expected to provide a better understanding of the lubricating aspects of this unique 2D material and help to utilise its potential for a wider spectrum of tribological applications.