AIR PLASMA SPRAYING BEHAVIOUR ON ZrO_2 AND Y_2O_3 OVER NI-BASED SUPERALLOY, AT HIGH TEMPERATURE AND ITS EFFECT ON TRIBOLOGICAL CHARACTERISATION - A REVIEW

[1]SUBASH CHANDRA BOSE SOMU, [2]MOHAMMAD FAROOQ WANI

[1] Research Scholar, Department of Mechanical Engineering, NITSrinagar, Srinagar, India.
[2] Professor, Department of Mechanical Engineering, NITSrinagar, Srinagar, India
E-mail: [1]nitsri.bose@gmail.com

Abstract— The studies were carried out using a high temperature version of the friction and wear test sophisticated machine which 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 desirable process parameters to influence on the properties of base substrate to improve in applications. The results prove both friction and wear of tribological behaviour of materials with the coatings are temperature dependent. The aim of this work is to obtain a better understanding of friction and wear mechanisms of Ni based superalloys at high temperature on the tribological pairs. The corresponding wear and friction 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— Airplasma Spraying, Coating Materials, High Temperature Tribology, Ni-based Superalloy.

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 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, 23]. 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 [10, 14, 16], tribo-corrosion [3], tribo-erosion and other forms of wear, extensively used in the gas turbines.

Stott [4-8] experimented on the Ni-based superalloys revealed hard glazed oxide layer tends to form on the surface when temperature increases resulted in reduction of friction and wear. Pollock [9], et al. emphasized on the properties due to major and minor alloying elements, understood integration of material design processes at par with complexities of materials which works at high temperature resulting better properties in reactive environments. Hatab [10], experimented in air at high temperature cyclic oxidation, concluded that oxidational behaviour is due to diffusion of substrate elements in the alloy. Envisaged, on oxide scale and oxidations rate, advised major oxides responsible for protection against high temperature oxidation Cr_2O_3 [14], Fe_2O_3, NiO and $NiCr_2O_4$ and maintains low parabolic rate constant. Gupta [11], et al. analyzed major oxides formations is 20% by weight ferrous and nickel based superalloys shows better oxidation resistance. Kim [12], et al. showed severe wear (adhesive) 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. Dosovitsky [13], 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 [15], 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 [16], et al. points if working condition of materials are at contacts under a specific load, mechanical-chemical and diffusion phenomena can occur and thus wear mechanisms occurring at these points of asperities at macro, micro and nano level stipulates importance of abrasion and tribo-oxidative wear at high temperatures which shown hot wear. Vencl [17], on atmospheric plasma spraying revealed about quality of coating and production of coating are still based on trial and error approach.

Suryanarayana [18], 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 [19], 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 [20], 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 [21], 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 nanostructured ZrO_2 showed improvement in hardness and wear behaviour of coatings, and decrease in friction coefficients. Kumaragurubaran [22], et al. investigated on Atmospheric Plasma Spray process parameters which are suitable Thermal Barrier Coatings of 7-8% Yttria-Stabilized-Zirconia powders for Ni-based superalloys concludes Optimization of plasma spray process involves multiple factors which are desirable input variables for achieving the required qualities of coatings. Thermal Barrier Coatings [24], are now used in turbine engines, a ceramic layer is deposited onto the superalloy, which provides thermal insulation due to its low thermal conductivity and lowers temperature of metallic contact. Daroonparvar [25], 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 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 [26], et al. studied on coatings produced by mechanical alloying shows highest wear resistance on coatings and nanostructured ZrO_2 coating displays worst wear resistance.

Fauchais [27], 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 [28], et al. stated TBC system was thoroughly characterized after exposure to a high temperature. The top coat, Y_2O_3-stabilized

ZrO_2, exposed 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. 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 [29], 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.

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 in general for tribological interfaces, are exposed to elevated temperatures. Another investigation 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

3.1 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 shows improvements on properties, micro- nano- structure, hardness but the types of wear dominant at high temperature need further studies and experimental steps which unclear. The process parameters of APS techniques influence on harsh environments, hot corrosion, oxide formation, porosity as major concern.

3.2 Sample Preparation

The samples were as base- substrate IN 718, Superni 718, from Midhani, Hyderabad as per ASTM standard in the materials point of view. Nano- coating materials were 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.

i) *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.

ii) *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.

3.3 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.

i) *Polishing and Surface Roughness:* Surface waviness, asperities after coating needs uniform distribution of material composition, improves limitations.

ii) Microhardness Tests: To establish functionality of the base substrate with coating substrate, improved hardness properties to be resulted.

3.4 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 allied by Energy Dispersive Spectroscopy technique. Interesting surface morphological changes is to be obtained resulting in complete diffusion of nano materials.

3.5 Tribological Tests

The main objective is to obtain better understanding about the mechanisms that govern friction and wear behaviour through experimentally investigating on base substrates with 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 measured by 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 - 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.)		15 – 30

3.6 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 attains the required properties. 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.

IV. 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. 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.

CONCLUSION

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. 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.

ACKNOWLEDGMENT

The author wish to express their sincere thanks and gratitude to the board of management and governing council of NITSrinagar for their continuous moral support and guidance in the light of progress.

REFERENCES

[1] R. Schafrik and R.Sprague. Saga of Gas Turbine Materials: Part III. *Advanced Materials and Processes,162*, 27–30, 2004.

[2] H. Harada and T. Yokokawa. Present and Future of Ni-base superalloys: Toward higher Temperature Capabilities. *Journal of the Gas Turbine Society of Japan, 31*, 51-60, 2003.

[3] G.W. Stachowiak and A.W. Batchelor. *Engineering Tribology*. Butterworth-Heinemann, 2000.

[4] F. H. Stott. High temperature sliding wear of metals. *Tribology International, 35*, 489-495, 2002.

[5] A. Pauschitz, M. Roy and F. Franek. Mechanisms of sliding wear of metals and alloys at elevated temperature. *Tribology International, 415*, 84-602, 2008.

[6] J. Yoshihisa, F. Yokoyama, T. Yamasaki and N. Ohmae. The tribological characteristics of Ni-Cr cast alloy at 1000 degree C in air. *Tribology Online, 5(1)*, 27-32, 2010.

[7] I. A. Inman and P.S. Datta. Development of a simple 'temperature versus sliding speed' wear map for the sliding wear behaviour of dissimilar metallic interfaces II. *Wear, 265*, 1592-1605, 2008.

[8] S. R. Rose. *Studies of the high temperature tribological behaviour of some superalloys*. Ph.D. thesis, University of Northumbria, Newcastle, UK, 2000.

[9] M. T. Pollock and S. Tin. Nickel-based superalloys for advanced turbine engines: Chemistry, Microstructure, and Properties. *Journal of Propulsion and Power, 22(2)*, 361–374, 2006.

[10] A. K. Hatab, A. M. Bukhaiti and M. Kanthem. Cyclic Oxidation Behavior of IN 718 Superalloy in Air at High Temperatures. *Oxidation of Metals, Springer, 75(3-4)*, 209-228, 2011.

[11] O. P. Gupta, D. Mudgal, D. Puri and S. Prakash. High temp. cyclic oxidation of Ni based superalloys at 900 degree C in air. *International Journal of Advanced Scientific Research and Technology, 2(2),* 486-492, 2012.

[12] S. J. Kim and J. K. Kim. Effects of temperature and contact stress on the sliding wear of Ni-base Deloro 50 hardfacing alloy. *Journal of Nuclear Materials, 288,* 163-169, 2001.

[13] G. A. Dosovitskiy, S. V. Samoilenkov, A. R. Kaul and D. P. Rodionov. Thermal expansion of Ni-W, Ni-Cr, Ni-Cr-W alloys between room temperature and 800°C. *International Journal of Thermophysics, Springer, 30,* 1931-1937, 2009.

[14] M. Erdem and M. Turker. High temperature oxidation behaviour of a Ni based superalloy produced by mechanical alloying. *Scientific Research and Essays, 7(48),* 4123-4129, 2012.

[15] M. Wang. MCrAlY of IN 100 and heat treated at 950 at 1050 deg. C in a vacuum atmosphere for 2 hours exhibits the parabolic oxidation behaviour. *Surface and Coatings, Wear, 203,* 2186-2192, 2009.

[16] M. G. DeFlora and M. Pellizari. Behavior at elevated temperature of 55NiCrMoV7 tool steel. *Material and Manufacturing Processes, Taylor and Francis, 24,* 791-795, 2009.

[17] A. Vencl, M. Mrdak and I. Cvijović. Microstructures and tribological properties of ferrous coatings deposited by Atmospheric Plasma Spraying) on Al-alloy substrate. *FME Transactions, 34(3),* 151-157, 2006.

[18] C. Suryanarayana and N. A. Aqeeli. Mechanically alloyed Nano composites. *Progress in Materials Science, 58,* 383–502, 2013.

[19] J. Blachnio and W. I. Pawlak. Damageability of Gas Turbine Blades – Evaluation of Exhaust Gas Temperature in Front of the Turbine Using a Non-Linear Observer. *Advances in Gas Turbine Technology*, ISBN: 978-953-307-611-9, InTech, Croatia, 2011. Available from: http://www.intechopen.com/books/advances-in-gas-turbine-technology/damageability-of-gas-turbine-bladesevaluation-of-exhaust-gas-temperature-in-front-of-the-turbine-us

[20] ASM International. Introduction to Thermal Spray Processing, *Handbook of Thermal Spray Technology* (pp. 3-13). Ohio: ASM International, 2004.

[21] F. Fernandes, A. Ramalho, A. Loureiro, J. M. Guilemany, M. Torrell and A. Cavaleiro. Influence of nanostructured ZrO2 additions on the wear resistance of Ni-based alloy coatings by APS process. *Wear, 303,* 591–601, 2013.

[22] B. Kumaragurubaran, T. P .S. Kumar, T. S. Kumar and M. Chandrasekar. Optimizing the Plasma Spray Process Parameters of Yttria Stabilized Coatings on Aluminum Alloy Using Response Surface Methodology. *International Journal of Engineering and Advanced Technology (IJEAT), 2 (5), 377-384,* 2013.

[23] F. C. Campbell. Chapter 6–Superalloys. *Manufacturing Technology for Aerospace Structural Materials*, (pp. 211-272), 2006.

[24] K. Vaidyanathan, D. Pease, E. Jordan, H. Canistraro, M. Gell and T. Watkins. A Diffractometer for X-ray studies of TBC bond coats beneath Zirconia top coats, JCPDS-International Centre for Diffraction Data 2002. *Advances in X-ray Analysis, 45,* 48-53, 2002.

[25] M. Daroonparvar, M. M. Atabaki, M. A. M. Yajid, M. Sakhawathussain, M. Asgharifar and N. M. Yusof. Micro structural characterization of thermal barrier coating on Inconel 617 after high temp. Oxidation. *Association of Metallurgical engineers of Serbia, AMES, Metall. Mater. Eng.19 (2),* 95-106, 2013.

[26] F. Fernandes, A. Ramalho, A. Loureiro, J. M. Guilemany, M. Torrell and A. Cavaleiro. Influence of nanostructured ZrO_2 additions on wear resistance of Ni-based alloy coatings deposited by APS process. *Wear, 303,* 591–601, 2013.

[27] P. Fauchais. Understanding plasma spraying. *Journal of Physics D: Applied Physics, 37,* 86–108, 2004.

[28] J. D. Osorio, J.P. Hernandez-Ortiz and A. Toro. Microstructure characterization of thermal barrier coating systems after controlled exposure to a high temperature. *Ceramics International, 40,* 4663–671, 2014.

[29] N. Eliaz, G. Shemesh and R. M. Latanision. Hot corrosion in gas turbine components. *Engineering Failure Analysis, 9,* 31-43, 2002.

★★★