Chapter 1: Introduction

The term "tribology," derived from the Greek word "tribos" involves the study of friction, wear, and lubrication. It plays a vital role in various industries and sectors, influencing the performance, reliability, and longevity of machinery, transportation systems, and everyday devices. Tribology encompasses the study of surfaces in relative motion, the forces acting upon them, and the interactions between them. Friction, the resistance encountered when two surfaces slide or attempt to slide against each other, is a fundamental aspect of tribology. It affects the efficiency of mechanical systems and influences factors such as energy consumption, heat generation, and component wear. Understanding and controlling friction is essential for optimizing the performance of machinery, reducing energy losses, and preventing premature failure. Wear, another critical aspect of tribology refers to the progressive loss of material from solid surfaces in contact and can result from various mechanisms, including adhesion, abrasion, oxidation, erosion, fretting and fatigue wear. Uncontrolled wear can lead to reduced performance, decreased efficiency, and even catastrophic failures in machinery and devices. Therefore, studying wear processes and developing strategies to minimize wear is essential for extending the lifespan and reliability of components. Lubrication, the third pillar of tribology, involves the introduction of a lubricant between contacting surfaces to reduce friction and wear. Lubricants can be in the form of liquids, solids, or gases and are designed to form a protective film that separates and cushions the interacting surfaces. Proper lubrication is crucial for minimizing frictional losses, preventing excessive wear, and ensuring smooth and reliable operation of mechanical systems. The field of tribology has far-reaching implications and applications in various industries, right from our daily lives to advanced technologies including automotive, aerospace, manufacturing, energy, chemical and biomedical sectors. It impacts the design, performance, and maintenance of engines, bearings, gears, seals, and many other components. Moreover, it plays a crucial role in achieving energy efficiency, reducing costs, and mitigating environmental impacts.

The occurrence of wear in a system can result in severe failures that ultimately lead to reduced productivity, hence causing significant economic losses. A recent study conducted on frictional and energy losses in transportation, manufacturing, power generation and residential sector by Holmberg and Erdemir (2017) indicated that 23% (119 EJ) of the global total energy consumption is contributed by tribological contacts. Out of this, nearly 20% is used to overcome friction, and 3% is used to repair worn parts due to wear. It has been anticipated that energy losses due to friction and wear may be reduced by 18% (21.5 EJ) in 8 years and 40% (46 EJ) in 15 years, which are supposed to generate savings up to 1.4% of the GDP annually, by utilizing new materials, lubricants and surface modification technologies. Considering that a significant percentage of the gross domestic product (GDP) of a developed nation is wasted in overcoming the negative impacts of friction and wear (in the form of direct loss of useful energy as well as replacement costs associated with machine components damaged by wear), a major objective of tribology research is to design materials to minimize friction and wear. Hence, sincere efforts are being directed towards (i) understanding the properties and improving the usefulness of existing lubricants and (ii) coming up with new ways of lubricating interfaces in a more effective manner (e.g., by decreasing the coefficient of friction, reducing the wear rate and improving the lifetime of components).

Self-lubricating composites are a broad class of materials that incorporate one or more solid lubricants in a matrix of metal, ceramic and polymer, which reduce friction and wear in industrial applications involving severe sliding contacts without the need for further external lubrication. These composites are used in various industries, such as aerospace, automotive, construction, and more, where specific combinations of properties are required for particular applications. In recent years, their use under high-temperature (HT) conditions has become a subject of increasing importance in applications ranging from metal forming to aerospace and power generation. Solid lubrication technology has witnessed extensive advancement over the last five decades, driven mainly by the requirements of the automotive, aerospace, and manufacturing industries. Solid lubricants come into play in situations where liquid containment presents challenges or when liquid lubricants cannot meet the demands, particularly in conditions involving high vacuum (space environment), extreme temperature conditions (high and cryogenic), corrosive environments, dust, radiation, clean environments and their combinations. Materials used for solid lubrication must not only have desirable coefficients of friction (0.001 to 0.3) but also be durable in a variety of situations mentioned above.

Despite the availability of several processing techniques for fabricating composites containing solid lubricants, powder metallurgy (P/M) has been proven to be the most appropriate route to produce superior-quality products. It is a solid-state processing, which allows to process the components having dissimilar physical and chemical properties, e.g. melting temperature, density difference, difference in coefficient of thermal expansion, high reactivity, etc., and offers other advantages like uniform dispersion, improved structural stability, good surface finish, dimensional control and a good bonding between matrix and reinforcement.

Ni_3Al-based intermetallic compounds possess excellent properties at elevated temperatures, such as high-temperature strength, hardness, high melting point, chemical inertness, and excellent oxidation, as well as corrosion resistance, which make them suitable for various industrial applications like gas turbine engine parts, aerospace, tooling and machining, rolling and forming tools, defence industries, internal combustion engines and various furnace components. However, the inherent brittle nature of intermetallic compounds at room temperature as well as elevated temperatures affects their tribological performance in an adverse manner and restricts their use in components having relative motion while in contact with their mating counterpart. It has been indicated that friction and wear performance of Ni_3Al intermetallic compounds can be improved by integrating alloying elements, other reinforced phases, solid lubricants and regulating the reaction sintering process. Despite the progress achieved in the realm of high-temperature self-lubrication, ensuring sufficient lubrication of moving components at elevated temperatures has consistently been a formidable challenge for tribologists and engineers. Hence, the quest for innovative composite materials or coatings that self-lubricate at high temperatures and meet the requirements of contemporary mechanical systems is still on. The utilisation of a strategy aimed at synthesising composite materials with self-lubricating properties, incorporating a blend of solid lubricants, presents a highly promising approach. This approach offers the potential for continuous replenishment of lubricant at the sliding surface, thereby surpassing the limitations associated with coatings that possess a finite lifespan.

A plethora of solid lubricants that are being used or are currently under investigation, include soft metals (Cu, Au, Ag, etc.), layered materials (*h*BN, MoS_2, WS_2, graphite, etc.), metal oxides (CuO, NiO, MoO_3, etc.), double oxide phases (Ag_2MoO_4, $Ag_2Mo_2O_7$ etc.), alkaline halides (BaF_2, CaF_2, etc.), as well as MAX phases (Ti_3SiC_2, Ti_2AlC, etc.). Silver has long been used as a solid lubricant. It has a larger coefficient of diffusion and forms lower shear stress junctions at the sliding interface, resulting in good lubrication at temperatures of less than 500 °C. This characteristic of silver either alone or in conjunction with other solid lubricants has been effectively utilized by several researchers in composite coatings or materials for high-temperature tribological applications.

Tungsten disulphide (WS_2), a solid lubricant with a layered structure, forms an easy-to-shear film at the contact interface of mating materials and maintains its lubricating properties at high temperatures due to its higher oxidation temperature of 539 °C, which is higher than graphite (325 °C) and MoS_2 (370 °C). The lamellar structure of hexagonal boron nitride (*h*BN), as well as its high thermal stability, good chemical inertness, high thermal conductivity, and white colour, also make it a promising candidate as a clean, high-temperature solid lubricant. However, poor sintering and non-wetting features of *h*BN have restricted its applications, which may be improved by modifying its surface with the help of Ni and Cu due to the mutual solubility of Cu and Ni. Therefore, in the present study, the *h*BN has been modified with Cu with an aim to enhance the sintering and wettability characteristics of *h*BN with the Ni_3Al matrix. It is an established fact that a single solid lubricant cannot provide effective lubrication across temperatures ranging from room temperature (RT) to 800 °C. Hence, the use of a combination of low- and high-temperature solid lubricants has been found to be beneficial in realizing effective lubrication over a wide range of temperatures from RT to 800 °C.

In summary, the present study is aimed at synthesising the Cu-doped *h*BN nanosheets as a solid lubricating species and fabricating self-lubricating Ni_3Al-based composites containing either a single solid lubricant (Ag, WS_2 and Cu-doped *h*BN nanosheets) or a combination (Ag-WS_2, Ag-Cu doped *h*BN nanosheets and WS_2-Cu doped *h*BN nanosheets) of solid lubricating materials. The investigation also intends to explore the tribological performances of composites under dry sliding conditions at different temperatures (RT, 200 °C, 400 °C, 600 °C and 800 °C) at a constant load of 10 N and constant sliding speed of 0.2 m/s. The *h*BN powder has been doped with copper to overcome the poor integrating properties of *h*BN with the matrix, and this combination (Cu and *h*BN) results in the formation of a hybrid nanomaterial (Cu-doped *h*BN nanosheets), which may be used as a potential solid lubricant in various sectors such as aerospace, automotive, manufacturing etc. The investigation also intends to reveal the prevailing mechanisms of wear and lubrication due to the formation of compounds by tribo-chemical reactions in these composites.