Functionally Graded Material Coatings (FGMC) – A Review

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Abstract. The coatings are substances that are applied over the surface of an object to prevent it from wear, tarnish and corrosion. Coatings maintain the properties of base metals (thermal, optical and electrical) over a long duration of time. The coatings are generally characterized by the properties like good adhesion, low porosity and substrate compatibility that include geometry and temperature. Coatings often suffer from problems like variable thermal expansion coefficient compared to their base metals. To overcome the variable thermal expansion issue, the functionally graded material (FGM) layers may be imposed. Present work aims to study the FGM coatings capable of enhancing the mechanical, thermal and tribological properties of base metals by providing scratch resistance. An attempt has been made to present a comprehensive review of high-velocity-oxy-fuel, plasma spray and other techniques adopted by industries and other groups. The effects of applying FGM coatings on the operating conditions and the performance of the base metals are also covered in detail.

Keywords: Functionally graded material, HVOF, Plasma spray, PLD, Thermal spray.

1. INTRODUCTION

Functionally graded material (FGM), a keystone of advanced materials research that finds wider applications in aerospace, medical, defense, and energy sectors, may be treated as the state of art research in materials technology. Availability of substantial research in FGM technology provides a deep insight into the factors that steer the properties of developed coatings [1]. To develop high-performance systems in modern industries, FGM may prove to be a suitable technique that takes care of the desirable materialistic properties. FGM coatings are exceptionally appreciated for high-temperature applications owing to their improved mechanical behavior. Fig. 1 presents a summary of the applicability of FGM in various fields.

The characterization of tribological and mechanical properties of the developed coating can be studied on a macro as well as a micro-scale. Although, a macro-scale analysis provides a better characterization of the coating. In the last few decades, indentation testing was conducted with a steel ball. This method, called Automated Ball Indentation (ABI) testing, [2-3] uses a steel ball to make indentations in the millimeter range. However, it is not reasonable to use this method and is expected to obtain completely accurate results of coatings with a thickness in the micrometer range, as the
indentation depth is on the macro-scale. At a millimeter-scale depth, the substrate will affect the data collected for the modulus and hardness results, which means that the results will not be an accurate reflection of the properties of the coating itself. In general, electro/electroless plating, physical vapor deposition (PVD), chemical vapor deposition (CVD), pulsed laser deposition (PLD) and thermal spray coating techniques are used to deposit coatings over the surfaces. Some details of these techniques are presented in the preceding section.

**Fig. 1** Various fields of functionally graded material coating

**Electroplating**

In this technique, a suitable coating material (metal or alloy except for titanium and aluminum) is deposited over an electrode that behaves as a cathode as shown in Fig. 2. Brush plating, on the other hand, uses a manual plating tool that replaces a bath. To anodize the aluminum and aluminum alloys, anodes dipped in an aqua-electrolyte mixture are used, and an oxidation layer is created at the surface.

**Fig. 2** Electroplating
**Chemical Vapour Deposition (CVD)**

Metals, borides, carbides, alloys, boron silicon, sulphides, silicide and oxides are deposited using CVD technique. The microstructure of the coatings generated using CVD technique are functions of temperature, actual concentration, and equilibrium concentration. By maintaining the substrate at elevated temperature, excellent diffusion bonding between substrate and coating is obtained.

**Physical Vapour Deposition (PVD)**

In general, the solids can be deposited over another solid material with appropriate treatment. PVD incorporates three main processes that include evaporation, ion-plating, and sputtering. The ions required to evaporate the low temperature material is generated from a target using dc power supply as shown in Fig. 4. The processes are carried out at low pressures of the order of $1.3 \times 10^{-6}$ N/m$^2$ to 13 N/m$^2$. Thin coatings with thickness below 1μm may be easily created even at the low-deposition rate.
**Pulsed Laser Deposition (PLD)**

PLD employs an intense power beam of laser that is periodically focussed over the target material utilizing laser pulses of some nanoseconds. Absorbed laser energy is used to locally heat the material under target. Due to this, the target material evaporates and creates a plasma environment (containing electrons, ions, and atoms) around it. The electrons, ions, and atoms are transferred at high speed towards the substrate under controlled vacuum. Some gases are also infused inside the reaction zone to reform the chemical composition of the material that is being deposited over the surfaces of substrates as shown in Fig. 5.

![Fig. 5 Pulsed Laser Deposition (PLD)](image)

**Thermal Spray**

In thermal spraying technique, a high-temperature stream of metallic or non-metallic particles is used to impinge the coating material over the prepared substrate. When the layers of platelets (splat) are subsequently applied over the substrate, a good quality coating is observed. By applying appropriate impact, a strong bond with a required thickness is formed over the base metal. Fig. 6 shows the basic principle of operation of thermal spraying technique.

![Fig. 6 Thermal spraying technique](image)
2. DEVELOPMENT IN COATING TECHNIQUES

This paper reviews the developments in FGM coatings, focusing primarily on High-velocity-oxy-fuel (HVOF), plasma spray, combined (HVOF and plasma spray) and other techniques adopted by various research groups.

2.1 HVOF Technique

Moskowitz [4] reported that due to oxide network and interconnected porosity, the thermal spray coatings are less suitable for corrosion applications. However, post-treatments or vacuum chambers are capable of removing defects, besides the fact that they are less economical. They also studied a modified HVOF technique under the shrouding of an inert gas and observed that it results in low-oxide and highly dense metallic alloy coatings. Rastegar and Richardson [5] have tested some HVOF fuel sprayed coatings on engines and wear test rigs. They prepared a dense HVOF cermet coating having good crack resistance feature while in service. They reported that the HVOF coatings are more compatible with the environment compared to chrome plated coatings. Further, the HVOF coatings have equivalent or low production cost compared to chrome plated coatings. Nygards et al. [6] developed a spherical indentation method to evaluate the interfacial adhesion that exists in between substrates and thick film coating. They adopted an experimental-numerical method to determine the threshold stress for interfacial delamination and reported that this technique is capable of evaluating the residual indent topographic changes. Stewart et al. [7] used WC–Co cermets as wear-resistant materials and observed that the nanostructured cermets improve the properties significantly compared to conventional coating techniques. Their reporting about the nanocomposite and conventional coatings exhibited that the wear rate with silica abrasive is less than that with alumina abrasive coating. Kawakita et al. [8] analyzed the dissolved substances that are derived from coated steel when it is immersed in HCl solution and investigated the porosity of HastelloyC high-velocity oxy-fuel spray coating. Their analysis enabled them to predict through-pores that depends upon coating stack structure and thickness. They also calculated both coating’s through porosity as well as corrosion resistance in conditions that fail to detect the properties using electrochemical measurements. Their results revealed that with an increased coating density, the corrosion resistance predominates over the coated material. Sahraoui et al. [9] studied the wear resistance, microstructural properties and the possibility of using HVOF-sprayed-Tribaloy®-400 (T-400), Cr3C2-25%NiCr and WC–12%Co coatings as a substitute of hard chromium plated coating for repairing the gas turbine shafts. They found thermal spraying as convincing coating technique compared to hard chromium coating done using electrodeposition. Fedrizzi et al. [10] investigated the hard chromium coatings using advanced HVOF cermet coating. They prepared the coatings that were prepared using conventional coating materials and nano-powders that composed of 75Cr3C2–25NiCr sprayed on AISI 1045 steel. These coatings find wider application in cylinders of earthmovers. They found that nano-powder coating exhibit smaller weight loss compared to conventional HVOF coatings and hard chromium coatings under all working conditions. Ivosevic et al. [11] studied the high-velocity oxy-fuel splashed polyimide/WC-Co functionally graded material coating with topcoats of flame sprayed WC-Co. They claimed that this technique is capable of improving the oxidative resistance of composites of polymer matrix and solid-particle erosion in the gas entrance paths of the advanced turbine engine. They evaluated the adhesion strength of the bonds of three kinds of coatings by ASTMD4541. They also measured the adhesive and cohesive strengths of functionally graded coatings and compared them with polyimide/WC-Co and polyimide composites. They showed that FGM coatings have low adhesive bond strengths of about 6.2 MPa compared to that of pure polyimide coating that has a bond strength of around 8.4 MPa. They found that the bond strength was less compared to the tensile strength of uncoated Polymer matrix composites substrate that exhibits a value of around 17.6 MPa. Tan et al. [12] studied the erosion-corrosion behavior of solid-particle by conducting experiments on high-velocity-oxy-fuel-sprayed-nickel-aluminum-bronze coating using situ electrochemical analysis as well as conventional gravimetric technique. They reported that for both materials a synergy (positive) occurs at peak erodent kinetic energies. On the other hand, negative synergies come in the picture due to de-passivation/re-passivation kinetics and the generation of corrosion products even at lower energies. Sidhu et al. [13] reviewed the problems of hot corrosion of superalloys and HVOF coatings in power
producing equipment, IC Engines, and gas turbines. They focussed on the need of a mathematical model for the development of simulators of the real industrial environment to forecast the corrosive nature and the life of the coatings. Sidhu et al. [14] also observed that coatings using high-velocity-oxy-fuel technique provides good hardness, high strength, low porosity (below 1%), and high erosion-corrosion resistance and enhanced wear resistance. Ivosevic et al. [15] investigated functionally graded (thermally sprayed) coatings based on polyimide matrix that encompasses varying volume fractions of WC–Co capable of improving the oxidation and erosion resistance of polymer matrix composites. They applied to design of experiments concept to study the coating effectiveness by accomplishing an erosion barrier using the statistical technique. They compared the results of uncoated and coated solid particle erosion polymer matrix composite and observed that with an increase in the angle of incidence of the eroding material from 20 degrees to 90 degrees, the volume loss increases. Further, the erosion volume loss at 250°C was approximated as twice as that at room temperature. Li et al. [16] adopted the first-principles approach to exploit the fluid dynamics and HVOF flow field particle inflight behavior. They used rule-based stochastic simulation to capture the microstructure that encompasses the key features involved in the process of deposition. They developed a feedback system for applying the mathematical model of the process. They reported that the controlled outputs could be set to the desired set-point values using a feedback controller. Sidhu et al. [17] used the HVOF method for depositing 250-300 µm thick NiCrBSi coatings on Ni and iron-based superalloys to make them suitable for hot corrosion applications. They also studied the corrosion characteristics of coatings under the heated state that are deposited on nickel-based superalloys when exposed to molten salt (Na2SO4–60% V2O5) at 900°C under cyclic conditions. They analyzed the developed coatings using techniques like XRD, optical microscopy, SEM (scanning electron microscopy), X-ray spectroscopy, energy dispersive and electron probe microanalysis techniques. They used thermogravimetric technique to understand the corrosion kinetics. They observed that the micro-hardness of the coated alloys are better than uncoated super-alloys. Also, the micro-hardness changes with the change in distance between the coating-substrate interfaces. Cherigui et al. [18] investigated the magnetic features and microstructure of the coatings obtained using HVOF spraying technique using feedstock powders based on nanostructured FeSi. Their measurement results indicated a ferromagnetic behavior for the developed coatings under study. They also found that the copper, niobium, and boron present in the feedstock powders have less effect on magnetic properties of the coatings. Guilemany et al. [19] prepared three coatings with HVOF spray technology using bimodal, nanostructured and WC-Co cermet powders. The ball-on-disk (BOD) test for friction-wear resistance and rubber-wheel-test RWT) for abrasive wear resistance was used. The corrosion resistance has also been studied using salt fog spray test and electrochemical technique. They found that nanostructured coatings were harder than other coating methods used in practice. However, bimodal coatings showed better friction wear resistivity with less expense. Boelli et al. [20] compared the corrosive resistance of HVOF (spray) coatings (WC–17Co, WC–10Co–4Cr, Co–28Mo–17Cr–3Si) with electrolytic hard chrome (EHC) coating using CorrodKote test and electrochemical polarization test. They observed that no damage takes place in HVOF coatings after corrodkote test. Lima et al. [21] investigated the adhesion properties and general features of thermal barrier coatings with HVOF (Thermal spray) bond coats and plasma-spray-ceramic-top coats. They studied the microstructure, morphology, micro-hardness and adhesive/cohesive resistances and reported that the main failure location lies in the bond coat/ceramic interface that corresponds to lowest adhesion values. Ibrahim and Berndt [22] conducted a detailed analysis of deformation and fatigue over two groups of steel (AISI-4340). The first group was treated with HVOF WC–Co coating and the second was coated with hard chrome. They conducted rotating beam fatigue tests over the uncoated and coated specimens and reported a higher fatigue life HVOF coated specimens compared to the uncoated ones. Ni et al. [23] prepared amorphous steel coating (Composition: Fe48Cr15Mo14C12B8Y2) using HVOF thermal spraying technique. They observed that the wear resistance and micro-hardness of the coatings to be better than electroplated Ni and Cr based amorphous coatings. They also reported about the paramagnetic features of coatings at room temperature. Fedrizzi et al. [24] analyzed the degradation mechanisms for industrial HVOF cermet coatings using tribocorrosion approach. They studied tribocorrosion phenomena of cermet coatings in the presence of sodium chloride solution underneath sliding wear state. They showed that the grinding that is done after coating often produces structural damages that significantly affects the mechano-
chemical characteristics of cermet coatings. They further interpreted that the coating corrosion can be governed using electrochemical techniques and main degradation mechanisms can also be studied. Hasan et al. [25] investigated the optimization and design of functionally graded coatings of a multi-powder HVOF thermal spray device deposited aluminum/tool-steel. They developed a multi-powder feed device. Their idea dealt with a standalone two-powder chamber device that is coupled to a common hopper system to facilitate better mixing of the powders while undergoing through the thermal spray deposition process. They validated their idea by simulating their design of multi-powder flow using FEA technique and thus obtained an optimum dual feed design for better mixing. Leivo et al. [26] prepared aluminosilicate/mullite coatings using nano-sized sources of Al and Si using HVOF technique. Their results revealed that by applying agglomerated and heat-treated powders, good overall bearing properties and less porous coatings could be generated. Mahesh et al. [27] reported that the sprayed coatings become denser with splat layered morphology. They computed the porosity of the coatings referring to the optical micrographs of the coatings and reported it to be lesser than 1.7%. They concluded that HVOF sprayed NiCrAl coatings, that exhibit superior behavior, may prove to be an effective means of protection of superalloys from high-temperature environment. Valaizo et al. [28] investigated the effective damage tolerance of coatings based on FGM concept that is prepared using the HVOF technique. Through the in-situ curvature measurement method, they observed that while depositing FGM coatings, the top layers experience high compressive stresses and lower (metallic layers) experiences peening effect due to successive impact. Their findings revealed comparable microhardness values for different FGC layers with single layer coatings (Fig. 7) irrespective of peening effect and different residual stress due to the presence of adjacent layers.

![Fig. 7 Vickers microhardness of the single-layers and of the FGC layers. The rule of mixtures prediction for the composite layers of the FGC is shown by the solid line [28].](image)

Alleg et al. [29] prepared coatings that were partially amorphous containing Fe$_{75}$Si$_{15}$B$_{10}$, that were created using nanostructured feedstock powders through the HVOF spray method. They refined the X-ray diffraction patterns and visualized the presence of an unformed phase, nanocrystalline α-Fe (SiB) structure that have lattice structure of 0.2841 nm with an average crystallite size of about 78-83 nm, along with small amounts of Fe$_3$O$_4$ oxide (of about 104 nm) and Fe$_2$B boride (of about 151 nm). They found that Fe$_3$O$_4$ and Fe$_2$B disappear with an increase in the thickness of the coating. However, the
porosity decreases. Bolelli et al. [30] investigated the manufacturing technique of an HVOF-sprayed FGM coating containing a pure WC–Co top layer flowed by two NiAl/WC–Co composite layers. They varied the concentrations of cermet in the bottom two layers and observed that the stress build-up and thermal stresses of NiAl-rich layers are significantly subsidized during thermal spray. They further observed that thick coatings could also be deposited without any risk of delamination. Bolloli et al. [31] also investigated the tribological features of two alloy coatings of Fe-Cr-Ni-Si-B-C (Colferoloy) that were manufactured through HVOF thermal spray using rubber-wheel-dry-particle-abrasion and ball-on-disk-sliding-wear tests. They compared the obtained results with those obtained with bulk tool steel, hard chromium electroplating, Cr$_2$C$_2$-NiCr, and Ni-Cr-Fe-Si-B-C based layers. They reported that electroplated chromium and Ni-based alloys could be a suitable substitute with coleroloy coatings, especially for sliding wear cases. On the other hand, the coatings of coleroloy are unsuitable for the cases with particle abrasion resistance. Rodriguez et al. [32] reinforced multiwall carbon nanotubes in tungsten carbide-cobalt coatings and tried to improve their mechanical and wear properties using a thermal spraying technique. Thermal spray HVOF process over a plain steel substrate was applied. They also evaluated the coatings deposited with nanostructured and microcrystalline powders of WC-12%Co and compared their results with the results of the samples that were reinforced with carbon nanotubes. Reinforced coatings exhibited better abrasive wear characteristics compared to non-reinforced ones. Their investigation showed that the carbon nanotubes are good alternatives that are capable of improving the abrasion and wear resistance of tungsten carbide-cobalt coatings. Berger [33] reviewed various thermal spray coating techniques, focusing on HVAF and HVOF techniques. They also emphasized on the preparation of feedstock powder and reported that the thermal spray process appreciably modifies the phase compositions and chemical strength of the feedstock powders and sprayed coatings. Bolelli et al. [34] investigated the abrasive and sliding wear properties of hard metal coatings of WC-10Co$_2$Cr. They sprayed a feedstock powder with two particle size distribution onto the carbon steel substrate using HVAF and HVOF methods. They performed ball-on-disk tests at room temperature against Al$_2$O$_3$ counterparts and obtained mild wear rates of 10$^{-7}$ mm$^2$/Nm and friction coefficients of around 0.5 mm for all developed samples. They reported that the coatings deposited using coarse feedstock powders often suffer from higher wearing tendency compared to those obtained with fine powders. Taillon et al. [35] investigated the cavitation erosive nature of ferrite and martensite (stainless steel) using HVOF coatings that were prepared from Fe$_3$Al (pure) in powder form and Fe$_3$Al (reinforced with boride and nitride phases) using a vibratory set up (G32). They reported that coatings produced with HVOF coatings execute lower rates of erosion compared to the martensite-based stainless steels coatings. Vashishtha et al. [36] investigated the erosive and abrasive wear characteristics of WC–12Co, WC–10Co–Cr (HVOF deposited) and Cr$_3$C$_2$–25NiCr coatings. They observed that the Cr$_3$C$_2$–25NiCr coating shows the lowest friction coefficient owing to the formation of a tribo-oxide film. Vashishtha and Sapate [37] studied the abrasive and friction wear characteristics of WC–12Co and Cr$_3$C$_2$–25NiCr HVOF sprayed coating. They observed that the friction coefficient and rate of abrasive wear, decreases with an increase in sliding velocity by varying the magnitude. They further observed that the mechanisms of wear, oxidation, operating condition and microstructure affect the wear and friction characteristics of the coatings. They used some wear maps to recognize the transition in the severity of oxidative wear and rates of abrasive wear. Their results revealed that the different wear regimes of the coatings are due to the change in the relative contribution of oxidative wear and mechanical wear in context to the operating variables. Karaoglanli et al. [38] compared wear and friction characteristics of five different HVOF spray coating sliding against Al$_2$O$_3$ counter body in a dry environment. They performed ball-on-disk (single way) tests over Cr$_3$C$_2$/NiCr (75/25), NiCrBSi/WC (50/50), WC/Co (88/12), NiCr (80/20) and WC/CoCr coatings deposited over stainless steel substrates, under the influence of normal load (5 N and 15 N) having the sliding speeds of 10 and 20 cm/s (Fig. 8). They observed that the WC/CoCr coating method is best suited HVOF spray technique that extends the life of components that works at higher wear and temperature environments. This behavior was owed to high wear resistance and low friction coefficient. They also reported a decrease in wear rate with an increasing load and decreasing sliding speed.
Katrinidis et al. [39] studied the effects of stand-off distance, gun traverse speed and angle of spray on the coating attributes in applications with floating stand-off distance and spray angles. They conducted several experiments simulating spray technique of non-circular cross-sections that permit individual control over the kinematic parameters by spraying WC-17Co powders using HVOF technique on steel substrates. They precisely observed the effects of like residual stresses, deposition rate, micro-hardness, and porosity of the developed coatings. They observed that large stand-off distances and oblique spray angles compromise the coating properties. Also, they found that kinematic parameters interplay produces non-linearity in a few coatings. They reported that micro-hardness has a negative correlation using oblique spray angle at a small distance. However, it has a positive correlation with an increase in stand-off distance. Katrinidis et al. [40] used an experimental setup capable of isolating kinematic parameters and developed a systemic study for interplay. They evaluated the effects of spray distance, spray angle and traverse speed of gun on the phase composition and microstructure of the HVOF (WC-17) sprayed coatings. Their experimental observations revealed that with a smaller angle of inclinations, the WC distribution in the developed coatings is sprayed at larger stand-off distances. Vignesh et al. [41] developed iron-based amorphous metallic coatings over 316- stainless steel (SS) substrate using HVOF spray method of coating. They developed some empirical correlations to estimate the micro-hardness and the porosity of amorphous coatings that are iron-based and incorporate HVOF parameters like fuel/oxygen/carrygas flow rates, powder feed rate and spray distance. They used response surface method to detect optimal values of HVOF parameters so that the coatings with minimum porosity and maximum hardness can be prepared. Lavigne et al. [42] prepared CaviTec powders, which is an alloy that has high resistance to cavitation erosion by water mechanical alloying and atomization. In the case of cavitation, CaviTec powders absorb impact loads and exhibit phase transformation over their structures. They used the HVOF technique to deposit the coating on 304 stainless steel (SS) substrates. They evaluated the mechanical properties of CaviTec by indentation. They used an ultrasonic cavitation erosion testing machine to analyze the properties associated with cavitation erosion. The microstructures of the developed coating were studied using scanning electron microscopy (SEM) and X-ray diffraction (XRD) method. They observed that erosion resistance (cavitation) of the developed coatings,
developed using atomized CaviTec powder improves when these powders were milled a few moments before deposition. Lamana et al. [43] investigated two distinct WC cermet with different Co (as binder) contents to determine the effect of Co concentration on the cavitation resistance and fracture toughness of tungsten coatings that were deposited using HVOF method applied with different fuels. They studied the effect of HVOF technique (based on the fuel type) on the residual stresses, microstructure and coating properties. They observed that with increasing Co content the cavitation resistance and fracture toughness increases. Also, by using liquid fuels with the HVOF process, the compressive residual stresses were enhanced. This had also resulted in an improvement in properties like the toughness of the fracture accompanied by an improvement in resistance to cavitation. Tailor et al. [44] reported that the problems of the coatings like porosity, density, wear-resistivity, etc. can be overcome by depositing using molybdenum coatings over low-carbon steel (LCS) substrates through wire-HVOF thermal spray procedure. They fabricated Mo coatings by flame/arc spray and powder-HVOF process. They used SEM and XRD techniques for microstructural and phase analysis respectively. Their results revealed that the coatings deposited by W-HVOF showed superior mechanical, wear and microstructural property compared to the thermal spray process (plasma spray and flame spray processes. Vashishtha et al. [45] investigated the effect of tribo-chemical reactions under variable load conditions and sliding speed on the abrasive wear and friction response of high-velocity-oxy-fuel-sprayed WC-10Co-4Cr coatings. They found that the friction coefficient, as well as rate of abrasive wear, decreases with an increase in sliding speed whereas, the coefficient of friction increases with an increase in applied load. They attributed the decrease in the rate of wear and coefficient of friction to the formation of surface films and tribo-oxides that attains better lubricating properties. They observed an increase in coefficient of friction with an increase in load irrespective of the fact that the sliding speed comes in the picture due to the dominancy of fracture-assisted mechanical wear when compared to oxidative wear. Crescenzo et al. [46] developed a revolutionary coating technique that was dependent upon coatings of shape memory alloys deposited on-site to large-scale metallic structural elements that are generally encountered while working in extreme environmental condition. This generally happens in case of buildings and heavy steel bridges. They claimed that this revolutionary technology would help in improving the nobility of civil structures that are metallic in nature to: (i) vary and control the mechanical properties using external stimuli (ii) improve the rigidity and stiffness of metallic as well as elastic structures (iii) confront the expected load conditions (iv) provide resistance to. To justify their idea, they deposited NiTinol Ni50.8Ti (Commercial) powder, over SS substrates using HVOF thermal spray technique. Singh et al. [47] used the HVOF technique to analyze the erosion of trubo-performance of Stellite-6 and Colmonoy-88 micron surface layers deposited over SS 316L. They used Ducom slurry pot tester to conduct erosion wear experiments at various process parameters. Their observations revealed that the relative erosion wear of SS-316L and Stellite-6 peak appears at an impact angle of 30º. Whereas, that of Colmonoy-88 peak appeared at 60º. Furthermore, the micro-hardness of SS-316L upgrade by about 2.5-3.2 times by depositing Colmonoy-88 and Stellite-6. Hao et al. [48] prepared a metal based NiCoCrAlYTa coating surface on Inconel 718 (Ni-base superalloy substrate) using HVOF spray process. The as-sprayed-NiCoCrAlYTa coating was then heated to 1000 °C for different time-durations to afford coatings C1, C2, C3, and C4. Their results revealed that the as-sprayed coatings are denser and have uniform microstructure along with good oxidation resistance.

2.2 Plasma Spray Technique

Jian et al. [49] conducted thermal fatigue and shock tests under specified temperature environments over ZrO2-based thermal barrier coatings that may be used in advanced gas turbines. They monitored the temperature and acoustic emission signals using carbon dioxide laser heating technique for heating various types of cylindrical specimens that have traditional two-layer coating and FGM coating. Khor et al. [50] fabricated functionally graded thermal barrier coatings (yttria stabilized zirconia NiCoCrAlY) using plasma spraying with pre-alloyed composite powders as feedstock. They prepared different composite powders by varying the compositions of composite using plasma powder spheroidisation and mechanical alloying. They adopted plasma spray technique to prepare 5-layered functionally graded coatings that exhibited outstanding properties compared to the traditional dual thermal barrier coatings. They owed it to the unique microstructure developed over the functionally
graded coating using the advanced plasma spraying methodology that has helped in minimizing residual thermal stresses of the coatings. Khor and Gu [51] developed functionally graded (FG) ZrO2/NiCoCrAlY coatings by plasma spray technique. They used pre-mixed and spheroidized powders as feedstock for their work. They observed that the density, modulus of elasticity, diffusivity, thermal conductivity, microstructure and thermal expansion coefficient varies gradually through the developed five-layered FG coatings. This in turn significantly improves the thermal as well as mechanical properties of the coatings. They also simulated the residual stresses of spray coatings having different thicknesses and different graded layers using finite element analysis and showed that the residual stress were lowest for five-layered FG coating compared to 2 and 3 layer coating having same thickness. Further, the residual stresses increases as coating thickness decreases. Okumura et al. [52] developed a thermal spraying-sintering technique to be used with an electrolyte and interconnect layer capable of improving the properties like gas tightness and higher electrical conductivity as desired by solid oxide fuel cells. They concluded that the thermal spray-sintering technique proves to be an effective way of the development of thin gas tight layer for solid oxide fuel cells. Schulz et al. [53] analysed thermal barrier coatings by depositing them over copper substrates using pulse-laser deposition technique and observed significant improvement in spallation behaviour due to the development of a graded lamella microstructure that have significantly improved fracture toughness at the interfaces. They also observed that a surface structure graded by means of particle-hardening reduces the wear resistance of plasma sprayed thermal barriers appreciably. They also found that arc-sprayed titanium graded layers within situ particles (welded alloy) improves the wear properties. Skopp et al. [54] used plasma spray technique to develop two new sub-stoichiometric Titania (TiOx) coatings on specimen of grey cast iron (GG20HCN) having high carbon content for cylinder liner application. They found that the wear rate of the atmospheric plasma spraying coating (TiO2.95,1) coatings were lower than vacuum plasma spray coating (TiO1.95,3) coatings. Chen et al. [55] designed a new FG thermal barrier coating (FG-TBC) based on LaMgAl11O19 (LaMA)/YSZ that were developed using air plasma spraying technique. They investigated the phase stability and microstructure using SEM, XRD, and DSC analysis (High temperature based). They showed that all the LaMA as well as LaMA-containing intermediate composite coatings often suffer irreversible phase transformations due to the recrystallization of amorphous LaMA coating and γ to α-Al2O3 transition while heating. Furthermore, YSZ and LaMA coatings are chemically stable even at high temperatures. Carpio et al. [56] reported that zirconates having pyrochlore structure (like Gd2Zr2O7), prove to be new and promising TBC owing to their good chemical resistivity and low thermal conductivity compared to molten salts. But, their thermal expansion coefficient very low that results in low fatigue resistance (thermal). They suggested that when yttria-stabilised zirconia (YSZ) and Gd2Zr2O7 combined together can reduce the thermal contraction differences between the TBC parts. They further evaluated the observed the sintering, oxidation and thermal fatigue resistance of multilayer and FGM coatings while passing them through isothermal and thermally-cycles. They observed that multilayer coatings of YSZ/Gd2Zr2O7 exhibits better thermal characteristics compared to the monolayered coatings of Gd2Zr2O7. However, the fatigue resistance (thermal) was less compared to the traditional YSZ coating. Also, the FGM coatings shows good fatigue resistance (thermal). Carpio et al. [57] studied the molten salt attack behaviour of various YSZ coatings with FG and multi-layered design. They used two varieties of microstructures (i) APS coating obtained using conventional powder (ii) bimodal structure with nanozones that were obtained using feedstock of nanostructure type. Their results revealed that nanozones acts as inhibitors of molten salts penetration toward the deeper layers. They also showed that a layer formed using nanozones can however be detached when the salt attack intensity is very high. Therefore, the FGM coatings are ideal coatings that are capable of diminishing the molten salt attack. Vaben et al. [58] presented the manufacturing of FGM coatings using vacuum plasma spraying. At first, they produced the coatings using two different feeding lines. They produced samples with 3 and 5 layered configurations (excluding tungsten and steel) and investigated their microstructures. They used the hole drilling method to measure the residual stress and hardness. They modified the composition and morphology of (Ti–6Al–4V) surface using laser cladding technique to enhance the bioactivity and biocompatibility of orthopaedic implants. They reported that The FGM cladding has high apatite precipitation compared to 100% HA cladding. In addition, they shown that both laser
cladding samples have significantly high amount of protein adsorption which in turn increases the cyto-compatibility and cell adhesion when compared to Ti-6Al-4V alloys that are non-cladded.

2.3 Combination of HVOF and Plasma spray coating technique

Rastegar and Craft [59] developed face coatings using thermal-spray-deposition for top compression ring of high horsepower diesel engine operating at high temperature and pressures. They deposited the coatings with HVOF and plasma spray method over the top faces of the piston rings. Then certain wear and engine tests were conducted to evaluate the coating property. They found that the developed coatings showed good wear resistance compared to modern molybdenum carbide and electroplated chromium coatings. Further, the liners of the cylinder generally undergo similar or less wear in case of thermal spray coatings when compared to electroplated chromium coatings. Pchlik et al. [60] studied FGM coatings that are relevant to industries. They used HVOF deposited WC-Co/SS and plasma sprayed Mo-Mo-C/SS FGMs for their work. They evaluated abrasive wear and sliding friction response using damage and thickness mechanism that controls the friction coefficient and wear rates and reported an enhancement in coating properties of Mo-Mo-C with stainless steel using FGM coating technique. Khoddami et al. [61] varied the amount of Zirconia in FG coatings from 30-100 percentage by volume. They studied duplex and FG coatings using SEM, optical microscope, X-ray Spectrometry (energy dispersive type), map analysis and XRD technique. They also measured substrate’s adhesive coating strength and showed that the composition, microstructure and porosity gradually vary in case of FGM coatings. They observed that spray functionally graded coatings have good adhesion strength compared to duplex coatings. Lima et al. [62] investigated Cr₃C₂ ceramic transitional layer’s performance created using PVD technique between ceramic top coat and bond coat in a TBC system. The thickness of the intermediate layer was kept around 1-2 µm. They combined two substrates with two distinct bond coats for their investigation. They used atmospheric Plasma Spraying (APS) as well as HVOF techniques for top coat and bond coat respectively. They suggested that oxidation resistance of the bond coat improves due to the appearance of transitional layer that changes the stress distribution due to improvement of the surface imperfections in the intermediate layer. A change in oxidation kinetics was also noticed. Dokur and Goller [63] evaluated the thermal, mechanical properties and microstructures of multi-layered ceramic coatings made of CYSZ/Al₂O₃ and CYSZ/Al₂O₃ that were developed using 4, 8 and 12 layers having total thickness of around 400 µm using APS and HVOF processes. They observed that the thermal cycle strength as well as thermal conductivity of CYSZ/Al₂O₃ + YSZ TBCs were significantly improved compared to that of CYSZ/Al₂O₃ (based on TBC) owing to their improved properties. Kirbiyik et al. [64] produced CYSZ/Al₂O₃ ceramic TB coatings in twin layered and FG design containing 4, 8, 12 layers using APS and HVOF processes. They evaluated the thermal, mechanical and microstructural properties of the produced TBC. They observed that the bonding strength and the thermal cycle performance of the developed CYSZ/ Al₂O₃ functionally graded design are better than double layered CYSZ/Al₂O₃ and single layered (CYSZ) coatings.

2.4 Other Techniques

Hoornaert et al. [65] studied the industrial benefits and basic requirements hard coatings like carbides, nitrides, multi-components etc. They also compared the properties of hard coatings with new generation coatings like multi-layers, gradient, multiple layers and nano-scaled. They reported that the hard coatings are industrial efficient and beneficial for economic growth. Kapsiz et al. [66] performed experimentation to study the tribological behaviour of specific pairs of piston ring/ cylinder liner. They optimized the process parameters like oil type, applied load and sliding velocity adopting mixed L16 Taguchi orthogonal design to minimize the friction, wear and weight loss. They reported that sliding velocity is most significant parameter that affects weight loss as well as friction behaviour of cylinder liner/piston ring pair. Further, the combined effect of oil type and sliding velocity exhibit remarkable effect on the weight loss of the piston rings. Mahamood and Akinlabi [67] studied the laser material deposition process to produce FGMs from 3D computer-aided-design model of various parts in a single process. Their results showed that for all material combinations, the developed FGM exhibit better properties compared to those developed keeping the processing parameters constant.
Schutz et al. [68] conducted in-situ tests on waste-to-energy plant to enumerate the associated corrosive elements. They reported that the low-alloyed steel that were unprotected undergoes local corrosion to great extent. They also showed that corrosion was more along α-ferrite’s grain boundaries. Their observations revealed that the corrosion rate gets enhanced due to FeCl₃ and a mixture of FeCl₃ and HCL. Thruthiruselvam [69] reviewed the different aspect and usage of thermal barrier coatings as applicable to internal combustion engines. He concluded that application of TBC to different components of combustion zone has produced appreciable improvements in thermal and mechanical efficiency and other performance parameters like specific fuel consumption and causes reduced exhaust emissions. Yilbas et al. [70] incorporated twin wire arc spray system and generated different thicknesses of coatings over the steel substrates. The coating characteristics were evaluated using 3D imaging optical and SEM, XRD and energy dispersive. They reported that the surface roughness and texture of the coatings changes with change in coating thickness. Further, the tensile residual stresses are observed in coatings that also changes with coating thickness. Goyal et al. [71] presented modelling based on Finite element method (FEM) for a powder stream inside a supersonic nozzle in which gas flow under adiabatic condition and gas expansion takes place uniformly. The velocity and temperature contours of the coatings were computed using FEM. Their result are useful in predicting the behavioural features of powder stream at supersonic nozzle’s exit. Shi et al. [72] used laser cladding coating and developed gradient composite coatings with alloy steels of 20CrMnTi. They selected parameters like laser power, cladding velocity and flow rate of powder that affects the orthogonal cladding experiments. They optimized important factors through TOPSIS method and Taguchi OA technique. ANOVA technique was used to validate the selected parameters and results. They used SEM, laser microscope, micro-hardness tester and XRD to characterize the microstructures of the prepared composites. They reported that the micro-hardness of the gradient coating gets enhanced by 3 times compared to 20CrMnTi substrate. They also found that the wear resistance of the 20CrMnTi cemented (quenching sample) and gradient composite coatings gets accelerated by 15.9 and 36.4 times compared to that of 20CrMnTi coatings. Yazdani and Isfahani [73] fabricated composite coatings with powdery mixtures by varying the mass ratios of Ni/Al₂O₃ from 1:1 to plain Nickel. They adopted SEM, XRD and TEM methods to investigate the structural properties of coatings. They observed that the starting mixture’s composition is significantly affects the microstructure and Al₂O₃ concentration of prepared coatings. It was further observed that the mixtures with higher content of Al₂O₃ exhibits Al₂O₃ particles to a higher volume in the prepared coatings. In addition, metallurgical and mechanical bonding are the key mechanisms of the coating adhesion to the aluminium substrate. Rahmani et al. [74] used the pulsed current method to study the nano-composite coatings of FGM Zn–Ni with a nanoparticle mixture of 80% alumina (by weight), 5% yttria and 15% graphene that were electrodeposited over mild steel. They evaluated the pulse parameters effects like frequency and duty cycle on microstructure, chemical composition, tribological properties and corrosion resistance of coated specimens. They observed that wear and corrosion properties of coatings are significantly improved by adding nanoparticles and increasing the frequency. Shourgeshty et al. [75] electroplated the Zn–Ni–Al₂O₃-FG coatings by continuously varying the duty cycle or frequency. They used two types of coatings (i) First was synthesised by gradually reducing the duty cycle from 88 to 11% at a specified frequency and (ii) Second was plated when the frequency gradually raised constant duty cycle from 100 to 1500 Hz. They studied the composition and microstructures of the coatings using SEM fitted with energy-dispersive spectroscopy. Their results showed that in first type of coating, the microhardness as well as Ni and alumina contents increases along the surface. However, in second type, the composition gets rarely affected by altering the frequency. Behera et al. [76] modified the composition and morphology of Titanium alloy surface (Ti-6Al-4V) using laser cladding technique in order to improve the bioactivity and biocompatibility of orthopaedic implants. They processed the substrates of Ti-6Al-4V with a pulsed laser Nd:YAG having various precursors (100% HA and functionally graded TiO₂–HA material). Their results revealed that the laser cladding technique significantly improves the bioactivity as well as biocompatibility of the developed (Ti-6Al-4V) surface (Fig. 9).
Yin et al. [77] proposed a hybrid additive manufacturing technique for fabricating FGM coatings that combines two additive manufacturing techniques named as cold spraying and selective laser melting. Their proposed additive process included targeted experiment of Al+Al₂O₃ and Al that were deposited over SLM-Ti6Al4V through cold spray process. The additives exhibited a machinable, thick and dense FGM that basically composed of metals that were difficult to weld in absence of an intermetallic phase transformation at the interfaces of the multi-layered coatings. They reported that the FMG’s overall hardness is higher compared to the original feedstock.

Lee and Erdogan [78] studied the simple strain elasticity problem in context to multi-layered homogeneous and FGM coatings bonded over a base metal substrate (nickel-based alloy- Rene-41 and zirconia) under uniform temperature change environment. They observed that FGM coatings are capable of eliminating stress singularities and helps in uniformly distributing the stress over the substrate. Cai and Bao [79] analysed the propagation of cracks of the coatings made through FGM technique using crack-bridging technique. They used FGM coating of ceramic/metal composite whose grades were specified by local volume fractions of metal phases and ceramics. They observed that the bridging of crack in FGM coatings are capable of reducing the intensities of crack-tip stresses. Furthermore, the gradation of coating generates appreciable effect on the crack length at the arrest and the fracture driving force. They further observed that FEM can be further elaborated for large-scale plastic deformation studies in order to analyse the growth of cracks in FGM coatings. Lee and Erdogan [80] investigated the problems based on simple strain thermal stress of interface crack in homogeneous substrates made from superalloy having graded coating similar to substrate along with partially stabilized zirconia. They varied zirconia from 0% (by volume fraction) at the transitional layers to 100% over the base surface. The surrounding surfaces of the coating is maintained at high followed by forced-cooling and exposing the specimen ends to an environment of natural convection.

Kim and Paulino [81] studied the arbitrary geometry’s FGM assemblages having stationary cracks using finite element computation technique of fracture parameters. They computed the stress intensity factors (SIF’s) for mode-1 and mixed mode 2D (two-dimensional). They compared the results for three different approaches made to be used with FGMs. The first approach was path-independent (J_k^- integral). The second approach was modified crack-closure integral and the third one was displacement correlation technique. They observed that path-independent J_k^-integral method is
superior to displacement correlation technique. Chi and Chung [82] investigated the SIF’s of multilayered (cracked) and FGM coatings of composites of substrate-coating using FEM. They approximated the substrates to be made of homogeneous material and the coating of multi-layered medium or sigmoid FGMs. The developed sigmoid were simply a kind of FGM material in which the materialistic properties of the coatings are controlled by two power-law functions of volume fractions in such a way that the material property functions represents the sigmoid distributions along its thickness (called as S-FGM). They reported that in case the coating is stiffer compared to its substrate, then there may be possibility of crack development in single-layered coating compared to multi-layered coatings. But the growth of the crack may be ceased by using S-FGM coatings. However, in case the substrate of the developed coating is harder than the coating, the S-FGM coating acts as bridge that joins the hard substrate with soft coating. Dong et al. [83] used integral transform and derived a Cauchy singular integral equation for the cracks present in coatings. They adopted allocation technique to solve it numerically and reported that SIFs of the interfacial cracks are greatly affected by weak discontinuity. Furthermore, coating thickness, substrate thickness and applied peel stresses significantly affects the dynamic SIFs. Gerard [84] identified that the modern thermal spray technique provides coatings with good wear resistance when applied over the surfaces of engine cylinders made of magnesium or aluminium. They obtained unique surface topography with suitable finishing technique that helps in reducing friction coefficient to great extent and also reduce the fuel consumption by 2-4%. Further, thermal spray technology provides better advantage in conservation of energy and fuel and oil consumption. Buyukkaya [85] studied the thermal characteristics of piston materials made from steel and AlSi using FGM coating technique by simulating them through ANSYS software package. They deposited MgZrO3, NiCrAl+MgZrO3 and NiCrAl powders over the substrates and compared the computed results of steel and AlSi pistons. They observed that peak surface temperature of FGM coating AlSi alloy is raised by 28% while that of steel pistons is raised by 17%. Li et al. [86] studied the natural vibration behaviour of rectangular plates developed through FGM having clamped as well as simply supported edges. They conducted their studies in a thermal environment in consonance with 3D linear elasticity theory. They considered clamped and simply supported FGM plates that were subjected to non-linear, linear and uniform temperature rise environments. They found that the temperature predominantly affects the vibrational frequencies of clamped plates as compared to simply supported ones. Afsar and Song [87] presented the effect of varying the thickness of FGM coating on the apparent fracture toughness (AFT) of a thick cylinder wall that have edge cracks of two diametrically-opposed nature that were created from the inner surface of the cylinder. They reported that the proposed methodology proves to be simple and effective for calculating the AFT of thick wall cylinder using FGM coating evaluated at the inner face of the cylinder. Mao et al. [88] studied the interface layer damage characteristics of shallow spherical shells developed through FGM coatings that are exposed to velocity impacts of lower intensity. An analytical model based on continuum theory is developed and used. Their model predicted a smaller relative displacement in transitional layers (interfaces) for mode-I crack directions compared to II-mode crack direction. Further, an increase in FGM coating thickness increases the stiffness of the surface. Monfared and Ayatollahi [89] investigated the dynamic stress intensity factors (DSIFs) for an orthotropic strip developed through FGM coating that were weakened by using multiple arbitrary cracks under the influence of time-harmonic excitation. They solved the integral equations using the method proposed by Erdogan’s collocation and computed the DSIFs. They observed that DSIFs increases with increasing load frequencies, then reaches to a maximum value, and then falls with rapid rate under point load traction. Bagheri et al. [90] investigated the fracture characteristics of an orthotropic strip developed though orthotropic FGM coating that was weakened due to the presence of multiple defects when applied with time-harmonic excitation condition. They reported that SIF increases with increasing load frequencies and attains a maximum value which then decreases with rapid rate for a single and multiple collinear crack. They also reported that the imperfect bonding assumption has remarkable effect on the amount of maximum DSIF of cracks and resonance frequency. Mao et al. [91] studied the thermo-elastic instability of the FGM coatings whose properties vary arbitrarily including contact resistances due to thermal and friction. They used the perturbation and heat transfer matrix technique derive the characteristic equation of thermo-elastic instability problems. The equations were solved to derive the expression correlating critical heat flux and critical
sliding speed. They also examined the effects of varying material properties and gradient index on the stability of the developed FGM coatings and reported that FGM coatings are capable of adjusting the thermo-elastic contact stability behaviour of sliding systems. Ayatollahi et al. [92] studied the dynamicity of an orthotropic substrates that were weakened with moving cracks and reinforced with a non-homogenous coating material. They calculated the screw dislocations of an orthotropic strip containing FGM coating with imperfections of orthotropic nature. In addition, they derived integral equations to compute the density function of dislocation on the surface of the cracks in order to do the anti-plane crack analysis, in which the screw dislocations were distributed in line with the cracks. They reported that along the material interfaces, the SIF decreases with an increase in stiffness coefficient. Ma et al. [93] proposed an original idea for the fabrication of tungsten copper FGMs that have high density and electrical conductivity. They observed coating’s thermal conductivity at room temperature as 98 W/mK. They further observed that the thermal conductivity decreases with increase in temperature. Also, the microhardness of WCu rises gradually from the near surface towards the core layer. Han et al. [94] studied cylindrical shell’s buckling behaviour subjected to thermal loads using FGM technique and showed that the theoretically calculated solution of the rise in critical buckling temperature agrees well with the numerical solution. Furthermore, they derived an empirical formula to compute the critical buckling temperature increase that have precise mathematical expression in order to solve the practical engineering problems that are complex in nature. Kumar et al. [95] performed a comprehensive study of structural, vibrational and thermal properties of SS301 (a conventional material) and FGM (WC-SS) in context to low capacity power plant boiler shells. They modelled the preliminary boiler shell structure and analysed its properties. They showed that the material deflections stress and thermal stress difference gets reduced by about 25% with an improvement in the life of boiler shell. Monfared et al. [96] studied mixed mode fracture behaviour of orthotropic strip (FGM based) that were based on dislocation distribution. They employed Fourier transform and developed a system of singular integral equations based on Cauchy’s recommendations. Then they numerically evaluated the equations using the integration formula of Lobatto–Chebyshev and calculated the dislocation density over a crack face. They also analysed the stress intensity factors of the coatings. They concluded that the SIFs are significantly affected by the material non-homogeneity constant. Also, the stiffer zone showed higher normalized SIFs of the crack tip compared to less stiff zone. Szubartowski and Ganczarski [97] determined the effect of several approximations of TBCs (FGM coatings) on the stress and temperature distributions. They found that the traditional approximations of exponential functions or specific power reflect FGM distributions that comes neither from theory nor from practice. They also demonstrated that the presence of tensile hoop stress inside the ceramic layer is valid only when it encompasses residual stress of compressive nature. Guo et al. [98] developed a model based on piecewise-exponential (PE) function for the evaluation of the interface crack problems of FGM coating substrate structure where the mechanical properties are continuous and the substrate properties are homogeneous in nature. They evaluated the different properties of coatings using exponential functions series along with sustained continuity. Many mathematical manipulations have been applied and the problem was reduced to a group of integral equations (of singular type) that can be solved using numerical techniques. The mix-mode SIFs and the rates of strain energy release were analysed under the plane loading conditions. They presented the influence of the variation of coating properties and geometrical parameters on the fracture behaviours of the cracks that are generated at interfaces. Cai et al. [99] prepared Ti3SiC2/SiC FGMs using hot pressing impregnation that is a unique local impregnation method targeting at layers and exhibit dull sintering characteristics. This in turn improves the density due to positioning impregnation and hence, the density of the developed hot pressed FGM at 1600°C increases from 3.47 to 3.79 g/cm³. On the other hand, a decrease in open porosity from 11.2% to 1.98% is observed. Furthermore, the oxidation resistance of the FGM that was hot pressed at 1600°C and position impregnated was appreciably improved. Wang et al. [100] developed a theoretical solution for buckling critical temperature applied over a cylindrical shell having an axisymmetric imperfection and FGM coating. Their theoretical solutions were based on Galerkin method, Koiter model and Donnell shell theory. They analysed the effect of ceramic volume fraction, axisymmetric imperfection profile and thermal loading types on the thermal buckling phenomena of the coatings with an imperfect cylindrical nature. They also provided a scientific solution for coated imperfect cylindrical shells suffering from thermal buckling problems.
Cheng et al. [101] presented a bond-based peridynamic model for FGM coatings capable of simulating several dynamic brittle fractures. They investigated the gradient patterns of FGMs and effect of loading and suggested that loading conditions as well as material gradient patterns may significantly affect the FGM’s crack propagation. However, they showed that use of specific elastic modulus is limited for fracture characteristics of FGMs. They also showed that the FGM sample’s crack curving angle increases by increasing the dynamic biaxial ratio. Zhou et al. [102] used the integral transform of Fourier and Laplace along with the principle of superposition and thermal field’s general solutions were evaluated. They also evaluated the homogeneous solutions of complex and real eigenvalues. They also computed the particular solutions for electro-elastic field. They applied the time-dependent technique based on numerical Laplace-transform inversion and analysed the convergence behaviour. Their numerical solutions represented that due to thermal relaxation effect, the results of the heat conduction model based on non-Fourier domain, attained peak values at later stages compared to Fourier model.

3. CONCLUSION OF THE LITERATURE REVIEW
On the basis of detailed literature review of the coating techniques generally used in industries and by researchers, the following conclusions are drawn:

1. HVOF coating is a widely accepted technique for industrial and process applications. It significantly improves the chemical strength, fatigue life, micro-hardness, density, wear resistance, corrosion resistance and reduces the oxide formation. However, the adhesive bond strength of the intermediate layers is adversely affected. HVOF technique often suffers from problem like weight loss compared to nano-particle coating techniques. Also, the top and bottom layers of the coatings are subjected to different stress intensities.

2. Plasma spray technique (PST) significantly improves the microstructure and bond strength of the intermediate layers of the coating. The thermal expansion coefficient, thermal conductivity, modulus of elasticity and density varies gradually for multi-layered functionally graded coatings. Furthermore, PST reduces the residual stresses and improves the mechanical and thermal properties of the developed coatings. However, the fatigue thermal stresses are less in case of PST coating compared to HVOF coatings.

3. When the top face of the piston rings is coated using HVOF and PST, the wear resistance is significantly improved as compared to electroplated chromium and molybdenum carbide coatings.

4. Sufficient efforts have not been undertaken towards the improvement in deposition efficiency/ productivity of cylinder liners in terms of particle size and corrosion characteristics. A consistent literature about the thermal spray coating mechanism especially for cylinder liners is limited in literature.

Very less data is available on the numerical analysis of spray coating on cylinder liners using tools like FEA. Abundant data is available in literature for mechanical characteristics of coatings. However, the thermal behaviour is not critically analysed in detail.

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