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A Review of Coating Methods and Their Applications in Compression and Spark-Ignition Engines for Enhanced Performance

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REVIEW ARTICLE

Abstract- Coating of metallic surfaces such as cylinder heads, cylinder liners, piston heads and exhaust-valves in Internal Combustion Engines (ICEs) has improved engine performance in areas of brake-thermal-efficiency including brake-specific-fuel consumption, etc. This review showed different methods of coating in compression and spark-ignition engines for improved performance using different coating thicknesses on the metallic surfaces. These coating thicknesses may be either minimum or maximum depending on the coating method used. The coating methods discussed in this paper were Thermal Spraying (TS), Physical-Vapour Deposition (PVD), Chemical-Vapour Deposition (CVD) and Ion Implantation methods. Minimum thicknesses were achieved using the PVD, CVD and Ion-Implantation methods. In addition, Sol-Gel and Slurry coatings were also discussed. Having considered these methods of coating, thermal-spraying method was recommended for compression and spark-ignition engines because it produces temperature ranging from 8000 K-14000 K on surfaces with thick coating thicknesses.

Keywords- Compression, Coating methods; Thermal-Spraying, Physical-Vapour decomposition, Chemical-Vapour decomposition.

1 INTRODUCTION

Coating metallic surfaces in compression and spark-ignition engines improves performance by preventing wear, corrosion, oxidation and excessive heat on engine-parts (Ravikumar *et al.*, 2014). However, its major advantages in Internal Combustion Engines (ICEs) are increase in brake-thermal efficiency, decrease in brake specific fuel-consumption (BSFC) and control of gas emissions (Behzad *et al.*, 2019). Achieving this objective resulted in discussing coating methods and recommendations made on the better coating method for ICEs (Ravikumar *et al.*, 2014; Isaac, 2021).

Combustion chambers made of cast iron from literature were unable to withstand thermal and mechanical loads (Nguyen *et al.*, 2007). Initially, glass and its derivatives materials were considered due to their low thermal conductivities (Kawasaki & Watanabe, 2002; Stefano *et al.*, 2021). However, in spite of low thermal-conductivity, low-expansion rate and cost, glass was not used in ICEs due to lack of strength (Kawasaki & Watanabe, 2002). The use of ceramic-materials in engine-parts was first reported in 1950s (Robert, 1996). Reason for ceramic-coatings for high-temperature applications started increasing in the 1960s (Ravikumar *et al.*, 2014).

Ceramic coating-technology was first used for space and aviation industry and then in the 1970s its application to ICEs, especially diesel engines started (Kawasaki & Watanabe, 2002). Reported performance-increase and BSFC decrease of ceramic-coated systems established a renewed interest (Miyairi, Matsumsa, Ozawa, Odcawa, & Nakashima, 1989). A diesel piston crown with thermal barrier coated was previously introduced using the thermal spraying method with better results (Isaac, 2021).

2 COATING METHOD CLASSIFICATIONS

The Coating methods explained and reviewed in this work are classified as Thermal Spraying, Physical-Vapour Deposition, Chemical-Vapour Deposition and Ion Implantation methods (Thiruselvam, 2015; Behzad *et al.*, 2019). Minimum thicknesses from Fig. 1 are achieved by Physical-Vapour Deposition (PVD), Chemical-Vapour Deposition (CVD) and Ion-Implantation methods. Other methods are Sol-Gel and Slurry Coatings (Nishant *et al.*, 2018).

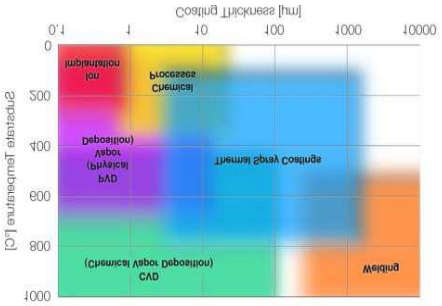

Fig. 1: Range of coating thicknesses for different methods

2.1 THERMAL-SPRAYING METHOD

Thermal-Spray techniques are processes whereby powders are heated to melting temperature and deposited in molten or semi-molten state on prepared

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substrate (Nishant *et al.*, 2018). The source of heat utilize in this method is either electrical arc or thermal plasma (Sobhanverdi & Akbari, 2015) [8]. Metals, alloys, ceramics or plastics materials in the form-of-powder or wire are used (Sobhanverdi & Akbari, 2015). Some thermal spraying methods are discussed below (Azadi *et al.*, 2013):

2.1.1 Atmospheric Plasma Spraying (APS)

The APS method is basically used because of its high deposition rate, low cost, high-porosity microstructure that reduces the thermal conductivity and coating ability of large components (Sobhanverdi & Akbari, 2015). In atmospheric plasma-spraying, particles having a typical diameter of 5 μm–50 μm are injected into a plasma-jet with a temperature ranging from 8000 K–14000 K (Fauchais *et al.*, 2014). Refer to Fig. 2.

Fig. 2: The surface of an APS YSZ coating, showing how a molten particle has flattened on impact

2.1.2 Plasma-Spray Coatings

Here, a powdered feed-stock is injected-into a high-temperature plasma-jet in which finely-divided-metallic and non- metallic materials are-deposited either in-molten or semi-molten-state on prepared-substrate (Khor *et al.*, 1995; Harjit *et al.*, 2022). This coating is executed under vacuum or atmospheric-conditions (Harjit *et al.*, 2022). This coating gave an-effective and economical-method for producing ceramic-coatings on metallic-substrates and production-of bulk-powders from spheroidization (Malmberg & Heberlein, 1993). Plasma-Spray coating is presented in Fig. 3 and the spraying-gun illustrated in Fig. 4 (Kuldeep & Jakhar, 2014).

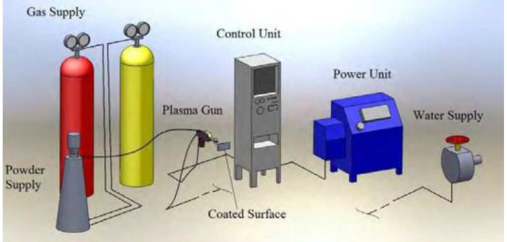

Fig. 3: Plasma-Spray coating system

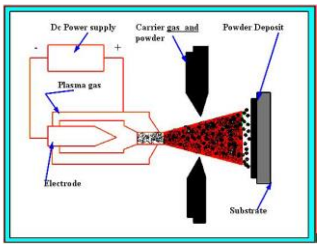

Fig. 4: Plasma-Spray gun

Plasma-Spray is a widely accepted method of coating (Geckinli, 1992). Plasma-Spray coated piston tops are presented in Fig. 5 (Stefano *et al.*, 2021).

Fig. 5: Ceramic coated piston tops

2.1.3 High-Velocity Oxy-Fuel (HVOF) coatings

This process is a subset of flame spray process (Khor *et al.*, 1995; Safavi *et al.*, 2021). Known HVOF devices operate at hypersonic-gas-velocities greater than Mach-number of 5 (Taymaz *et al.*, 2005). Refer to Fig. 6 (Safavi *et al.*, 2021).

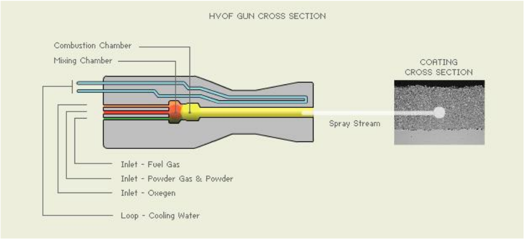

Fig. 6: Cross-section of an HVOF gun equipment

2.1.4 Flame-Spray Coatings

Here, oxy-hydrogen and oxy-acetylene approached are preferred and refractory-oxides which have lower-melting-point greater than 2760 ^{0}C are usually used in coating-with-these systems (Taymaz *et al.*, 2005). Before ceramic-coatings, a binding-layer-resistant to high-temperature like nickel-chromium is applied to metallic surface so as to prevent oxidation which is displayed in Fig. 7. Otherwise, ceramic-coating will hardly stick to the surface properly (Ilker, 2010).

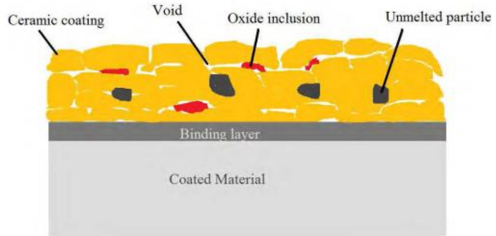

Fig. 7: Use of Nickel-chromium material as bond coat to prevent oxidation

2.1.5 Detonation Gun (D-Gun) Coatings

The design of conventional flame-spray processes limits their ability to produce dense (<2% porosity), well-bonded coatings (Davis 2004). Detonation gun, however, produces higher thermal and kinetic-energy-jets by confining the combustion-within a tube or barrel into which powders-are-introduced (Beg, Bose, Ghosh, Banerjee & Ghosh, 1997). This design produces greater heat and momentum transfer to the powder particles (Donald 2010). Detonation spray diagram is presented in Fig. 8.

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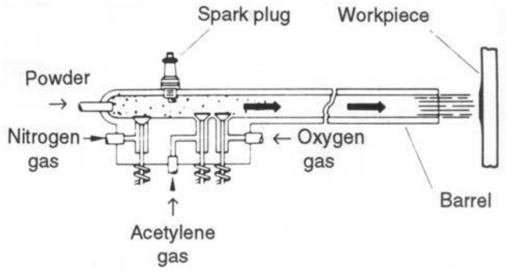

Fig. 8: Detonation gun system (D-Gun)

2.1.6 Electric Arc (Wire Arc) Coatings

In this coating process, two consumable-wire-electrodes connected to a high-direct-current (DC) power-source are fed-into the-gun, meet and established an-arc-between them that melts the tips-of-the-wires (Davis, 2004). The molten-metal is then atomized and propelled toward-the-substrate by a stream-of-air. This coating is energy-efficient because all the input-energy is used to melt the-metal (Srinivasnaik *et al.*, 2016).

2.1.7 Cold-Spray coatings

Cold-spray coating is material deposition-process in which-relatively small-particles (ranging-in-size from approximately 1 to 50 μm diameter, as seen in Fig. 9) in the solid-state are accelerated to high-velocities (typically 300 to 1200 m/s, or 980 to 3940 ft/s), and subsequently develop a deposit on an appropriate substrate by an impaction-process (Thiruselvam, 2015).

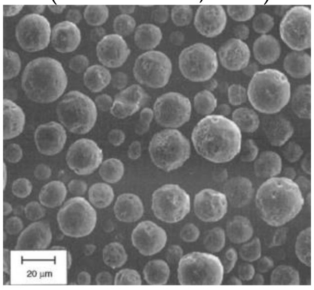

Fig. 9: Micron-sized copper powder used in cold-spray experiments/applications

Fig. 10 shows the comparison between particle velocity and gas temperature ranges of cold-spray and other thermal-spray processes (Kuldeep & Jakhar, 2014). When the particle-velocity (V_P) is too low for the given coating or substrate combination, the feed-stock particles are simply reflected from the surface and will unable to form a contiguous coating or deposit. At higher values of (V_P) solid-particle erosion within the surface may occur, as with shot blasting of surfaces (Srinivasnaik *et al.*, 2016). When (V_P) exceeds a critical value V_{crit} (which varies with particle and substrate-material), particles begin to plastically-deform, form an overlay coating and adhere to substrate (Behzad *et al.*, 2019; Ramaswamy *et al.*, 2000).

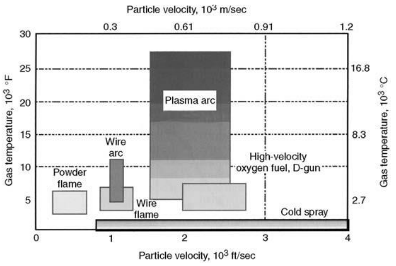

Fig. 10: Temperature/velocity regimes for common thermal-spray processes compared to cold-spray technology

The diagram of a typical cold-gas spray-system is presented in Fig. 11 (Karger *et al.*, 2011).

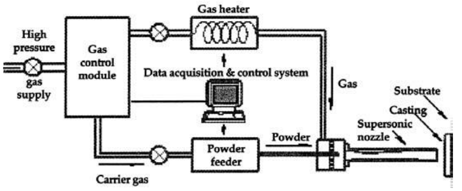

Fig. 11: Schematic diagram of a cold-spray system

2.2 PHYSICAL-VAPOUR DEPOSITION (PVD) METHOD

Here, material vaporization from either solid or liquid source-in the form-of-atoms or molecules and transported in the-form-of a vapour-through a vacuum-or-low pressure-gaseous environment to-the-substrate, where it-condenses is executed (Donald 2010). Typically, PVD method deposit-films with thicknesses ranging from a few nanometres to thousands-of-nanometres; however, they are also used to form multi-layer coatings, graded composition-deposits, very thick-deposits, and free-standing structures. There are many types of PVD method such as Electron Beam – Physical Vapour-Deposition (EB-PVD), Vacuum (Evaporation) Deposition, Sputter Deposition, Arc-Vapour Deposition and Ion-Plating (Ravikumar *et al.*, 2014).

2.3 CHEMICAL-VAPOR DEPOSITION (CVD)

This method produces high-purity and high-performance solid-materials (Ravikumar *et al.*, 2014). Its biggest application is the semi-conductor industry where it produces thin films (Nishant *et al.*, 2018). During Chemical Vapour-Deposition, the substrate-is-exposed to one-or-more volatile-precursors which brings the desired-deposit due to reaction or decomposition-on the surface. Volatile process by-products are removed-by-gas flow-through the reaction-chamber (Beg *et al.*, 1997). This method is a highly attractive process to produce TBCs because of its capacity to coat complex surfaces with excellent conformal coverage (Ravikumar *et al.*, 2014). The main drawback is seen in its typical deposition rates which are often below 10 μm/h. Research was conducted on plasma and laser as auxiliary energy sources to enhance the deposition rates (Trapaga *et al.*, 1992).

2.4 SOL-GEL AND SLURRY METHOD

Slurry spraying is a relatively cheap and simple method for producing TBCs (Hocking *et al.*, 2013). Slurry consists of powder suspended in fluid and usually applicable to a surface in several layers using a spray gun. After drying,

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the multilayer coating is pressed in a compression chamber, followed by sintering in a furnace or with an acetylene torch (Nguyen *et al.,* 2007). Advantage of this method is the coating ability of complex-geometries, including surfaces inside pipes that are out of direct sight (Nguyen *et al.,* 2007). Slurry-coating is also applied by dipping substrate in mixture of ceramic-powder and then leaving it to dry (Kawasaki & Watanabe, 2002). This is repeated until the desired thickness has been reached, after which coating densified by hot isostatic pressing (Nguyen *et al.,* 2007). A sol-gel-coating is done by spraying the solution or dipping substrate into it, followed by gravitational-draining and evaporation of the-solvent (Beg *et al.,* 1997). A firing process then compacts the dried sol into a hard oxide-coating. A sol-gel coating with incorporated ceramic particles is presented in Fig. 12 (Kawasaki & Watanabe, 2002).

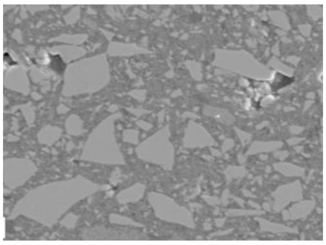

Fig. 12: Sol-gel composite TBC, showing CaSZ (large particles) and YSZ (small particles) in a silica matrix

2.5 ION-IMPLANTATION METHOD

Ion-Implantation is a process conducted in-a-vacuum (133×10^{-6} to 1.33×10^{-3} Pa), wherein a beam of ions is directed and accelerated-toward the-substrate (Srinivasnaik *et al.,* 2016). The ions are typically accelerated to an energy of 100 keV. The ions penetrate to an average depth of 0.1 μm and a maximum depth of 0.25 μm (Davis, 2004).

3 REVIEW OF RESULTS OBTAINED USING THE THERMAL SPRAYING COATING METHODS

It was noted from a work, which was on modelling and thermal barrier coating (TBC) of a diesel engine piston crown, that plasma-spray and flame-spray coating methods were better for compression and spark-ignition engines because they produce temperature ranging from 8000 K-14000 K on surfaces with thick coating thicknesses (Isaac, 2021).

4 CONCLUSION

Having considered the different coating methods, it was noted that using ceramic material as the coating-layer by Plasma-Spray and Flame-Spray coating methods, respectively increase the temperature in the combustion chamber of ICEs, reduce erosion-corrosion, friction-wear and improve heat insulation on metallic surfaces. In gas-turbine-industry from literature, coating turbine-blade and stator-blade including combustion-chambers using thin layer-coatings have been successful. Hence, plasma-spray and flame-spray coating methods are recommended in this review.

REFERENCES

Azadi, M.; Farrahi, G.H. and Moridi, A. (2013). Optimization of Air Plasma Sprayed Thermal Barrier Coating Parameters in Diesel Engine Applications. *Journal of Materials Engineering and Performance*, 4, pp. 24-30.

Beg, R.A.; Bose, P.K.; Ghosh, B.B.; Banerjee, T.K. and Ghosh, A.K. (1997). Experimental Investigation on Some Performance Parameters of a Diesel Engine using Ceramic Coating on the Top of the Piston, *1997 International Congress & Exposition*, Detroit, Michigan, USA, pp. 158-163.

Behzad, F.; Navid, N. and Amir, D. (2019). On Coating Techniques for Surface Protection: A Review. *Journal of Manufacturing and Materials Processing*, 3, 28, pp. 1-23.

Chan, S.H. and Khor, K.A. (2000). The Effect of Thermal Barrier Coated Piston Crown on Engine Characteristics. *Journal of Materials Engineering and Performance*, 9, 1, pp. 103-109.

Davis, J.R. (2004). *Handbook of Thermal Spray Technology*, USA: ASM International, pp. 347.

Donald, M.M. (2010). *Handbook of Physical Vapour Deposition (PVD) Processing*, 2nd ed. UK: Published by Elsevier Inc., pp. 771.

Fauchais, P.L.; Heberlein, J.V.R. and Boulos, M. (2014). *Thermal Spray Fundamentals from Powder to Part*, 2nd ed. Boston: Springer International Publishing, pp. 320.

Geckinli, A. (1992). *Advanced Technology Materials,* Turkey: Istanbul Publishing House, pp. 250.

Harjit, S.; Raman, K.; Chander, P. and Sunpreet, S. (2022). HA-Based Coating by Plasma Spray Techniques on Titanium Alloy for Orthopedic Applications, *Materials Today: Proceedings,* 50, 5, pp. 612-628.

Hocking, M.G.; Vasatasree, V. and Sidky, P.S. (1989). *Metallic and Ceramic Coatings, High Temperature and Applications*, London, UK, pp. 213.

Ilker, T.Y. (2010). Thermal Barrier Coatings for Diesel Engines, 2010 Proc. *10th International Scientific Conference*, Gabrovo, 2, pp. 173-77.

Isaac, F.O. (2021). *Unpublished PhD Dissertation*, Ambrose Alli University, Ekpoma.

Karger, M.; Vaßen, R. and Stöver, D. (2011). Atmospheric Plasma Sprayed Thermal Barrier Coatings with High Segmentation Crack Densities: Spraying Process, Microstructure and Thermal Cycling Behavior. *Surface and Coatings Technology,* 206, 1, pp. 16-23.

Kawasaki, A. and Watanabe, R. (2002). Thermal Fracture Behavior of Metal/Ceramic Functionally Graded Materials. *Engineering Fracture Mechanics*, 69, 14–16, pp. 1713-1728.

Khor, K.A.; Murakosh, Y.; Takahashi, M. and Sano, T. (1995). Plasma Spraying of Titanium Aluminide Coatings: Process Parameters and Microstructure. *Journal of Materials Processing Technology*, 48, pp. 413–419.

Kuldeep, S. and Jakhar, O.P. (2014). The Behaviour of Temperature on Insulated ($MgZrO_3$) Diesel Engine Piston with ANSYS. *International Journal of Emerging Technology and Advanced Engineering*, 4, 8, pp. 692-695.

Malmberg, S. and Heberlein, J. (1993). Effect of Plasma Spray Operating Conditions on Plasma Jet Characteristics and Coating Properties. *Journal of Thermal Spray Technology*, 2, 4, pp. 339–344.

Miyairi, Y.; Matsumsa, T.; Ozawa, T.; Odcawa, H. and Nakashima, N. (1989). Selective Heat Insulation of Combustion Chamber Wall, for a Diesel Engine with Monolithic Ceramics. *SAE Technical Paper,* 890141.

Nguyen, P.; Harding, S. and Ho, S.Y. (2007). Experimental Studies on Slurry Based Thermal Barrier Coatings. *Proceedings of the 5th Australasian Congress on Applied Mechanics,* pp. 545.

http://doi.org/10.46792/fuoyejet.v7i2.810 http://journal.engineering.fuoye.edu.ng/

Nishant V.; Divyansh, M.; Pawan, K.A.; Subhash, G.; Chandan, B.B. and Abhishek, K. (2018). Thermal Analysis of Ceramic Coated Piston Head in Diesel Engine. *International Research Journal of Engineering and Technology (IRJET),* 5, 5, pp. 3770-3779.

Ramaswamy, P.; Seetharamu, S.; Varma, K.B.R.; Raman, N. and Rao, K.J. (2000). Thermomechanical Fatigue Characterization of Zirconia (8% Y_2O_3-ZrO_2) and Mullite Thermal Barrier Coatings on Diesel Engine Components: Effect of Coatings on Engine Performance. *Proceedings of the Institution of Mechanical Engineers,* 214, pp. 729-742.

Ravikumar, T.; Kiran, K.; Ravichandra, V. K. and Chetan, A.C. (2014). Alternative Thermal Barrier Coatings for CI Engines - A Research Review. *International Journal of Research in Advent Technology,* 2, 5, pp. 2321-9637.

Robert, B.H. (1996). *Plasma-Spray Coating Principles and Applications*, 2nd ed. New York: VCH Publishers, Inc., pp. 352.

Safavi, M.S.; Walsh, F.C.; Surmeneva, M.A.; Surmenev, R.A. and Khalil-Allafi, J. (2021). Electrodeposited Hydroxyapatite-Based Biocoatings: Recent Progress and Future Challenges. *Coatings,* 11, 110, pp. 1-62.

Sobhanverdi, R and Akbari, A. (2015). Porosity and Microstructural Features of Plasma Sprayed Yttria Stabilized Zirconia Thermal Barrier Coatings. *Ceramics International,* 41, 10, pp. 14517-14528.

Stefano, R.; Francesca, R. and Massimo, C. (2021). Durability of Vitreous Enamel Coatings and their Resistance to Abrasion, Chemicals, and Corrosion: A Review, *J. Coat. Technol. Res.,* 18, 1, pp. 39–52.

Taymaz, I.; Çakır, K. and Mimaroğlu, A. (2005). Experimental Study of Effective Efficiency in a Ceramic Coated Diesel Engine. *Surface and Coatings Technology,* pp. 1182-1185.

Thiruselvam, K. (2015). Thermal Barrier Coatings in Internal Combustion Engine. *National Conference on Recent Trends and Developments in Sustainable Green Technologies,* 7, pp. 413-418.

Trapaga, G.; E. Matthys, E.F.; Valencia, J.J. and Szekely, J. (1992). Fluid Flow, Heat Transfer, and Solidification of Molten Metal Droplets Impinging on Substrates: Comparison of Numerical and Experimental Results. *Metallurgical Transactions B,* 23, 6, pp. 701-718.

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