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HIGH TEMPERATURE CORROSION AND ROLE OF PLASMA SPRAY COATINGS - A REVIEW

Shehbaaz Singh Brar[1], Dr. Gurbhinder Singh Brar[2] & Dr. Vikas Chawla[3]

Abstract- Hot corrosion is a serious problem in coal fired boilers, gas tubines, internal combustion engines etc. The purpose of this review is to explore thermal plasma spray process for coating fields. Plasma spray deposition is workable and likely to survive process for coatings for more than three decades without significantly heating the substrate. So far various researchers have done research in the field of plasma spray coatings and few of them performed these coatings on superalloys and other metals . These coatings were effective in decreasing weight gain to about one third. This paper summarizes the results of previous research done by various authors on different coatings done by plasma spraying technique.
Keywords : Plasma spray, Coatings, Hot Corrosion, High Temperature, Superalloys.

1. INTRODUCTION

Thermal spraying is an effective and low cost method to apply thick coatings to change surface properties of the components [1]. Coatings are used in a wide range of applications including automotive systems, boilers components, and power generation equipment, chemical process equipment, aircraft engines, pulp and paper processing equipment, bridges, rollers and concrete reinforcements, orthopedics and dental, land-based and marine turbines, ships [1]. Plasma spraying has been around for more than four decades and has been used to deposit a wide range of metals, ceramics and even composite materials for many different applications [2]. Despite this long and successful history, there has still been a great interest among engineers and scientists in developing new coating materials and researching phenomenon associated with the formation and application of coatings [3].

2. THERMAL SPRAYING

Thermal spraying has grown into a well accepted industrial technology. Today turbine blades and other components of aircraft engines are coated with corrosion and temperature resistant coatings but the science base for this technology is still poorly established and for certain aspects virtually non-existent. More than 35 years ago, plasma spraying was established as a commercial process, but only recently some serious attempts have been reported to establish a solid scientific base for this technology [4-5].

Spray torch and in most cases (99%) plasma spraying is achieved by using plasma torches [6 & 7]. A high intensity arc is operated between a stick-type cathode and nozzle-shaped watercooled anode. In thermal spraying, feedstock materials in the form of powder or wire are fed into a heat source of spray equipment, where they are fully or partially melted and accelerated in a gas stream toward a substrate to be coated [8]. The high temperature exposure and the following rapid quenching, which intrinsically involved in thermal spraying, can either improve or deteriorate the nanoscale microstructure of the coatings. Therefore, several challenges still remain in terms of feedstock preparation and processing itself. In order to produce a coating with desired properties, e.g. with high fracture strength, it is not sufficient to control only material structure inside one lamella. Interaction between lamellae, stress stages of the final coating, adhesion to the substrate and cracking must be also controlled [1].

Heath et al (1997) [9] has summarized the thermal spray processes that have been considered to deposit the coatings, are enlisted below:

(1) Flame spraying with a powder or wire,
(2) electric arc wire spraying,
(3) Plasma spraying,
(4) High Velocity Oxy-fuel (HVOF) spraying,
(5) Detonation Gun.

2.1 Plasma Spray Coatings

The demand for protective coatings has increased recently for almost all types of super alloys with improved strength, since high-temperature corrosion problem become much more significant for these alloys with increasing operating temperatures of modern heat engines. Among the different kinds of coating technologies, plasma spray coating should be one of the most

[1] Corresponding Author, Research Scholar, I.K.G.P.T.U, Jalandhar-148107, India
[2] Mechanical Department, Guru Kashi University, Talwandi Sabo-151302, India
[3] Mechanical Engineering Department, I.K.G.P.T.U, Jalandhar-148107, India

promising. Plasma gas, introduced along the cathode, is heated by arc to plasma temperatures, leaving the anode nozzle as a plasma jet or plasma flame.

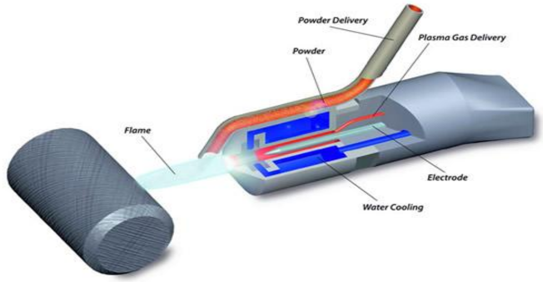

Figure 1 The plasma spray process [11]

Fine powder suspended in a carrier gas is injected into the plasma jet where the powder particles are accelerated and heated. As the molten powder particles impinge with high velocities on substrate, they form a more or less dense coating [10].

2.1.1 Plasma Generation and Formation

The arc is initiated between the tip of the cathode (typically thoriated tungsten) and the water cooled anode nozzle. The working gas is introduced either axially or with an additional swirl component. The latter improves arc stability in the vicinity of the cathode and rotates the anode arc root which may be desirable for reducing anode erosion. The gas heated by the arc emanates as a plasma jet from the torch orifice. For typical plasma spray applications, the gas flow rate is sufficiently high to ensure a highly turbulent jet with a visible length of several centimeters.

Argon and mixtures of argon with other noble (He) or molecular gases (H_2, N_2, O_2 etc.) are frequently used for plasma spraying. The addition of He and in particular of molecular gases results in a drastic increase in the enthalpy of the plasma, which may be important for complete particle melting [10]. The maximum temperature in the plasma jet is a function of the design and of the operating parameters.

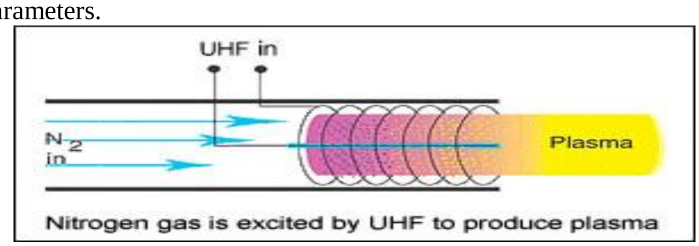

Figure 2: Plasma generation [12]

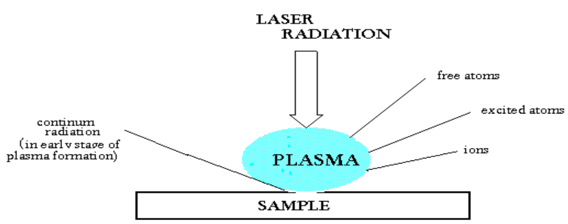

Figure 3: Plasma formation [13]

3. STUDIES RELATED TO PLASMA SPRAYED COATINGS

Mishra et al[14] Studied erosion behaviour of plasma sprayed coatings on a Ni-based superalloy In the present investigation NiCrAlY, Ni-20Cr and Ni3Al metallic coatings were deposited on a Ni based superalloy (18.5Fe-19Cr-0.15Cu-0.5Al-3.05Mo-0.18Mn-0.9Ti-0.18S-0.04C-5.13 (Ta + Cb)-balance Ni). NiCrAlY was used as bond coat in all the cases. Erosion studies were conducted on uncoated as well as plasma spray coated superalloy specimens at room temperature. The coatings have been characterised by scanning electron microscope (SEM), optical microscope, microhardness tester and X-ray diffractometer (XRD). It was found out that the average porosity and microhardness of the Ni-20Cr coating was found to be the highest amongst the three coatings whereas that of Ni3Al coating was found to be the lowest and for all uncoated and coated samples, the erosion rates at a 30◦ impact angle were somewhat higher than at a 90◦ impact angle, thus indicating their ductile behaviour. The relative ranking of the coatings, however, remained strikingly similar for both impact angles, with resistance to erosion being in order of Ni3Al > NiCrAlY > Ni-20Cr.

Wang et al[15] found out Influence of pores on the thermal insulation behavior of thermal barrier coatings prepared by atmospheric plasma spray. They discovered that the defects in materials play very important role on the effective thermal conductivity. Especially, the spatial and geometrical characteristics of pores are significant factors for the thermal insulation behavior of thermal barrier coatings (TBCs). In this paper, finite element method was employed to simulate the thermal transfer behavior of TBCs with different spatial and geometrical characteristic of pores. The simulation results indicate that the thermal insulation effect of TBCs would be enhanced when the pore size, pore volume fraction and pore layers which are perpendicular to the thickness direction increase and the space between the adjacent pores decreases. It is predicted that the effective thermal conductivity is different at different directions for the atmospheric plasma spray (APS) TBCs. A novel method, Computational Micromechanics Method (CMM), was utilized to depict the thermal transferring behavior of actual coatings. At the same time, model with different kinds of defects were established, and the effective thermal conductivity as the function of defect orientation angle, defect volume fraction and defect shape coefficient was discussed in detail. The simulation results will help us to further understand the heat transfer process across highly porous structures and will provide us a powerful guide to design coating with high thermal insulation property.

Guo et al [16] experimentally checked the Compatibility of atmospheric plasma sprayed Al_2O_3 coatings on CLAM with liquid LiPb Aluminum oxide Al_2O_3 coatings on China Low Activation Martensitic (CLAM) steel substrates were prepared with atmospheric plasma spray (APS) method. Corrosion experiments of the coating specimens in static liquid LiPb were carried out in DRAGON-ST capsule for 5000 h at 550 ◦C. The results showed that there is no obvious thinning of external layer Al_2O_3 after 5000 h exposure. The phase Al_2O_3 in external layer and the dissolution of Ni in liquid LiPb from the edge of the internal layer Ni–Cr were the possible reasons for the corrosion of coatings.

Zhang et al [17] studied the Microstructure characteristics of Al_2O_3–13 wt.% TiO_2 coating plasma spray deposited with nanocrystalline powders **.** Nanostructured Al_2O_3–13 wt.% TiO_2 coating was fabricated by plasma spray with nanocrystalline powders and the microstructures of the feedstock and the coating were characterized by means of XRD, SEM and TEM. It was found that three forms of substructure existed in the coating: one evolving from the unmelted part of the feedstock and showing a roundshaped morphology; one resembling the liquid-phase-sintered structure consisting of the flattened partially melted region and fully melted region; another being of the particulatereinforced-solid solution type with fine particles distributed in the matrix. The TEM analysis revealed that partially melted _-Al2O_3 particles were in the size range of 20–70nm and were embedded in the TiO_2-rich matrix. The mechanism of the substructure formation was also explained in terms of the melting and flattening behavior of the powders during plasma spray processing.

Ctibor et al [18] studied about Plasma sprayed ceramic coatings without and with epoxy resin sealing treatment and their wear resistance . Plasma sprayed aluminum oxide-based coatings (Al_2O_3) are mainly used as a wear resistant surface covers in mechanical applications. Previous studies have shown that abrasion wear resistance of these coatings can be significantly improved by applying a sealing treatment. It was reported that this improvement is mainly due to microstructural toughening which takes place via the sealing process. Therefore, this study was conducted in order to determine the influence of the microstructural characteristics governed by the spray system settings and epoxy sealing on the wear resistance of these coatings. Unsealed and epoxy resin sealed plasma sprayed specimens prepared from alumina as well as alumina-13% titania were studied. Abrasion wear resistance of these coatings was evaluated employing the standard slurry abrasion response (SAR) and the standard dry sand rubber wheel (DSRW) abrasion tests. The coatings microstructure was characterized by light microscopy and their worn surfaces were analyzed using scanning electron microscopy. Porosity, microhardness and surface roughness of unsealed and sealed coatings were also compared. It was shown that the abrasion wear resistance of the epoxy resin sealed coatings is significantly better than that of the as-sprayed coatings for both types of applied tests.

Zhang et al [19] used finite element analysis . The thermo-mechanical behaviors and the distribution of residual stresses in functionally graded ZrO_2/NiCoCrAlY coatings due to thermal spraying were analyzed by thermo-mechanical finite element analysis (FEA). To different coatings, they each have a remarkable stress concentration at the edge of the interfaces. The effects of ZrO_2 topcoat to substrate thickness ratio and cooling rate on the residual stresses distribution were obtained by ZrO_2/NiCoCrAlY two-layer duplex coating systems. Moreover, the effects of 50%ZrO2 + 50%NiCoCrAlY interlayer and its thickness on the residual stresses in the functionally graded ZrO_2/NiCoCrAlY coatings were also discussed. Modeling results showed that the level of residual stresses at the critical interface regions (i.e., coating/ substrate interface, coating surface etc.) is obviously influenced by coating to substrate thickness ratio, the presence of interlayer and cooling rate. Furthermore, the residual stress-induced failure model of coatings is also discussed. These studies can be used to optimize the design and processing of some plasma-spraying coating.

Zhang et al [20] experimentally investigated The rolling contact fatigue (RCF) resistance and failure mechanisms of plasma-sprayed CrC–NiCr cermet Coatings. Fatigue tests were conducted at two different contact stresses. At a given contact stress, thirteen rolling contact tests were performed to obtain the statistical result. The Weibull distribution plots of fatigue life data of the coatings were obtained. At higher contact stress, the bimodal distribution of the fatigue life data of the coatings was observed in the Weibull plot. The fatigue life of the coating decreased with increasing the contact stress. The failure modes of coatings could be classified into two main categories, i.e., spalling and delamination.

Morks and Akimoto [21] investigated the role of nozzle diameter on the microstructure and abrasion wear resistance of plasma sprayed Al2O_3-TiO_2 composite coatings. Al_2O_3-50 Wt% TiO_2 composite coatings were sprayed on a mild steel substrate by using Bay State Plasma spraying and SG-series plasma systems. Oxygen was used as a carrier gas for the feedstock powder during spraying with a Bay State Plasma gun to reduce the extent of reduction of alumina and titania (extraction of oxygen) in the high plasma jet temperature and provide higher heating energy to the particles in the plasma jet. The powder was injected internally into the plasma jet. The influence of nozzle diameter on the coating properties was studied. The interior diameter of the Bay State plasma gun (PG-series) nozzle (anode) was ±7.5 mm and it was increased to 8 mm by a mechanical drilling process. Al_2O_3-TiO_2 composite coatings were deposited with the two different nozzle diameters. The microstructure and mechanical properties of Al_2O_3-TiO_2 composite coatings were evaluated. The results showed that the nozzle diameter greatly affected the microstructure and mechanical properties of the composite coatings. Sprayed coatings with a smaller nozzle showed high hardness, low porosity and high abrasion resistance. Moreover, the Al_2O_3-TiO_2 composite coatings sprayed with the Bay State Plasma system showed better mechanical properties than Al_2O_3-TiO_2 coatings sprayed by a SG-series gun.

Sidhu and Prakash [22] studied erosion-corrosion of plasma as sprayed and laser remelted Stellite-6 coatings in a coal fired boiler. Unacceptable levels of surface degradation of metal containment walls and heat -exchanger tubing by a combined erosion-corrosion (E-C) mechanism have been experienced in some boilers. The laser remelting of the surface coating is suggested as a promising technique to improve its physical properties. The present investigation evaluated the erosion-corrosion (E-C) behaviour of plasma as sprayed and laser remelted Stellite-6 (St-6) coatings on boiler tube steels in the actual coal fired boiler environment. The cyclic experimental studies were performed in the platen superheater zone of a coal fired boiler where the temperature was around 755°C and the study was carried out upto 10 cycles each of 100 h duration followed by 1 h cooling at ambient temperature. Coated steels were found to possess higher resistance to E-C than the uncoated steels. The highest degradation resistance has been indicated by the T11 steel coated and subsequently laser remelted.

Rico et al [23] Dry sliding wear performance of Al_2O_3–13% TiO_2 nanostructured and conventional coatings has been experimentally analysed. An enhanced behaviour of the nanostructured material can be reported with substantially minor wear rates under all experimental conditions. Additionally, a transition from mild to severe wear can be established in both materials. However, the critical pressure at which the transition occurs is higher for the nanocoating. The main wear mechanisms controlling the mild and the severe regimes are related to brittle propagation of cracks. The hierarchical structure showed by the nanomaterial seems to control the improvements mentioned before. Crack deflection processes leading to a toughening effect can be identified, although, the microstructural feature which deflects the cracks changes depending on the wear regime.

Tian et al [24] studied the fretting wear behavior of conventional and nanostructured Al_2O_3–13 wt% TiO_2 coatings fabricated by plasma spray in this paper. The conventional coatings were deposited with commercial Metco 130 feedstock, and the nanostructured coatings were deposited with agglomerated feedstock with nanostructure. There were typical lamellar structures existing in conventional coating, however, those were not obviously observed in nanostructured coating. Amorphous phases, nanosized grains and some submicron grains existed in nanostructured coating. In fretting wear tests, the coatings wear against 52100 steel ball. In all of three conditions tests, the fretting maintained in gross slip regime for both nanostructured and conventional coatings. The coefficient of friction (COF) ranged from 0.7 to 0.9 in the fretting wear test. There was a transfer iron oxide layer formed on the worn coating surface. Fretting cracks propagate along the splat boundary in conventional coatings but propagate at random in nanostructured coatings. Test results showed that nanostructured coatings exhibited much better fretting wear resistance than conventional coating. The improved fretting wear resistance of nanostructured coatings was attributed to the nanosized grains, reduced lamellar structures and amorphous phases.

Galvanetto et al [25] have evaluated wear behaviour of iron boride coatings produced by VPS technique on carbon steels. The vacuum plasma spray (VPS) technique is a useful tool for designing the characteristics of the coatings and, thus, the tribological properties of coated components. In the present paper, the wear properties of iron boride coatings produced by means of VPS technique on AISI 1040 steel samples were evaluated as a function of their microstructural characteristics. One coating type was obtained by using Fe_2B pure powder, the other with differentiated FeB ± Fe blends, with the FeB content increasing and ± Fe content decreasing from the matrix to the surface. Wear tests were performed by means of a tribometer in block-on-ring configuration, without lubricant and in air, by using 40- and 60-N coupling loads and 0.8- and 1.6-m s^{-1} sliding velocities. On Fe_2B coated samples, wear is essentially oxidative until the failure of the coating, the fragments of which cause a third body abrasion. On the FeB ± Fe coated samples the wear mechanism is mainly oxidative and the coating totally wears out without spalling as a consequence of its graded structure, which succeeds in both improving the adhesion of the coating to the substrate and reducing the residual stress at the coating–substrate interface.

Zhang et al [26] studied the phase and microstructure of tungsten coating on C/C composite prepared by double-glow plasma. In this study, a dense W-modified layer was prepared on the C/C composite substrate by double-glow plasma method using pure W as target. Argon was input into the chamber as the plasma and the reactive gas. Phase and microstructure of as-prepared coating were examined by the X-ray diffraction and scanning electron microscopy, respectively. The results indicated that the dense W-modified layer could be successfully coated on the surface of the C/C composite substrate by double-glow plasma method. The W-modified layer was made of many columnar grains extending perpendicularly outward from the C/C composite substrate. There was a transition layer honeycomb-like between W coating and the C/C composite substrate. The adhesive force of the W coating and C/C substrate was about 21 N.

Zhou et al [27] studied about the Fabrication of thick W coatings by atmospheric plasma spraying and their transient high heat loading performance. Both tungsten coatings with or without a W/Cu graded interlayer on an oxygen-free copper substrate were fabricated by atmospheric plasma spraying. High purity argon gas was used for cooling the substrate and preventing the coating from oxidation. The thickness of both coatings is ∼1mm. XRD and EDS measurements of the coatings show that minimal oxidation occurred during the deposition process. Transient high heat load tests by electron beam with a pulse duration of 5ms were performed on both coatings. The single pulse loading was applied on the virgin surfaces at several power densities (from 0.22 to 0.9GW/m2). Although the weight loss of the W/Cu FGM (functionally graded materials) based coating was slightly lower than that of the pure W coating, their transient high heat loading performances were quite similar.

Chen et al [28] determined and analyzed crack growth resistance in plasma-sprayed thermal barrier coatings. In this research, a sandwiched four-point bend specimen is used to evaluate the crack growth resistance in plasma-sprayed TBCs. Well controlled, stable and measurable crack extension is obtained. A rising crack growth resistance curve is found. The steady state strain energy release rate is obtained to be about 170 J/m^2. The delamination crack evolution behavior is in situ observed and simulated by the finite element analysis based on a crack bridging model.

Ceschini et al [29] performed the Comparison of dry sliding friction and wear of Ti6Al4V alloy treated by plasma electrolytic oxidation and PVD coating. The aim of the present study was to investigate the friction and wear behaviour of a PEO coating on the Ti6Al4V alloy. The tribological behaviour of the PEO treated Ti alloy was compared with that of thin PVD coatings, such as TiN, (Ti,Al)N and CrN/NbN superlattice deposited on the same substrate. The tests were carried out under dry sliding conditions (slider-on-cylinder geometry) against a plasma spray Al_2O_3–TiO_2 coated steel. TiN gave the best tribological performance among the PVD coatings, up to 20 N. The PEO treatment significantly reduced both wear and friction of the $Ti_6A_{l4}V$ alloy, even under higher applied loads, up to 35 N.

Patel et al [30] studied and established an experimental and computational protocol to manufacture thin walled ceramic (Al_2O_3) structures on the graphite mandrel (substrate) via plasma spray forming. The combination of experimental and computational approaches reduces currently used empirical methods for the similar purpose. Thermal profiles generated during plasma spraying of Al_2O_3 on the graphite mandrel for various mandrel designs and cooling conditions were computed by solving the conjugate problem of computational fluid dynamics and 3D unsteady heat transfer. Entire plasma spraying booth was modeled as per actual dimensions to consider the effect on the thermal profile of the mandrel/coating system. The computed temperature profile was compared with the experimentally measured temperature. The corresponding thermal stresses in the mandrel and spray deposited Al_2O_3 layer were computed. Computed thermal stresses were compared with the fracture strength of Al_2O_3 to prevent cracking of the spray formed structure during spraying and its successful removal from the mandrel. An optimum temperature increase rate (TIR) during plasma spray forming is defined for the successful deposition and removal of the freestanding ceramic structure.

Sidhu et al [31] obtained the fly ash coatings by shrouded plasma spray process on carbon steel. The coating was characterized with relative to important behavioural parameters. Wear, oxidation and salt corrosion behaviour have also been evaluated and it was found out in the study that plasma spray process could be used to deposit fly ash coating on the given steel under the given parameters. The porosity of the coating has been observed to be in the range 5–7%. Identical to the fly ash composition the formation of Fe_2O_3, Al_2O_3, Al_2SiO_5, Fe_2SiO_4 and $FeAl_2O_4$ phases have been observed. The higher microhardness up to 1100 Hv might be attributed to the presence of alumina and silica. The rate of wear for fly ash coated steel was more than that of similar type of uncoated steel, which might be ascribed to the coarse grain size of fly ash particles. Further comparatively more increase in wear rate with increase in load has been observed for fly ash coated steel than that of uncoated steel. The fly ash coating was found to be very effective in increasing the oxidation and salt corrosion resistance of the given carbon steel at 900 1C. Parabolic behaviour with slight variation in case of bared steels was observed for the whole range of the cyclic study. The presence of SiO_2 and Al_2O_3 might have contributed to increase the oxidation resistance of fly ash coated steel.

Tekmen et al [32] studied that Graphite formation and degradation in thermally sprayed cast iron coatings is a technological barrier for achieving superior wear resistant coatings. Therefore, there is a need to understand the in-flight particle behavior of cast iron powder and introduce new approaches to control the graphite content. In this study, it has been demonstrated that the graphite content can be controlled by means of in-flight particle diagnostic. For this purpose, cast iron coatings were plasma sprayed under a variety of spray conditions and characterized by using an optical microscope, X-ray diffractometer and electron probe micro-analyzer. As a result, a significant amount of graphite with respect to a wide range of in-flight particle temperature and velocity was preserved in cast iron coatings.

Singh et al [33] performed a study on sliding and erosive wear behaviour of atmospheric plasma sprayed conventional and nanostructured alumina coatings. Alumina coatings on stainless steel substrate (SS304) were deposited by using atmospheric plasma spray technique with a feed stock of manually granulated and sieved nano Al_2O_3 powder. The hardness, sliding, and erosive wear of the nanostructured alumina coatings (NC) were investigated and compared with that of conventional alumina coatings (CC). Pin-on disc type sliding wear test on the alumina coatings (NC and CC) was performed with load varying from 30 N to 80 N at a sliding speed of 0.5 m/s. Pot type slurry erosion test of the coatings was conducted for different concentrations of Al_2O_3 and a mixture of Al_2O_3 and SiO_2 slurry. The microstructural features of both NC and CC of alumina were characterized by using FESEM/EDS and SEM analysis to substantiate the failure of coatings due to wear. Wear and erosion resistance of nano alumina coating is better than the conventional alumina coating as observed in the present work. The bimodal structure of NC contributes for the enhanced wear resistance. The high fracture toughness of NC is due to suppression of cracks by partially melted particles in the coatings.

Culha et al [34] discovered the mechanical properties of in situ Al_2O_3 formed Al–Si composite coating via atmospheric plasma spraying. In this study, mechanically alloyed Al–$1_2Si/SiO_2$ composite powder was deposited onto an aluminum substrate by atmospheric plasma spraying. The composite coating consisting of in situ formed Al_2O_3 reinforced hypereutectic

Al–1_8Si matrix alloy was achieved. The produced coatings were extensively analyzed with respect to X-ray diffraction (XRD). The XRD patterns of the coatings include Al, Si and Al_2O_3 phase formation. Mechanical properties of layers were examined by Dynamic Ultra-micro hardness test machine for estimating Young's modulus due to load–unload sensing analysis. The hardness and Young's modulus of the composite coatings sprayed at different plasma current and the distance were measured under 200, 400, 600, 800 and 1000 mN of applied peak loads by indentation technique. The effects of spray distance and arc current on the hardness and Young's modulus have been investigated. Additionally, it was observed that the arc current and spray distance strongly influence the mechanical properties of the coatings.

McDonald et al [35] studied about the thermal contact resistance between plasma-sprayed particles and flat surfaces. Plasma-sprayed molybdenum and yttria-stabilized zirconia particles (38–63 lm diameters) were sprayed onto glass and Inconel 625 held at either room temperature or 400 _C. Samples of Inconel 625 were also preheated for 3 h, and then air-cooled to room temperature before spraying. Photographs of the splats were captured by using a fast charge-coupled device (CCD) camera. A rapid two-color pyrometer was used to collect thermal radiation from the particles during flight and spreading to follow the evolution of their temperature. The temperature evolution was used to determine the cooling rate of spreading particles. An analytical heat conduction model was developed to calculate the thermal contact resistance at the interface of the plasma-sprayed particles and the surfaces from splat cooling rates. The analysis showed that thermal contact resistance between the heated or preheated surfaces and the splats was more than an order of magnitude smaller than that on non-heated surfaces held at room temperature. Particles impacting on the heated or preheated surfaces had cooling rates that were significantly larger than those on surfaces held at room temperature, which was attributed to smaller thermal contact resistance.

Morks [36] did the Fabrication and characterization of plasma-sprayed HA/SiO_2 coatings for biomedical application. Fused silica powder has been mixed with hydroxyapatite (HA) powder and plasma sprayed by using gas tunneltype plasma jet. The influence of silica content (10 wt% and 20 wt%) on the microstructure and mechanical properties of HA–silica coatings was investigated. For investigating the microstructure and mechanical properties of HA–silica coatings, SUS 304 stainless steel was used as substrate material. The spraying was carried out on roughened substrate in an atmospheric chamber. Scanning electron microscope micrographs of crosssectioned HA/SiO_2 coatings showed that the sprayed HA coatings with 10 and 20 wt% SiO2 have dense structure with low porosity compared to the pure HA coatings. On the other hand, as the amount of silica was increased the coatings became denser, harder and exhibited high abrasive wear resistance. The presence of silica significantly improved the adhesive strength of HA/SiO_2 coatings mainly due to the increase in bonding strength of the coating at the interface.

Morks et al [37] investigated abrasive wear behavior of sprayed hydroxyapitite coatings by gas tunnel type plasma spraying. Hydroxyapatite (HA) coatings were sprayed using gas tunnel type plasma spraying at different arc currents. Abrasive wear test was carried out for the coatings sprayed at different arc currents under unlubricated conditions in air atmosphere. The abrasive wear rate was measured at different coatings thickness to study the effect of coating thickness on the anti-abrasion resistance of HA coatings. The results showed that the abrasive wear resistance of HA coatings increases as the operating arc current of the plasma torch increases. On the other hand, the abrasive wear rate reaches a minimum value near the substrate with coating thickness less than 50 m. The results showed that the coating hardness increases in the region near the substrate and increases as the arc current increases. The experimental results indicated that there is a relation between the abrasion resistance and hardness properties of HA coatings.

Mindivan et al [38] investigated the wear behavior of in situ formed Al_2O_3 reinforced hypereutectic Al–18Si matrix composite coatings . These coatings were successfully fabricated with mechanically alloyed Al–12Si and SiO_2 powder deposited on aluminum substrates by atmospheric plasma spraying (APS). The produced samples were characterized by means of microscopic examinations, hardness measurements and wear tests. The obtained results pointed out that the amount of in situ formed Al_2O_3 particles increased with increasing spray distance and decreasing in-flight particle velocity and temperature, which was accompanied by an improvement in hardness and wear resistance.

Song et al [39] performed the simultaneous synthesis by spark plasma sintering of a thermal barrier coating system with a NiCrAlY bond coat. As-fabricated thermal barrier coating (TBC) systems generally consist of a superalloy substrate, a MCrAlY bond coat (M=Ni, Co, Fe), and a ceramic (usually partially stabilized zirconia) top coat. The conventional methods for producing the two coating layers generally derive from thermal spray and physical vapor deposition techniques. Thermal exposure leads to the formation of an additional layer: the thermally grown oxide (TGO) between the bond coat and top coat. In the present work, a TBC system is synthesized through the application of spark plasma sintering (SPS), which provides not only the opportunity to synthesize all three layers at once, but the process is quite rapid and can produce dense layers. More specifically, this paper describes the application of this method to an yttria-stabilized ZrO_2 (YSZ) top coat and a NiCrAlY bond coat on a Ni-base Hastelloy X substrate. A one-micron thick Al_2O_3 TGO layer is also created from the reaction between an Al foil layer inserted in the stack prior to sintering and the ZrO2 in the top coat. The effects of select process conditions are considered. The resulting multi-layer system is characterized with optical microscopy, scanning electron microscopy (SEM), high-resolution transmission electron microscopy (HRTEM), energy dispersive X-ray analysis (EDAX) and X-ray diffraction (XRD). Differential thermal analysis (DTA) is used to investigate the reaction between the Al foil and the YSZ top coat.

Tian et al [40] studied Three body abrasive wear characteristics of plasma sprayed conventional and nanostructured Al_2O_3-13%TiO_2 coatings. In this paper, the conventional Metco130 coatings, and two kinds of nanostructured coatings (NP and NS coatings) were fabricated by plasma spray with different feed powders. The coatings were evaluated by indentation, scratch and three body abrasive wear tests. The NP coating sprayed with plasma densified feed powder had the highest hardness, crack growth resistance and scratch resistance. Test results exhibited that the nanostructured coatings had greatly improved three body abrasive wear resistance compared with conventional coatings. The three body abrasive wear resistance of NP coatings was about three times that of conventional coatings. The failure mode in scratch tests and wear mechanism of three coatings were also discussed.

Mohammadi et al [41] examined the effect of grit blasting parameters on the surface roughness of Ti–6Al–4V alloy as the substrate for plasma-sprayed hydroxyapatite (HA) coatings using the factorial and Taguchi designs of experiments. In this study, two grit materials (Al_2O_3 and SiO_2) each at two sizes, and two types of blasting systems (pressure and suction) were used. An equivalent surface roughness of 3.51 _m was obtained in three optimum conditions. The results of the Taguchi designed experiments were analyzed using signal to noise ratio. The tensile bonding strength of HA coatings deposited on the roughened substrates at the three different optimum conditions was measured by the standard adhesion test (ISO 13779-4). As the crystallinity of the coating at the interface, evaluated by the XRD analysis, reduced the bonding strength of the coatings was increased. These findings suggest that the substrate surface topography significantly influences the properties of the coating at the interface.

Sohi and Ghadami [42] did the Comparative tribological study of air plasma sprayed WC–12%Co coating versus conventional hard chromium electrodeposit . In this work, the properties of air plasma sprayed WC–12% Co coating before and after heat treatment were compared with the properties of the hard chromium electrodeposit. WC–12% Co coatings were heat treated at 650, 900 and 1150 1C for 1h in an argon atmosphere. XRD patterns confirmed the formation of anamorphous phase in the as-sprayed coating.

Li et al [43] found the relationship between particle erosion and lamellar microstructure for plasma-sprayed alumina coatings. The lamellar structure determines mechanical properties of a thermal spray coating. A model for the erosion of thermally sprayed ceramic coatings resulting from the debonding of flattened ceramic particles is proposed based on the examination of the erosion mechanism. The relationship between erosion rate and microstructural parameters is established both experimentally and theoretically to reveal main lamellar structural parameters controlling erosion of thermally sprayed ceramic coating. The microstructural parameters include the mean bonding ratio between lamellae and thickness of the lamellae. The erosion rate of plasma-sprayed Al_2O_3 coatings was measured at impact angle of 90◦ under the fixed erosion test conditions. The correlation of theoretical model with the observed structural parameters and erosion data of alumina coatings was examined. It is revealed that the theoretical relationship agreed well with the observed relation. The results clearly revealed that the erosion of plasma-sprayed ceramic coating was inversely proportional to the mean lamellar bonding ratio. The influences of spray parameters on erosion effected mainly through their influences on the lamellar bonding. The erosion resistance of a thermally sprayed ceramic coating was controlled by coating fracture toughness.

Yang and Li [44] found the effect of remelting process on characterization . To develop a composite material with good mechanical and radiation shielding properties, the Fe–Ni–B ($Fe_{67.5}Ni_{23.5}B_9$, wt.%) coatings onto $1Cr1_8Ni_9Ti$ stainless steel substrate (SS, same as below) were prepared using air-plasma spraying (APS) technique in this work. A remelting process (1050°C/2 h) was performed on the Fe–Ni–B coatings laminated composite under vacuum condition. The microstructure, phase composing, adhesion strength, Vickers hardness distribution and residual stress of Fe–Ni–B coatings before and after the remelting process were contrastively characterized. The results show that the remelting process decrease the coating defects and make the coating more cohesive and stable. The element diffusion and new compounds formation within the coating and interface area improves the adhesion and thermal fatigue of Fe–Ni–B coatings. In addition, the drop of variability of Vickers hardness data and residual stress level qualitatively identify that the Fe–Ni–B coatings possess more consistent microstructure and mechanical integrity after the remelting process.

Bala et al [45] studied the accelerated hot corrosion of cold spray Ni–50Cr coating on boiler steels. In the current investigation Ni–50Cr powder was deposited on two boiler steels SA-213-T22 and SA 516 (Grade 70) by cold spray process. The hot corrosion performance of coated as well as bare boiler steels was evaluated in an aggressive environment of Na_2SO_4–60% V_2O_5 under cyclic conditions at an elevated temperature of 900°C. The kinetics of the corrosion was approximated by the weight change measurements made after each cycle for a total period of 50 cycles. Each cycle consisted of 1 h heating in a tube furnace followed by 20 min cooling in ambient air. X-ray diffraction (XRD), scanning electron microscopy/ energy dispersive X-ray analysis (SEM/EDAX) techniques were used to analyse the corrosion products. Both the uncoated boiler steels suffered intensive spallation in the form of removal of their oxide scales, which may be attributed to the formation of unprotective Fe_2O_3 dominated oxide scales. The Ni–50Cr coated steels showed lesser weight gains and the oxide scales remained intact till the end of the experiment. The phases revealed in the oxide scales of the coated specimens were mainly oxides of chromium and nickel and their spinels which are reported to be protective against the hot corrosion.

Sahu et al [46] described the processing, characterization and the erosion wear response of a new class of metal–ceramic composite coatings deposited on metal substrates by plasma spraying. Coatings are developed on aluminum substrates using fly ash pre-mixed with aluminum powder in different weight proportions at various plasma torch power levels ranging from 9 to 18 kW DC. The coatings are characterized in terms of thickness, interface adhesion strength and deposition efficiency. Maximum adhesion strength of about 35 MPa is recorded with coatings deposited at 12 kW power level. It is noticed that the adhesion strength of fly ash coating is improved with pre-mixing of aluminum up to 15 wt.% in the feed material. To study the erosion wear behavior of the coatings, a plan of experiments based on the Taguchi technique is used to acquire the erosion test data in a controlled way. An orthogonal array and signal-to-noise ratio are employed to investigate the influence of the impingement angle, impact velocity, erodent size, stand-off-distance and the aluminum content in the feed stock on the erosion rate. The study reveals that the impact velocity is the most significant factor influencing the erosion wear rate of these coatings.

Niu et al [47] microstructure and thermal property of tungsten coatings prepared by vacuum plasma spraying technology. Tungsten coatings were deposited by vacuum plasma spraying technology and their microstructure and composition were characterized using SEM, XRD, TEM and EDS. Some basic properties of tungsten coating were detected and the thermal property of the coating was focused. The obtained results showed that the tungsten coating was consisted of well-melted particles overlapped each other and exhibited typical lamellar microstructure. Pores in line and irregular shapes and interfaces between layers were also observed. The thermal diffusivity of the as-received tungsten coating was about 47.7mm^2s^{-1}, which was lower than that of bulk tungsten. Gradient interlayer composed of tungsten and copper improved the bonding strength between the tungsten coating and copper alloy substrate.

Tobler and Durisch et al [48] studied about plasma-spray coated rare-earth oxides on molybdenum disilicide– High temperature stable emitters for thermophotovoltaics. Selective emitters for thermophotovoltaics consisting of intermetallic alloy MoSi2 substrate with plasma-spray coated rare-earth oxides ytterbium oxide Yb_2O_3, Yb-doped garnet $Yb_{1.5}Y_{1.5}Al_5O1_2$, and erbium oxide Er_2O_3 have been successfully tested till 1650°C. The emitters are fully operable in an oxygen containing atmosphere, are highly thermal shock stable, and show good selective emitting properties. Shielding the high out-of-band emittance of the $MoSi_2$ substrate with a 4 lm thick Pt intermediate layer has resulted in reduced radiation power and emittance of the rare-earth oxide film due to multiple reflections at the interfaces. The novel technique of vacuum plasma-spray coated rare-earth oxide films on MoSi2 is a promising way for the production of effective and high temperature stable selective thermophotovoltaic emitters.

Borgioli et al [49] found sliding wear resistance of reactive plasma sprayed Ti–TiN coatings . The reactive plasma spraying (RPS) of titanium powders in a nitrogen containing plasma gas produces thick coatings characterised by microdispersed titanium nitride phases in a titanium matrix. In this paper, the wear resistance properties of Ti–TiN coatings deposited on carbon steel substrates by means of RPS technique are studied. Wear tests were performed in block-on-ring configuration and dry sliding conditions, at different applied loads (45 and 100 N) and sliding velocities (in the range 0.4–2.0ms−1) by using hardened and stress relieved AISI O_2 disks as counterpart. At low applied load the wear volumes are low, and tend to slightly increase as the sliding velocity increases. At high applied load and low sliding velocities the highest wear volumes for the coated samples are observed, due to adhesion in the contact area with the tool steel counterpart and decohesion of coating particles. As the sliding velocity is increased, the wear volume of the coated samples tends to decrease owing to oxidation phenomena.

Zhao et al [50] studied the properties of Al_2O_3–40 wt.% ZrO_2 composite coatings from ultra-fine feedstocks by atmospheric plasma spraying. In the present study, both ultra-fine and coarse Al_2O_3–40 wt.% ZrO_2 grains were used as the starting materials to prepare ultra-fine structured and micro-structured Al_2O_3–40 wt.% ZrO_2 composite coatings (coded as NZTA coating and MZTA coating, respectively) by atmospheric plasma spraying. The ultra-fine Al_2O_3–40 wt.% ZrO_2 feedstocks for spraying were prepared by means of crushing sintered, starting from commercially availed powders of ultra-fine Al_2O_3 and ZrO_2. The microstructures and phase compositions of the crushing sintered powders and the corresponding composites coatings were investigated by means of scanning electron microscopy (SEM) and X-ray diffraction (XRD). The friction andwear behaviors of the composites coatings sliding against stainless-steel under dry friction conditions and at room temperature were investigated using an optimol SRV oscillating friction and wear tester. The wear mechanisms of the coatings were discussed based on the SEM observation of the worn surface morphologies and wear debris, and the elemental composition analysis of the wear debris by energy dispersive X-ray analysis as well. Results showed that aside from the typical splat lamellae, equiaxle grains were also observed in the Al_2O_3–40 wt.% ZrO_2 composite coating made from the corresponding ultra-fine crushing sintered powders. The NZTA coatings had higher microhardness and better wear resistance than that of the MZTA coatings, which could be largely attributed to the better inter-splats bonding of the former. And the stainless-steel counterpart matched with the NZTA coatings had a smaller wear rate as well. Moreover, the two types of composites coatings were dominated by spalling and fracture as sliding against the stainless-steel counterpart, and the MZTA coatings experienced more severe worn surface damage at a larger load than the NZTA coatings tested under the same conditions,well corresponding to the difference in the wear resistance of the two types of composite coatings.

Sabiruddin et al [51] studied variation of splat shape with processing conditions in plasma sprayed alumina coatings. This research is on various splat shapes obtained using three alumina based powders sprayed on various substrates. The parameters considered were substrate preheating temperature, nozzle diameter, and secondary and primary gas flow rates. The splat shape was found to be strongly dependent on spraying conditions. The substrate preheating temperature determined the degree of substrate wetting by the splat. A change in either nozzle diameter or primary gas flow rate brought about a change in the particle momentum and subsequently, a change in splat shape. The splat shape differed widely on an as – sprayed bond coat as compared to a polished one, owing to splat confinement by surface asperities. Sub-microscale surface roughness of polished substrate surfaces showed an increase with the preheating temperature and this in turn, resulted in better substrate wetting by the splats.

Sarikaya et al [52] studied the Wear behaviour of plasma-sprayed AlSi/B4C composite coatings . researchers described the wear behaviour of AlSi/B4C composite coatings with 0–25 wt% B4C particles for diesel engine motors. These coatings were successfully fabricated on AlSi substrates using an atmospheric plasma spray technique. The produced samples were characterized by means of an optical microscope, scanning electron microscope and microhardness tester. The obtained results pointed out that an increase of B4C particles in AlSi coatings was caused on the rising of the microhardness values and the decrease of the thermal expansion coefficient of the coatings. The friction and wear experiments were performed under dry conditions using a ball-on-dics configuration against WC/Co counter material for different loads. It was concluded that wear resistance of the coatings produced using B4C powders is greatly improved compared with the substrate material. The highest wear resistance of the coatings were also determined in the 20% B4C coating.

Torres et al [53] studied wear behaviour of thermal spray Al/SiCp coatings. Aluminium matrix composite coatings reinforced with more than 20 vol.% of SiC particles have been successfully prepared by simple and low cost oxy-acetylene thermal spraying process on steel substrates. The porosity and voids of the coatings have been diminished by a compaction procedure at 20°C or at 350 °C. The wear behaviour of these coatings has been tested using the ball-on-disc technique. The wear resistance of the aluminium coatings was greatly enhanced by the incorporation of the SiC reinforcement which delayed the transition from mild to severe wear. The wear resistance of the post-sprayed treated coatings was higher than that of the as-sprayed composite coatings for all loads studied. The wear process of Al/SiCp coatings is controlled by plastic deformation and the wear rate has been expressed as a single function that only depends on normal load and plasticity index of the coatings.

Zhang et al [54] investigated the tribological properties of Ni–Cr–B–Si–RE alloy coatings, thermal spray welded onto steel substrate. A study was conducted that characterized the critical normal loads and sliding speed on the wear behavior of a Ni–Cr–B–Si–RE alloy. The worn surfaces of the Ni–Cr–B–Si–RE alloy coatings were examined with a field emission gun scanning electron microscopy (FEGSEM), energy dispersive spectroscopy (EDS) and X-ray photoelectron spectroscopy (XPS). The results show that an adhered oxide debris layer was formed on the worn surface in friction which contributed to decreased wear. Wear rate of the coatings increased with the load, but decreased with the sliding speed in the range of 0.02–0.08 m/s, then increases a little at 0.1 m/s sliding speed. The average friction coefficient is about 0.48, and decreased with the load, but increased with sliding speed at first, and then tended to slight decrease. Wear mechanism is dominated by a large amount of counterpart material transferred to the coating.

Sidhu and Prakash [55] studied the behaviour of stellite-6 as plasma sprayed and laser remelted coatings in molten salt environment at 900°C under cyclic conditions . Stellite-6 (St-6) coating was obtained on boiler tube steels namely ASTM-SA210-Grade A1 (GrA1), 1Cr–0.5Mo steel ASTM-SA213-T-11 (T11) and 2.25Cr–1Mo steel ASTM-SA213-T-22 (T22) through plasma spray process. Ni–Cr–Al–Y was used as a bond coat before applying St-6 coating. Nd:YAG laser has been used for the post-coating treatment. As sprayed and laser remelted steels were subjected to molten salt environment (Na2SO4–60%V2O5) at 900°C under cyclic conditions. The samples were visually examined and subjected to weight change measurements at the end of each cycle of study. Techniques like XRD, SEM/EDAX and EPMA analysis have been used to analyse the oxide scale. The coating was found to be effective in decreasing corrosion rate of the boiler tube steels. Protection is higher when GrA1 steel was the substrate steel and lower for T22 base steel. Due to the formation of vertical cracks, laser remelted coatings have indicated slightly higher corrosion rate in the given molten salt environment.

Goyal et al[56] prepared carbon nanotube(CNT) reinforced Al_2O_3 coatings and successfully deposited on ASME-SA213-T11 boiler tube steel by plasma spray coatings using Ni-Cr as bond coat.they found after investigation that porosity of CNT-Al_2O_3 mixed coatings was decreasing with increase CNT content. They also found that CNTs were uniformly distributed in Al_2O_3 matrix and were chemically stable during spray forming. Also it did not react to form oxides or aluminum carbides even at the very high temperature.

Rao et al [57] evaluated the erosion behavior of plasma sprayed Cr_2O_3 coatings on 410 grade steel using Ni-Cr as bond coat. Erosion analyses of both uncoated and coated samples were done using air –jet erosion test rig at room temperature at a speed of 30 m/s by varying stand-off distance as 10mm, 20mm, 30mm & 40mm. Surface morphologies were Characterized using SEM and EDS also Vickers micro hardness test was done. They observed that Cr_2O_3 coated specimen exhibits better Erosion resistance when contrasted with uncoated substrates because of its enhanced property like micro hardness.

Mishra et al [58] did Studies on erosion-corrosion behaviour of plasma sprayed Ni_3Al coating on superalloys in a coal-fired thermal power plant environment at 540°C for ten cycles of 100h duration. After experimentation it was found that in boiler environment Ni_3Al coating partially oxidizes and acts as a perfect barrier against erosion-corrosion of superalloys moreover coating remained intact even after 1,000 h cycle exposure.

Chen et al [59] evaluated the unlubricated wear properties of plasma-sprayed nanostructured and conventional zirconia coatings by SRV tester. Atmospheric plasma spraying method was used to deposit nanostructured and conventional zirconia coatings using spray-dried nanostructured zirconia powder and conventional zirconia powder as feedstock, respectively. Their wear properties were evaluated comparatively by a sliding, reciprocating and vibrating (SRV) tester under dry conditions. The obtained results show that the wear properties of the plasma sprayed zirconia coatings deposited from spray-dried nanostructured zirconia powder were greatly improved compared with those of plasma sprayed zirconia coatings produced from conventional powder. The wear rates of nanostructured zirconia coatings are approximately half of those of conventional zirconia coatings. Under dry conditions, the wear mechanism for the plasma-sprayed nanostructured zirconia coatings is abrasive wear. Whilst in the case of plasma sprayed conventional zirconia coatings, it is a combination of abrasive wear and brittle fracture, the former is dominant wear mechanism. Their wear properties were explained in terms of their microstructure as well as mechanical properties and compared with the wear properties obtained under distilled-water lubricated conditions. Based on the experimental results, it is concluded that the finer debris is a critical factor for the improvement of wear properties of plasma-sprayed nanostructured zirconia coating under dry conditions. The wear properties of plasma sprayed zirconia coatings can be increased by the presence of water during the SRV testing.

Khan and Lu [60] did the manipulation of air plasma spraying parameters for the production of ceramic coatings. Thermal barrier coatings (TBCs) were sprayed on stainless steel coupons by an air plasma thermal spray (APS) technique. The porosity of the topcoat was varied by controlling the different spraying parameters. Three types of thermal shock tests were designed to determine the TBCs life. Effect of different spraying parameters on the thermal shock life was observed. The spraying distance was found to be an important parameter that controls the thermal shock life. It was observed that the thermal shock properties could be related with an empirical parameter called the critical thermal shock parameter (CTSP). Fracture toughness (KIC) was determined by Vicker’s indentation technique and it was observed that for a certain range of the porosity the toughness increased with increase of porosity. The possible increase in thermal shock life for a certain range of CTSP may be attributed to residual stresses and increase in fracture toughness of the topcoat.

4. CONCLUSION

Various authors have done research related to high temperature corrosion and role of plasma spray on different materials in different conditions using various types of coatings. Authors experimented in different fields and ended with certain conclusions. Authors concluded that

plasma spray is one of the most promising and dense coating is formed . Many researchers did characterization of plasma coatings and they found resistance to erosion and also declared that erosion rate is less at higher impact angle . A lot of research established that plasma sprayed Al2O3 coatings are mainly used as a wear resistant surface covers in mechanical applications . It was shown that abrasion wear resistance is significantly better. The fatigue life of the coating decreased with increasing the contact stress .

The obtained results show that the wear properties of the plasma sprayed coatings were greatly improved . The wear resistance of the post-sprayed treated coatings was higher than that of the as-sprayed composite coatings for all loads studied. Coated steels were found to possess higher resistance to E-C than the uncoated steels. The laser remelting of the surface coating is suggested as a promising technique to improve its physical properties.

Test results showed that nanostructured coatings exhibited much better fretting wear resistance than conventional coating. The vacuum plasma spray (VPS) technique is a useful tool for designing the characteristics of the coatings and, thus, the tribological properties of coated components. More research can be done in the field of high temperature corrosion and plasma sparying technique so as to become more capable to identify regimes of safe and unsafe operating conditions in addition to providing a basis of materials selection and process optimization as a function of the conditions.

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