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Effect of nano coatings on Ni- based superalloy and its tribological characterisation at high temperature

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***Abstract*— The aim of this work is to obtain a better understanding of the friction and wear mechanisms of Ni based superalloys at high temperature on the tribological pairs. The experimental studies were carried out by using a high temperature version of the friction and wear test sophisticated machine. The tribological studies were performed at temperatures ranging from 25 ° C to 1000 ° C. The materials used in the experiments were Ni based superalloys of three different alloying compositions (with and without coatings). The coatings materials used on the base substrate of Ni based superalloys over were ZrO_2, Y_2O_3, HfO_2 coated through atmospheric plasma spraying techniques (APS) with the nominal compositions and with desirable process parameters to influence on the properties of base substrate to improve in applications. The results thus prove that both friction and wear of the tribological behaviour of materials are temperature dependent. The corresponding results of wear and friction will be obtained experimentally would show the wear resistance and thereby decrease in friction at high temperature. Hence the coating undergoes significant surface morphological changes when exposed to elevated temperatures, which are likely to influence greatly to its tribological behaviour accordingly.**

Keywords—tribological behaviour; airplasma spray technique; high temperature applications; Ni-based superalloy; coating materials

I. INTRODUCTION

Tribological interfaces are quite complex which were exposed to elevated temperatures in various applications. Typical examples are the interfaces of various moving assemblies such as in metal working processes, power generation and aerospace industry. At elevated temperatures, the exposure of materials is subjected to changes in morphology, microstructure and mechanical properties coupled with the occurrence of oxidation and diffusion phenomenon respectively. The above mentioned changes influence greatly on the tribological behaviour of materials at high temperatures. The main reason for wear and energy losses is friction, which reduces relative motion between two bodies or resists the tendency to motion between two bodies in contact. It depends upon the geometry, macroscopic contact points, elastic properties, adhesive forces, deformation of the surface during movement etc. Whereas the wear is the loss of material and is expressed in terms of volume that affected by loads, speed, temperature, contact type, type of environment etc. Another important major concern pertaining with reference to tribological behaviour at elevated temperature is lubrication, since conventional lubricants do not perform at temperature above 300 ° C. Reviews of published literature revealed that only a few studies pertaining to high temperature tribological behaviour (including those of in aerospace applications) have been carried out so far. The understanding of the high temperature tribological behaviour of Ni based superalloys is also highly inadequate. The aim of this research work is to obtain a better understanding of the tribological pairs by friction and wear mechanisms of coated and uncoated materials over Ni based superalloys at high temperature. The experimental studies were carried out by using a higher version of the friction and wear tester machine and the tribological studies were performed at temperatures ranging from 25 ° C to 1000 ° C in a real time conditions with base substrate of IN 718 and Superni 718 over which the aid of coatings ZrO_2, Y_2O_3, HfO_2 respectively.

II. REVIEW OF LITERATURES

Ni- based superalloys especially on the applications of gas turbines which typically constitute 40-50% of the total weight of an aircraft engine have been worked out past by various Tribologists and Researchers on the issues. They are mostly employed in combustor and turbine regions where high temperatures are maintained during operation [1, 27, 30]. Aero engines, gas turbines, turbo chargers etc. working at high temperature environments should possess the properties to withstand operating conditions from room temperature to the possible high temperature utilization. These components whether reliable in these environments such that the applications should withstand the tribological characteristics is a challenge. Schafrik [1, 2], et al. on these Ni-based superalloys stated that approximately 50% of the total weight of an aircraft engine which resists high temperature such as turbines, combustors and other related components most extensively employ Ni-based superalloys. Which possess high resistance to corrosion, oxidation and also maintain its stability over a period of time but the behaviour of superalloys at high temperatures becomes one of the major life-limiting factors in terms of wear. Since, surface temperature of gas turbine blades can reach up to 1150 ° C, operating parameters determines ability of the material and life for a longtime. To overcome this effect blades are coated with materials from surface temperature point of view as well as tribo-oxidation [12, 17, 19], tribo-corrosion [3], tribo-erosion and other forms of wear, extensively used in the gas turbines.

Stott [4-9, 11] experimented on the Ni-based superalloys revealed hard glazed oxide layer tends to form on the surface when the temperature increases resulted in reduction of friction and wear. Pollock [10, 11], et al. emphasized on the properties due to major and minor alloying elements, understood about integration of the material design processes at par with complexities of the materials which works at high temperature resulting better properties in reactive environments. Hatab [12], experimented in air at high temperature cyclic oxidation, concluded that oxidational behaviour is due to the diffusion of substrate elements in the alloy. Envisaged, on the oxide scale and oxidations rate, advised major oxides responsible for protection against high temperature oxidation are Cr_2O_3 [17], Fe_2O_3, NiO and $NiCr_2O_4$ and thus maintains low parabolic rate constant. Gupta [13], et al. analyzed major oxides formations is a 20% by weight ferrous and nickel based superalloys shows better oxidation resistance. Kim [14], et al. showed severe wear (adhesive) regardless of contact stress but at high temperature and high pressure shows low wear. The results are on the wear protective oxide layer on wear surface hardly oxidative wear. Jiang [15], et al. concluded in different forms that the transition of severe to mild wear during sliding can occur due to formation of wear protective oxide layers in various steps.

Dosovitskiy [16], et al. experiments, stated thermo physical stability is important, for coatings, base substrate. Wear Resistance is also an important property in these alloys which dominates failure in service condition at any temperature and encapsulated it can be improved by selecting a suitable coating materials and processes. Wang [18], et al. on NiCrAlY of 10 micrometer thicknesses coated over IN 100 and heat treated at 950 °C–1050 °C in a vacuum atmosphere for 2 hours exhibits the parabolic oxidation behaviour. Deflora [19], et al. points out if the working condition of the materials are at contacts under a specific load, the mechanical-chemical and diffusion phenomena can occur and thus wear mechanisms occurring at these points of asperities at macro, micro and nano level stipulates the importance of abrasion and tribo-oxidative wear at high temperatures which shown hot wear. Vencl [20], on the atmospheric plasma spraying revealed about quality of coating and the production of coating are still based on trial and error approach. Sue [21], et al. using ring- on-disc for the Inconel 718 for the uncoated with the coatings of TiN, ZrN, CrN under a normal load of 267 N at sliding speed of 1.24 ms-1 and sliding distance for 2.3 km at 500 ° C and 600 ° C respectively.

Suryanarayana [22], et al. defines powder processing technique called as Mechanical Alloying (MA) in synthesizing superalloys. It also states that decrease in particle size of the order of few microns to few nano levels would improve strength simultaneously, improves in mechanical properties. Blachnio [23], et al. focused on their work on the damageability of gas turbine blades and emphasized on durability of turbine vane and blades are the sum of factors, where material quality is matter of crucial importance. The colors of oxide layers also changes for increase in temperature and also indicates the materials constituents with amount of oxides formed during in service and are air-cooled respectively. ASM International [24], on thermal spray details about three advantages of processes and on various properties of importance for an aero gas turbines viz., resistances on wear, heat, corrosion, oxidation achieved along with clearance and dimensional control which favours Atmospheric Spray processes (APS). The tribological testing at high temperature in different environments for the aged coatings of materials should result minimum friction and very low wear.

Fernandes [25], et al. experimentally investigated on influence of the addition of nanostructure zirconia particles on microstructure, micro-hardness and wear performance of Colmonoy88 deposited by atmospheric plasma spraying on low carbon steel (AISI 8620). The wear rate was calculated by using Archards law for wear. It’s evident from the tests results that the nanostructured ZrO_2 showed improvement in hardness and wear behaviour of coatings, and decrease in the friction coefficients. Kumaragurubaran [26], et al. investigated on the Atmospheric Plasma Spray process parameters which are suitable Thermal Barrier Coatings of 7-8% Yttria-Stabilized-Zirconia powders for Ni-based superalloys concludes that Optimization of plasma spray process involves multiple factors which are desirable input variables for achieving the required qualities of coatings. Thermal Barrier Coatings [28], are now widely used in turbine engines, a ceramic layer is deposited onto the superalloy, which provides thermal insulation due to its low thermal conductivity and lowers the temperature of metallic contact. Daroonparvar [29], et al. reviewed that the nickel based superalloy and zirconia coating, as turbine blade were protected against high temperature corrosion, oxidation by thermal barrier coatings using atmospheric plasma spraying technique on Inconel 617. The coatings consist of laminar structure with interconnected porosity transferred oxygen from Yttria stabilized Zirconia layer toward the bond coat (NiCrAlY). The YSZ with higher Al content showed higher oxidation resistance. Fernandes [31], et al. experimented on coatings produced by mechanical alloying shows highest wear resistance on coatings and nanostructured ZrO_2 coating displays the worst wear resistance. Beele [32], et al. dealt with quality of APS coatings than to the flexibility and economical aspects. The structure of APS coatings consists of pores and cracks that are parallel to the interface. These pores and cracks result in APS coatings having a lower thermal conductivity and they have thus a greater effect.

Fauchais [33], showed improvement in conventional plasma spraying technologies towards spraying of nano-structured coatings, with coating thicknesses between a few and hundreds of µm, which can be either dense or very porous. Also, studies revealed the progress by spraying either agglomerates of nano-sized particles in a mushy state or suspensions of nano-size particles. Osorio [34], et al. stated TBC system was thoroughly characterized after exposure to a high temperature. The top coat, Y_2O_3-stabilized ZrO_2, was initially composed of a mixture of tetragonal and cubic phases. Exposure to 1100 ° C for 600 h reduced the stability of the tetragonal phase and a fraction of the monoclinic phase was formed during cooling. After 600 h, the amount of the monoclinic phase increased with exposure time, reaching 23.4 wt% in samples exposed for 1700 h. The TGO was essentially composed of Al_2O_3. However, after 800 h of exposition to 1100 degree C complex, highly porous (Ni, Cr) - enriched oxides were formed. These oxides are expected to reduce the fatigue strength of the coatings due to their effect on crack generation and propagation. After 600 h, the TGO reached a thickness of 5 µm, which is considered critical for catastrophic failure of the TBC system. Nevertheless, no delamination was observed at any point during the tests, even though the TGO thickness after 1700 h was 6.7 µm. The microstructure of the Inconel 625 substrate after exposure to a high temperature was composed of austenite and a large amount of Mo-rich precipitates. Eliaz [35], et al. classified hot corrosion as LT and HT based on various characteristics and mechanisms, since this failure mechanisms either totally prevented or detected at an early stage to avoid catastrophic failure. Hence, in this work a tribological comparison between Ni-based superalloy compositions obtained by the suitable parameters for Atmospheric Plasma Spray techniques conducted with nano structured materials of ZrO_2, HfO_2, Y_2O_3.

A. *Existing gaps in present research:*

The present applications for Ni based superalloys are mostly as stationary and dynamic parts in the aerospace applications however, there is an emerging interest to utilize these materials. A careful survey of literature revealed that there are hardly any published results pertaining to tribological properties of these materials available in the open literature. It is therefore necessary to investigate the friction and wear characteristics of these superalloys with a view to exploiting the useful properties of this interesting category of materials for utilization in various tribological applications. It is evident from the literature survey on high temperature tribology in general and hot aerospace applications in particular, as well as the tribological behaviour of Ni based superalloys, that there are several aspects that need to be investigated further. In the field of high temperature tribology for superalloys there are still insufficient explanations regarding the mechanisms governing friction and wear behaviour. This is also the case in general for tribological interfaces that are exposed to elevated temperatures. Another aspect to be investigated further is to identify conditions and material pairs which facilitate formation of certain surface layers that provide desirable optimal friction and low wear.

III. EXPERIMENT AND ANALYSIS

A. *Problem Identification*

The addition of nanostructured coating materials Zirconia, Hafnia, Yttria over the base substrates of Ni-based superalloys IN 718 and Superni 718 and their influences which were deposited by air plasma spray techniques have been identified. Hence it shows improvements on properties as micro- nano- structure, hardness but the types of wear dominant at high temperature need further studies and experimental steps which were unclear. The process parameters of APS techniques influence on harsh environments, especially hot corrosion, oxide formation, porosity as a major concern.

IV. Sample Preparation

The samples were as base- substrate IN 718 and Superni 718, obtained from Midhani, Hyderabad as per ASTM standard in the materials point of view. Nano- coating materials were procured from Sigma Aldrich and Air Plasma Sprayed as per the given process parameters. Materials chosen at par with real time applications were prepared, cleaned, degreased.

1) *Microhardness Tests*

The hardness of the material tested using Hardness testing machine, such that indentation on the surface withstands the load and correspondingly hardness of the material been taken into account applicable with power density ratio.

2) *Polishing and Surface Roughness*

The fine grade and super fine grade emery is used to clean and polish as mirror finish which is free from dust, rust.

V. Nano Powder Coating

The nano powders of Zirconia, Hafnia, Yttria were selected as per the requirement and the design to be complex while coating with the nominal process parameters through air plasma spraying techniques.

1) *Polishing and Surface Roughness*

Surface waviness, asperities after coating needs uniform distribution of material composition, improves limitations.

2) *Microhardness Tests*

To establish functionality of the base substrate with coating substrate, improved hardness properties to be resulted.

VI. Surface Morphological Tests

The surface topography of test specimen to be measured by using surface profiler, there by 3D topographical image of the surface is to be obtained. The surface morphology of test specimens and the type of wear mechanisms that are present were studied by using Scanning Electron Microscopy (SEM) allied by Energy Dispersive Spectroscopy (EDS) technique. Interesting surface morphological changes is to be obtained resulting in complete diffusion of nano materials.

VII. Tribological Tests

The main objective is to obtain the better understanding about the mechanisms that govern the friction and wear behaviour through experimentally investigating on base substrates with the coating substrates at high temperatures. The test equipment utilized in these studies at elevated temperatures is a high temperature version of reciprocating friction and wear tester. The machine utilizes an electromagnetic drive to oscillate an upper specimen, which is loaded by means of a spring and servomotor arrangement against a stationary lower specimen which can be heated to 1000 ° C by a heating cartridge positioned under the specimen. The friction force is measured by two piezoelectric force transducers mounted at the base of the lower specimen holder. A computerized control and data acquisition system enables accurate control and recording of load, temperature, frequency, stroke length, friction force and duration.

TABLE I TEST PARAMETERS FOR TRIBOLOGICAL TESTS

S.No	Test parameters	Range of Values
1.	Load, (N)	10 - 50
2.	Temperature, (°C)	25 - 1000
3.	Stroke length, (mm)	2
4.	Frequency, (Hz)	50
5.	Duration, (mins.)	- 30

VIII. ANALYSIS

The probable contamination leading to high temperature corrosion is also affected due to material selection and coating, as well as the uncommon source of mechanical damage erosion due to carbon deposits. The selected alloys and probable coatings would able to withstand very aggressive environments of high temperature and high stress found within the hot gas path of a turbine engine. The oxidation phenomenon is also a threat in this experimental regime pertaining to severe wear causing complete damage to the gas turbine applications. Tribological characteristics such as friction and wear reflect the suitability of the applications with respect to the various desirable and undesirable conditions of working at par with the competitive edge. The formation of thick or thin glazed oxide layer on the sliding pairs will be showing elemental distribution of its constituents including the wear track surface features. Particularly the necessary use of Air Plasma Spray technique, which is an art of state processes deals with the various possible parameters and effectively work on the design for better usage and thus prove its stability over failure modes of current scenarios.

IX. RESULTS AND DISCUSSIONS

Addition of nanostructured materials over the base substrates of Ni-based superalloys would show improvements on properties as its structure, hardness and the types of wear at high temperature have been studied. The experimental procedure and process parameters of Atmospheric Plasma Spraying techniques influences greatly on various harsh environments, such as hot corrosion, oxide formation, porosity etc. In the high temperature tribology for superalloys, mechanisms governing friction and wear behaviour depicts extraordinary tribological interfaces of the material pairs which will facilitates formation of certain surface layers, provides desirable optimal friction and low wear rate. Thus proves that both friction and wear of the tribological behaviour of materials are temperature dependent and corresponding experimental results of wear and friction will be obtained would show the wear resistance and thereby decrease in friction at high temperature. Integration of the material design and mechanical design processes remains an interesting challenge and opportunity from this review of research. Hence the nano- based coating undergoes significant surface morphological changes on the base substrate when exposed to elevated temperatures, are likely to influence greatly to its tribological behaviour.

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