CHAPTER 1

INTRODUCTION

Tribology, the science and technology of interacting bodies in relative motion, encompassing friction, wear and lubrication is fascinating but highly complex and interdisciplinary subject involving many research fields such as physics, mathematics, chemistry, materials science, mechanical engineering and therefore, connects both basic and applied sciences. However, tribology continues to be unknown to most of the people despite its enormous contribution to the industries as well as to the everyday life. The industrial world is full of machines of every kind that contain moving parts contacting each other. Tribology is of fundamental importance for understanding what happens at these interfaces and is essential for design and reliability of the machines. For instance, there is a strong urge today for machines that use less energy for the same output and have components that last longer in service, and tribology can play a very important role for their design and for online monitoring to increase the lifetime of the components.

The control of friction and wear at the interfaces of contacting surfaces is vital for the smooth, reliable, efficient and long-lasting operations of machines. Wear has been reported to be more critical than friction as it results in catastrophic failures and operational breakdowns that adversely affect the productivity and cause huge losses to economy. A recent study conducted on frictional and energy losses in transportation, manufacturing, power generation and residential sector by Holmberg and Erdemir (2017) has 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 saving up to 1.4% of the GDP annually, by utilizing new materials, lubricants and surface modifications technologies. Considering that significant percent 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 methods and materials to minimize friction and wear. Hence, a significant effort is being directed toward (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).

Due to technological development there is an increasing need to develop mechanical systems capable of running under severe conditions i.e., high loads, speeds and temperatures, etc. The friction and wear behavior of materials at elevated temperatures is of vital concern due to the changes that occur in bulk mechanical properties, bulk thermo-physical properties, surface reactivity and tribo-chemical reactions. Since there are few viable liquid or solid lubricants that work well at temperatures beyond 500 ^{0}C, a number of high temperature applications for contacting metals depend on the ability of the contacting surfaces to self-lubricate based on reactions with their environments and their ability to form protective glazes (tribo-layers) during the contact process as suggested by Blau (2010). In an effort to improve the performance of materials at elevated temperatures, attempts are being made use alternate materials or coatings with superior oxidation resistance and enhanced lubricating capabilities at elevated temperatures.

Self-lubricating materials form a broad class of compounds featuring the incorporation of one or more solid lubricants, which reduce friction and wear in industrial applications involving severe sliding contacts, without the need for further external lubrication. 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. The technology of solid lubrication has advanced rapidly in the past five decades, primarily in response to the needs of the aerospace and automobile industries. Solid lubricants are used where the containment of liquids is a problem and when liquid lubricants do not meet the requirements of advanced technologies such as high vacuum, high temperatures, cryogenic temperatures, radiation, dust, clean environments, or corrosive environments. The materials designed for solid lubrication must not only display desirable low coefficients of friction but must also maintain good durability in different environments. Therefore, the successful use of materials and coatings containing solid lubricants requires understanding their material and tribological properties.

The coatings containing solid lubricant coatings are primarily used to control friction and wear under severe application conditions (such as high vacuum, aerospace, high-speeds, high loads, and very low or high temperatures), where conventional materials and lubricants cannot provide the desired levels of performance or durability. During the past few decades or so, remarkable progress has been made in the design, development, and uses of solid lubricant coatings. The current trend in modern tribology is to limit or reduce the use of liquid lubricants as much as possible (mainly because of environmental concerns), and increase the use of solid materials and coatings with self-lubricating properties. Solid lubricant coatings have come a long way in recent years, and they are now capable of providing extremely low friction and wear coefficients under certain or highly controlled test conditions. At present, no single coating can provide both low friction and high wear resistance over a very broad range of temperatures and environments.

Solid lubrication over a wide range of ambient atmospheres is a challenging task that tribologists are facing from the decades and have yet to overcome as most lubricants perform efficiently, only within a narrow range of ambient conditions. The most well-known solid lubricants, such as graphite, molybdenum disulfide, and PTFE are effective from low temperatures up to 250–400 °C in air, above which they oxidize or decompose and lose their lubricity. Some oxides lubricate well above 600 - 800 °C, but act as abrasives at lower temperatures. Since it is impossible for a single lubricant to provide the lubrication over a wide spectrum of temperatures, therefore, a successful approach is to use a combination of solid lubricants and use their interaction with the environment to generate lubricious species at the interface to attain low friction and wear over a range of temperatures. Hence, the study on synthesis and tribological characterization of coatings containing a combination of low and high temperature lubricants to extend the regime of effective lubrication over a wide range of temperatures assumes significance.

Nickel is an element that can be alloyed with a variety of elements such as: iron, chromium, aluminum, titanium, tungsten, molybdenum, silver and cobalt having a high solubility. Ni-based alloys are used in several industrial applications such as gas turbine parts, medical applications and nuclear systems, which mainly solve wear resistance, corrosion and thermal fatigue problems. Silver is a widely used as a solid lubricant because it has a larger coefficient of diffusion and forms lower shear stress junctions at sliding interface resulting in good lubrication at temperatures about less than 500 ^{0}C. This characteristic of silver either alone or in conjunction with other solid lubricants has been effectively utilized by several researchers, in composite coatings for high temperature tribological applications. Among solid lubricants presently being used, molybdenum disulfide (MoS_2) holds special importance, due to its lamellar structure which comprises of individual atomically-thin planes that can easily slide against each other. MoS_2 can be used as a dry lubricant by itself, as an additive in oils or greases, or as an individual component of a composite coating and has the ability to lubricate effectively in oxygen-deficient environments. Combined with its ability to operate reliably in a wide range of temperatures (from the cryogenic regime to several hundred degrees Celsius), the ability to function effectively in vacuum makes MoS_2 a particularly attractive lubricant for aerospace/space applications. However, still active researches are underway on understanding and improving the lubricating properties of MoS_2, that focus on its interactions with other lubricants to generate new lubricious phases at elevated temperature through tribo-chemical reactions.

Hexagonal boron nitride (hBN), another solid lubricant possessing lamellar structure, is being used for high-temperature metalworking processes and wear sealing materials of aerospace engines. The high thermal stability, good chemical inertness, and high thermal conductivity, besides its white color, make it a potential candidate to be used as a ‘clean’ lubricant. However, despite its non-wetting and poor sintering characteristics, its use as a solid lubricant in composites and coatings is currently being evaluated for elevated temperature applications.

Thermal spraying is a versatile coating technique that utilizes a plasma, electric, or chemical combustion heat source to melt a set of intended materials and spray the melt on the surface to produce a protective layer. The thickness attained can range from 20 μm to several millimeters which is significantly higher in comparison to the thickness achieved in electroplating, physical vapor deposition (PVD) or chemical vapor deposition (CVD) processes. In plasma spray process, a plasma gun provides a high-temperature DC/induction plasma (up to 10000 K), which can easily melt refractory metals, ceramics, and polymers. The materials to be deposited are fed into hot plasma stream and the high temperature melts the feedstock. Due to the high speed of plasma at the tip of a converging nozzle, the molten droplets are deposited instantly on the substrate. The flexibility of this process facilitates the utilization of different types of feedstock such as powder, slurry, suspensions, and liquids. The resulting coating layer has a high corrosion and wear resistance and it is able to adhere to the substrate due to surface tension and high temperature.

In recent years, a number of solid lubricants (e.g., graphite, MoS_2, hBN, Ag, PbO, $SrSO_4$, WS_2, $BaMoO_4$, $BaCr_2O_4$, CeF_3, CaF_2/BaF_2 etc.) and their combinations have been incorporated in Ni-based composite coatings, to obtain favorable frictional properties and increased wear resistance to extend the regime of effective lubrication from room temperature (RT) to elevated temperatures (1000 ^{0}C). Among these, the high temperature tribological behavior of the combination of Ag, MoS_2 and hBN has not yet been fully explored.

In summary, the present study has been conducted to examine the friction and wear behavior of atmospheric plasma spray deposited Ni-based solid lubricating composite coatings containing Ag, MoS_2 and hBN at different loads (5, 10, 15 and 20 N), speeds (0.3, 0.5, 0.7 and 0.9 m/s) and temperatures (RT, 200, 400, 600 and 800 ^{0}C). The main focus of the study is to explore the possibility of a synergetic action among hBN, Ag and MoS_2 in achieving low friction and low wear under the conditions used in the present investigation. The knowledge base generated through the study is expected to enhance the understanding of the tribological behavior of these Ni-based coatings containing a combination of solid lubricants and help in utilizing their potential for high temperature applications.