Chapter 1: INTRODUCTION

TRIBOLOGY, derived from the Greek verb tribos, meaning "to rub," is the study of interacting surfaces in relative motion while in contact. These interactions dictate the functioning of nearly every man-made device, as most mechanical failures stem from issues with moving parts like gears, bearings, and clutches etc. The friction, wear, and lubrication are pivotal in the design, operation, and maintenance of any mechanical device, influencing its efficiency, durability, and overall performance. Friction, the resistance to motion between sliding surfaces, lies at the core of tribological investigations. The understanding of friction is crucial for designing efficient components. Tribologists study factors like surface roughness, material properties, surface chemistry, temperature, and contact pressure, all of which critically affect the friction. Surface roughness affects the real contact area and frictional forces, while material properties like hardness and elasticity also impact friction behaviour. Wear, the gradual loss of material from the contacting bodies in relative motion, presents significant engineering challenges. Excessive wear reduces performance, increases maintenance costs, and can cause component failure leading to the replacement of component. Lubrication is a fundamental concept in tribology, involving the use of substances known as minimizing frictional losses, preventing excessive wear, and ensuring smooth and reliable operation of mechanical systems. Lubricants can be liquids, solids, or gases, and their selection is based on operating conditions such as temperature, speed, and load. Tribology examines wear mechanisms to understand material degradation under various conditions. Key mechanisms include abrasive wear (caused by hard particles removing material), adhesive wear (material transfer due to high contact pressures), and fatigue wear (surface cracking from repeated loading). An understanding these mechanisms allows tribologists to develop strategies to minimize wear and extend component lifespan through material selection, surface treatments, and lubrication techniques. The fascinating field of tribology has extensive implications and applications covering broad horizon ranging from everyday life to advanced fields such as automotive, aerospace, manufacturing, energy, chemical, and biomedical sectors. It influences the design, performance, and maintenance of engines, bearings, gears, seals, and various other components. Additionally, tribology is vital for enhancing energy efficiency, lowering costs, and reducing environmental impacts.

The occurrence of excessive wear within a system can cause considerable failures, resulting in decreased productivity and significant economic losses. Holmberg et al.[1] have reported that 23% (119 EJ) of the total annual energy consumption worldwide originates from tribological contacts and 87% of that is used in overcoming friction while 13% is used to repair/replace worn parts due to wear and other failures related to wear. The picture becomes grimmer when the economic losses caused by the wear are taken into account because of the added costs of maintenance work and production losses apart from the cost of energy due to wear. It has been estimated that the total economic losses originating from tribological contacts in all societal sectors are 2,536,000 million euros annually, of which 73% is due to friction and 27% is due to wear. Since, a significant part of the gross domestic product (GDP) of a developed nation is wasted in overcoming the deleterious influences of friction and wear, it becomes imperative to develop new methods/lubricants/materials, which reduce the energy dissipation due to friction improving and result in the enhanced lifespan of machine elements. Therefore, the energy consumption can be reduced by controlling the means of energy dissipation in friction. A major challenge for tribologists is to fabricate materials to reduce friction and wear. Therefore, genuine efforts are focused on (i) enhancing the properties and effectiveness of traditional/new lubricants, and (ii) innovating new methods for lubricating interfaces more efficiently, such as by decreasing friction and wear, along with improving the lifespan of component lifetimes).

Self-lubricating composites encompass a diverse category of materials that incorporate solid lubricants within matrices of metal/ceramic/polymer. These composites effectively reduce friction and wear in industrial applications where intense sliding contacts occur, eliminating the need for additional external lubrication. They find application across multiple sectors such as aerospace, automotive, and construction, tailored to meet specific performance requirements for different uses. In recent years, there has been a growing emphasis on utilizing these composites in high temperature environments, which has become increasingly critical across industries ranging from metal forming to aerospace and power generation. The evolution of solid lubrication technology has been driven significantly by the demands of automotive, aerospace, and manufacturing sectors over the past fifty years. Solid lubricants play a pivotal role in scenarios, where liquid lubricants pose containment challenges or fail to meet operational demands, particularly in environments involving high vacuum (such as space), extreme temperatures (both high and cryogenic), corrosive conditions, dust, radiation, and clean environments, sometimes in combination. Materials selected for solid lubrication not only need to exhibit low coefficients of friction (ranging from ~ 0.001 to 0.3) but also must demonstrate durability across the aforementioned challenging conditions.

Despite the availability of various methods for fabrication of composites that contain either a single or a combination of solid lubricants, powder metallurgy (P/M) has emerged as the best approach for producing high-quality products. Powder metallurgy is a solid-state process that enables the fabrication of components with different physical and chemical properties, such as diverse melting temperatures, density differences, coefficients of thermal expansion, and high reactivity etc. The method offers several advantages, including uniform dispersion of components, enhanced structural stability, improved surface finish, precise dimensional control, and strong bonding between the matrix and reinforcement materials.

Nickel-based alloys exhibit excellent mechanical properties at elevated temperatures, apart from high oxidation and corrosion resistance in harsh conditions, 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 low wear resistance at elevated temperatures impedes their applicability. It has been shown that the friction and wear performance of Ni-based alloys can be improved by adding alloying elements and/or other reinforced phases, and solid lubricants and regulating the reaction sintering process. Despite considerable progress in the field of high temperature self-lubrication, tribologists and engineers are still facing tremendous issues in ensuring adequate lubrication of moving components at high temperatures. As a result, concerted efforts are being made by the researchers to synthesise the novel solid lubricants/composite materials/coatings that fulfil the requirements of not only realising the effective lubrication in modern mechanical systems at elevated temperatures but also to endure low friction and low wear properties across a range of temperatures starting from room temperature to as high as 800 or 1000 ^{o}C. The fabrication of self-lubricating composites containing a combination of low and high temperature solid lubricants has emerged as the most promising approach for attaining anti-friction and anti-wear properties over a wide range of environments as it ensures the continuous replenishment of the lubricant at the sliding surface and eliminates the constraints that arise due to the shorter life span of coatings.

Numerous studies are available in published literature involving solid lubricants such as soft metals (Cu, Au, Ag, etc.), layered materials (*h*-BN, MoS_2, WS_2, graphite and its derivatives 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.) and their combinations to achieve effective lubrication over a wide range of temperature. However, the tribologists are still exploring new combinations of solid lubricants to attain low friction and low wear characteristics in composites over an extended regime of temperatures. Silver has long been used as a solid lubricant at moderate temperatures (< 500 °C) due to its easy shearing ability at room temperature and high diffusion coefficient at relatively higher temperatures. Reduced graphene oxide (rGO), a graphite derivative, has also emerged as a potential solid lubricant due to its layered structure, which provides low shearing ability due to weak interlayer bonding. Hexagonal boron nitride (*h*-BN), with its lamellar structure, high thermal stability, chemical inertness, and excellent thermal conductivity has also been indicated to be a promising high temperature solid lubricant. However, poor dispersion ability of rGO and poor sintering as well as non-wetting properties of *h*-BN have restricted their use in metal matrix composites. It has been reported that the doping (modification) of rGO and *h*-BN with Ni effectively improve the above-mentioned characteristics. Hence, there is a need to explore the high temperature tribological performance of the combinations of Ag-(Ni-doped rGO), Ag-(Ni-doped *h*-BN) and Ag-(Ni-doped rGO)-(Ni-doped *h*-BN) as solid lubricants in Ni alloy-based composites.

In summary, the present investigation is aimed at synthesizing the reduced graphene oxide (rGO) and hybrid nanomaterial having two materials i.e., Ni-doped rGO (rGO-Ni), and Ni-doped *h*-BN (*h*-BN-Ni), which may provide improved lubricating properties as compared to single material due to the better wettability of Ni-doped rGO and Ni-doped *h*-BN in comparison to undoped rGO and *h*-BN, respectively. These hybrid materials may have the potential applications in various industries, including aerospace, automotive, and manufacturing and may also be used as lubricants either in engines/machines to reduce wear and increase efficiency. The main focus of the present study is to prepare the Ni alloy-based self-lubricating composites containing a fixed amount of Ag (10 wt.%), rGO (1.0 wt.%), and different contents rGO-Ni (0.5, 1.0, 1.5, and 2.0 wt.%) and *h*-BN-Ni (2, 4, 6, and 8 wt. %), and to evaluate their tribological performance at different temperatures of RT, 200, 400, 600, and 800 ºC. The combinations of Ag-rGO, Ag-(Ni-doped rGO), Ag-(Ni-doped *h*-BN), and Ag-(Ni-doped rGO)-(Ni-doped *h*-BN) are expected to endow enhanced anti-friction and anti-wear properties to Ni alloy-based composites over a wide range of temperatures. The study also intends to examine the occurrence of a probable synergistic action between these solid lubricants in expanding the regime of effective lubrication from room to elevated temperatures.