Chapter 14
Study of Development of Various Morphological Phases and Its Effects on the Thermal Coated Specimen—A Review

Sonia Dangi, R. S. Walia, N. M. Suri, and Sumit Chaudhary

Abstract Thermal spray coating techniques have been widely used for improving the surface properties of the specimen like corrosion resistance, hardness, friction resistance, wear resistance, erosion resistance etc. All these properties not only depend on the type of coating material but also on the surface morphology. The work material during thermal spray came across critical operating conditions like high temperature, pressure. Moreover, the coating morphology also depends on the size, type and shape of the coating material. This showed a noticeable effect on the performance of the coated surface. The different characterization techniques are available to study the morphological properties of the coated samples. In this review, the effect of various parameters on the surface morphology of thermal spray coating has been studied.

Keywords Morphology · Thermal spray coating · Tribology · SEM · Porosity · Cracks

14.1 Introduction

Coating techniques for protecting the substrate material form atmosphere have been used from ancient times. The advanced coating methods not only protect the substrate but enhancing the performance of the substrate. The advanced coating techniques enable multiple effects like protection from corrosion and erosion, reduction in wear, achieve desired friction by inducing desired hardness, atmospheric inertness, depositing desired material over the substrate and reinforcing the substrate material etc. [1–5]. There are various coating methods like PVD, CVD, Sol–gel, Electroplating and Thermal Spray each having its advantages and drawback in the field of application [6]. Some of the coatings are easy to achieve and cost-effective but the purpose is to provide a layer of desired material for atmospheric protection or

S. Dangi (✉) · R. S. Walia · N. M. Suri
Production and Industrial Engineering Department, PEC, Chandigarh, India

S. Chaudhary
Mechanical Engineering Department, Thapar Institute of Engineering & Technology, Patiala, India

R. Pratap Singh et al. (eds.), *Proceedings of the International Conference on Industrial and Manufacturing Systems (CIMS-2020)*, Lecture Notes on Multidisciplinary Industrial Engineering, https://doi.org/10.1007/978-3-030-73495-4_14

aesthetics. The material subjected to dynamic load, erosion, wear and friction has to be coated such that the coating should service the adverse working conditions [7–10].

Thermal spray coating emerged as one such coating techniques in which the coating material has been sprayed over the substrate material at high temperature (upto 15,000 °C), the flow of particles is assisted by high velocity gas/air. Classification of various thermal spray coating techniques is depending on heat source i.e. plasma spray coating, high velocity oxyfuel coating (HVOF), arc spray coating [11–15].

The most common thermal spray coating method is Plasma spray coating, in this method the temperature of the heat source is more than 15,000 °C. The molten accelerated particles of coating material move towards the substrate and strike the substrate with a governed speed. The continuous bombardment of the particles on the substrate resulted in the formation of a dense layer of coating [16–18]. The coating density in the case of HVOF and arc spray coating is less as compared to plasma spray coating. High heat in the case of plasma spray coating resulted in stress induced to the specimen. The thermal spray coating can be applied to a wide variety of substrate and coating material such as metals, ceramics, polymers, composites etc. The multilayer coating of the same or different compositions can also be achieved via thermal spray coating [19, 20].

The mechanical, thermal, tribological, electrical and chemical performance and properties of the coated specimen depend on the coating parameters, coating material and another important parameter is the coating morphology [21–23]. Most of the major properties and performance of the coating depends on the morphology. In this review article the impact of coating morphology on the various properties of the coated specimen has been discussed. The review focuses on the different thermal spray coating methods applied for coating the variety of substrate materials.

14.2 Mechanism of Coating Build-Up

The principle of material deposition is quite similar for all the coating methods. The heat source in the form of arc or flame has been used for depositing the desired coating material over the substrate surface. The temperature of the flame may go upto 15,000 °C and the high velocity of carrier gas assists the impact of coating material over the substrate [24, 25]. The flame generated moved towards the substrate material through the nozzle. The coating material is supplied to the heated flame and forced towards the substrate. The coating material having thermal energy due to heat transfer from the flame and kinetic energy due to the momentum transfer by the carrier gas strikes the substrate in solid, semi-solid or molten state and gets deposited over the surface of the substrate [26–29].

In the case of cold spray coating, the coating material doesn't melt so the coating is achieved by plastic deformation due to the impact velocity of heated material.

Whereas, in the case of thermal spray coating, the coating material gets melted and the molten material gets deposited due over the substrate surface [6, 30].

The substrate surface should be clean from physical and chemical impurities as the coating material and the substrate may have mechanical interlocking and metallurgical bonding. The first layer of material deposited on the substrate governs the thermo-physical properties of the coating. The multiple passes of the flame result in multilayer coating over the surface [31–33].

14.3 Morphological Development for Thermal Spray Coatings

The coating material has a very vital role and it affects the quality of the coated specimen largely. The mechanical and chemical properties of the coating material affect the coating but it has been observed morphology of coating material before coating plays a very important role the determining the properties of coated specimens. The morphological development of coating depends mainly on substrate material, coating material, gas dynamics and coating process. Figure 14.1 shows all the major parameters affecting the coating process. Moreover, the morphology of the

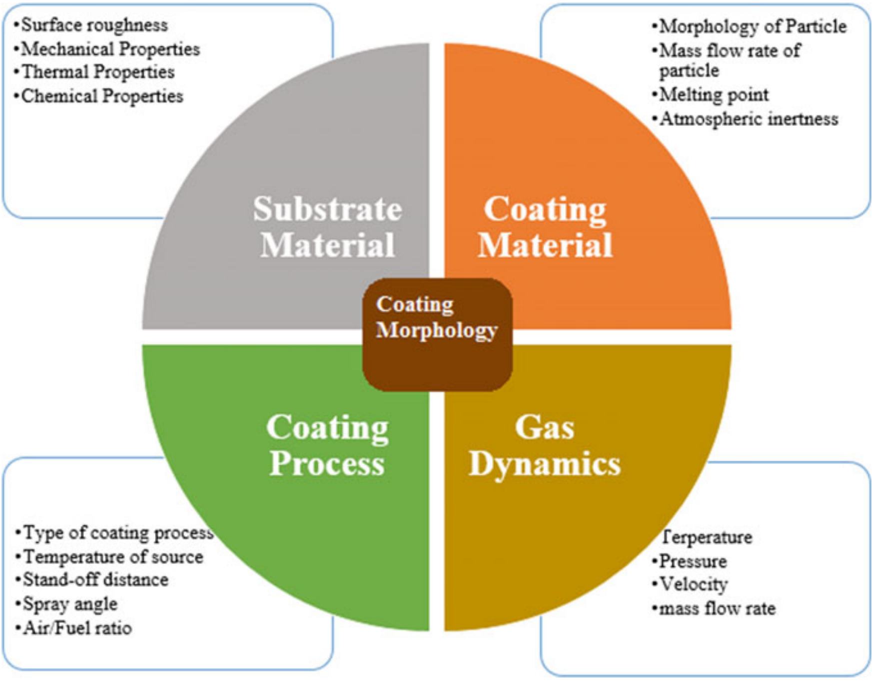

Fig. 14.1 Parameters affecting coating morphology

coating deposited on the specimen also affects the mechanical, chemical, thermal and tribological performance of the coated specimen.

14.3.1 Morphology of Coating Material

The morphology of coating material is one of the very crucial parameters which affects the performance of the coating. The coating material having the same particle size and chemical composition reported different mechanical, chemical, thermal, tribological, electrical behavior as there was some morphological difference observed among the coating materials used. The particles which are deposited by complete melting are least affected by their initial morphology [28]. Still, the effect of initial morphology for those particles has also been reported by the researches. There might be a possibility that the particles don't get melted completely and deposited by the mechanical action, in that case, the initial morphology of particles governs the morphology of coating and the performance of the coating. The particle morphology may provide the solidification front for the coating. The solid particles assist the grain growth and directional solidification of the molten material [34, 35].

The particle morphology may affect the direction of motion, the velocity of particles through the feed mechanism or spray gun. The particles having non-aerodynamic morphology may create an obstacle in the movement, the actual mass flow rate in this case decrease and cause clogging of the spray gun. The particles having spherical morphology move smoothly without many obstacles whereas the annular particles experience large drag created by the carrier gas. The hard coating material having annular morphology causes the wearing of spray gun as the sharp edges present on the annular morphology to strike the spray gun and plough the material of gun due to the high drag force created by the carrier gas. This affects the accuracy of the process which is minimum in the case of spherical morphology [36–38].

The annular morphology coating material has a larger surface area as compared to spherical morphology. These materials show a higher heat transfer rate i.e. it gets heated in cold quickly. The peak temperature obtained in case of annular morphology may be higher than the spherical morphology but these particles lose heat very swiftly, as a result, the solidification rate is very high which results in smaller grains [28]. The bigger size coating materials can't melt completely, the grain growth in such cases has been governed by the initial morphology of the particles. The annular morphology assists the heat transfer rate as the morphology of coating material becomes spherical the heat transfer rate decreased. The slower heat transfer rate may be responsible for the bigger grain size but the presence of voids on the coated samples resulted in decreased elastic modulus and toughness [39–41].

The density of coating also depends on the plastic deformation of the under-melted coating material. The coating material having higher plastic deformation, the coating produced might be more closely packed and the voids eliminated. This results in a very dense coating. The substrate initial temperature also governs the morphology of the coating. If the substrate initial temperature is less than 200 °C, the bonding of coating on the substrate would not be strong due to the poor wetting of the substrate surface and the morphology produced would be irregular [42, 43]. The partial melting of coating material may result in decreased efficiency as there is a possibility of rebounding of particles from the substrate surface (Fig. 14.2).

14.3.2 Morphology of Coated Material

The thermal spray coating over the substrate surface is generally obtained by either spherical, elliptical, or any other annular splats combing together to create a lamellar microstructure. The molten or semi-molten droplets of coating material strike the substrate with high velocity. The molten droplets may be micro or nano in size which strikes the substrate and the cohesion between the substrate and coating material assists the formation of a stable layer of coating over the surface. The morphology of coated material primarily has deposited material, voids, porosity, semi-melted material. Each having a different effect on the performance and properties of the coating. The lamellar microstructure is governed by the process parameters such as morphology and size of coating material, the velocity of particles, flame temperature, angle on impingement etc. The molten coating material has a huge affinity for agglomeration, such agglomeration result in the enhanced size of the coating material over the surface. The morphological characteristics observed in the thermal spray coated specimen shown in Figs. 14.3 and 14.4 are voids, porosity, delamination, spalling, interface contamination, cracks, unmelted particles, pull-outs, oxidation, metal inclusion [26, 44–48].

14.3.2.1 Porosity

The porosity in thermal spray coating may go upto 8–10% depending upon the type of process, solidification rate, initial morphology of particles. Porosity in the case of plasma spray coated was observed more than HVOF thermal spray coating. In the case of plasma spray coating, there might be a lesser impact of coating material on the substrate or splashing of the molten material from the surface due to a high melting point, which resulted in higher porosity [49].

As the deposition in case of thermal spray coating is lamellar i.e. the deposition is such that one layer gets deposited over the other. Due to the impact of accelerated coating material, the previous layer of deposition gets flattened over the surface and the porosity present in the previously coated layer disappears, hence the density of coating increases. The deposition of more and more layers over the surface enhances the density of the coating [50–54]. There have been some crakes and porosity observed on the interface of the respective layers that is generally termed as voids. These voids affect the mechanical, chemical, thermal, and electrical properties of the coated material. The globular voids present at the parting line may be carried to the upper surface of the coating and form open pores. These voids act as

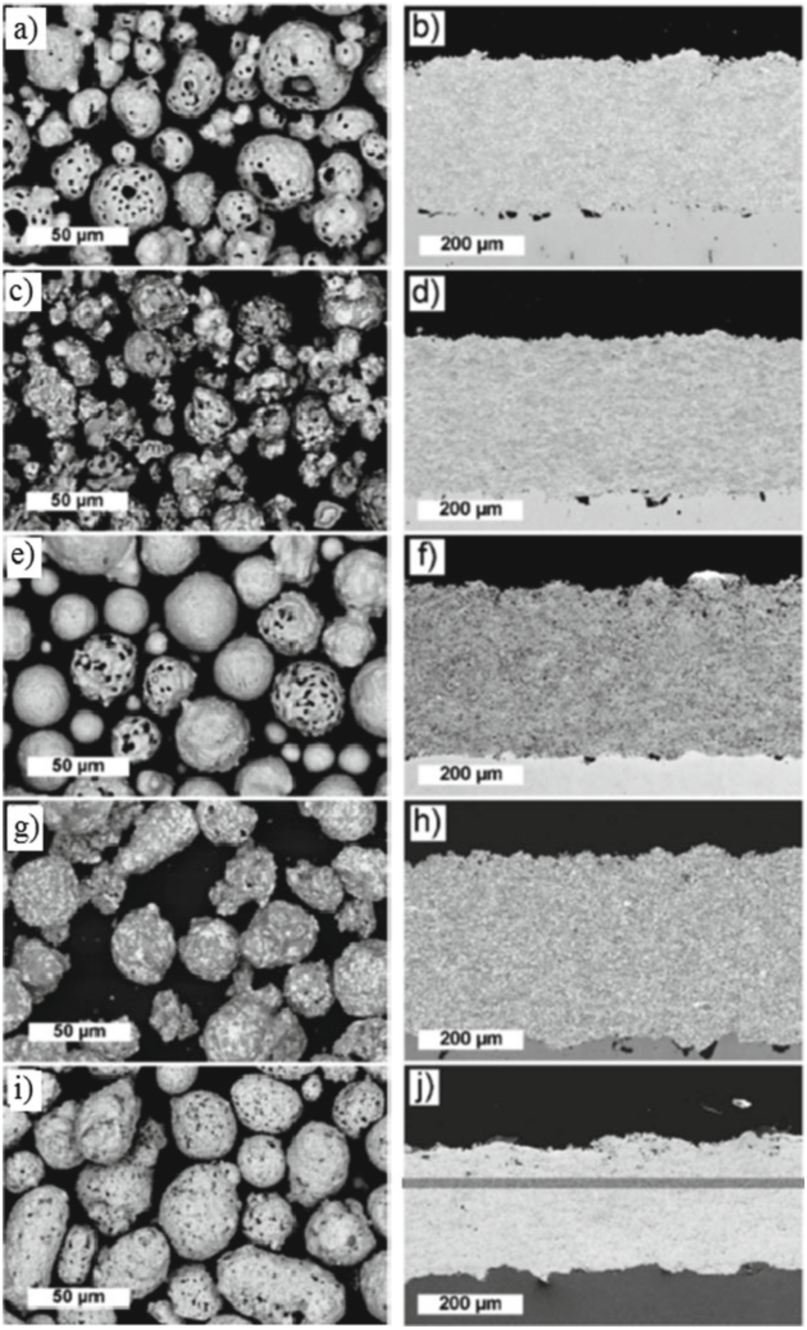

Fig. 14.2 SEM micrographs of the various coating material (left) and obtained thermal sprayed coatings (right): Cr_3C_2–50NiCrMoNb (**a**, **b**), Cr_3C_2–25NiCr (**c**, **d**), Cr_3C_2–25NiCr (**e**, **f**), Cr_3C_2–37WC–18NiCoCr (**g**, **h**) and WC–10Co4Cr (**i**, **j**) [66]

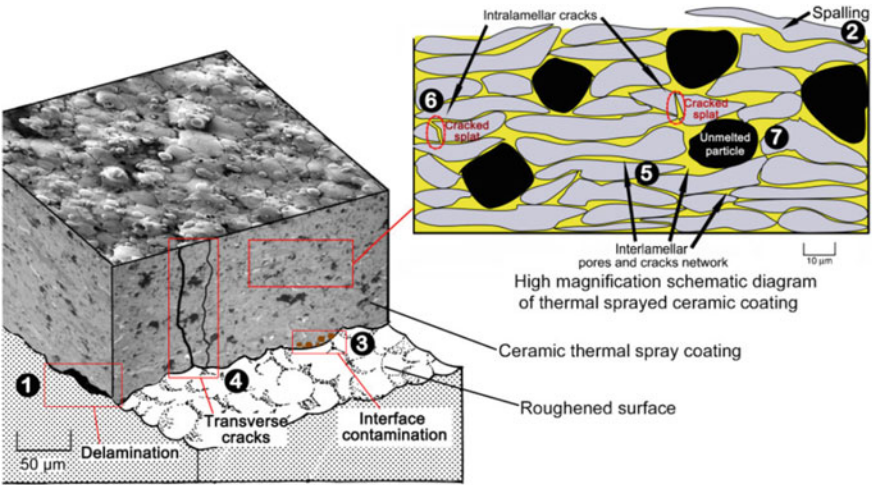

Fig. 14.3 Typical ceramic coating microstructure (1) delamination (2) spalling (3) interface contamination (4) transverse crack (5) inter-lamellar pores (6) inter-lamellar cracks (7) unmelted particles [44]

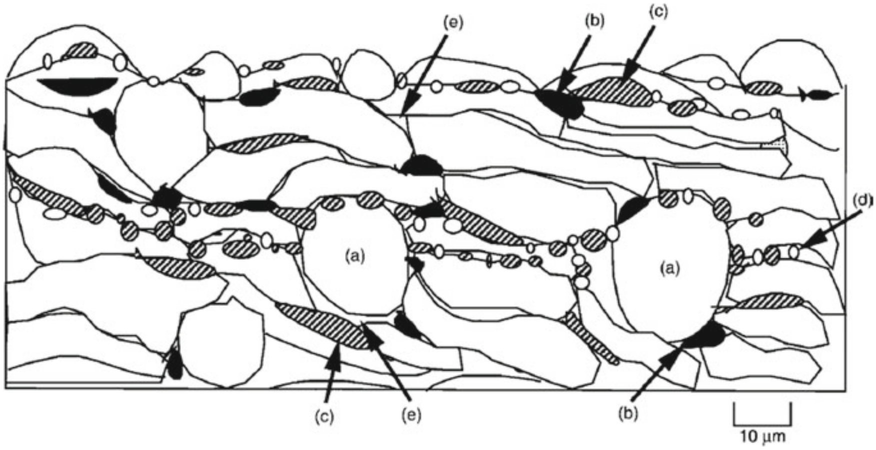

Fig. 14.4 Schematic illustration of metallic coating microstructure (a) unmelted particles (b) oxides (c) debris (d) fine particles (e) porosity [26]

launchpad oxidation of the material. The vapours from the chemical reaction formed and produce porosity in the coating. the dirt and inclusion of foreign material is also responsible for voids generation. The inter-lamellar pores due to rapid solidification resulting in micro-cavities. These pores may act as a crack propagation site and the rate of reaction at these sites increases drastically when working under elevated temperature and pressure. The pores provide a site for air hence decrease the thermal and electrical conductivity of the coating [55–57].

14.3.2.2 Cracks

The cracks can be commonly observed in the thermal spray coating. The cracks may be present on the interface of substrate and coating are known as delamination. Such types of cracks are produced due to less impact of coating material striking on the substrate so the cohesive forces become weak and result in delamination. The transverse cracks may also be observed in the coating which is perpendicular to the substrate surface. The coating obtained is in the form of lamellar i.e. deposition of one layer of coating over the other. There might be a possibility of cracking at the inter-lamellar site. Such cracks are very critical as they reduce the fatigue life of the coating [58, 59]. These cracks get widen heat treated as observed by Lui et al. shown in Fig. 14.5 [60].

The cracks reduce the fatigue life of the coating and the coated specimen. These cracks widen and propagate to the surface resulting in sudden failure of the coating. These cracks may also act as the site for the accumulation of internal stresses in

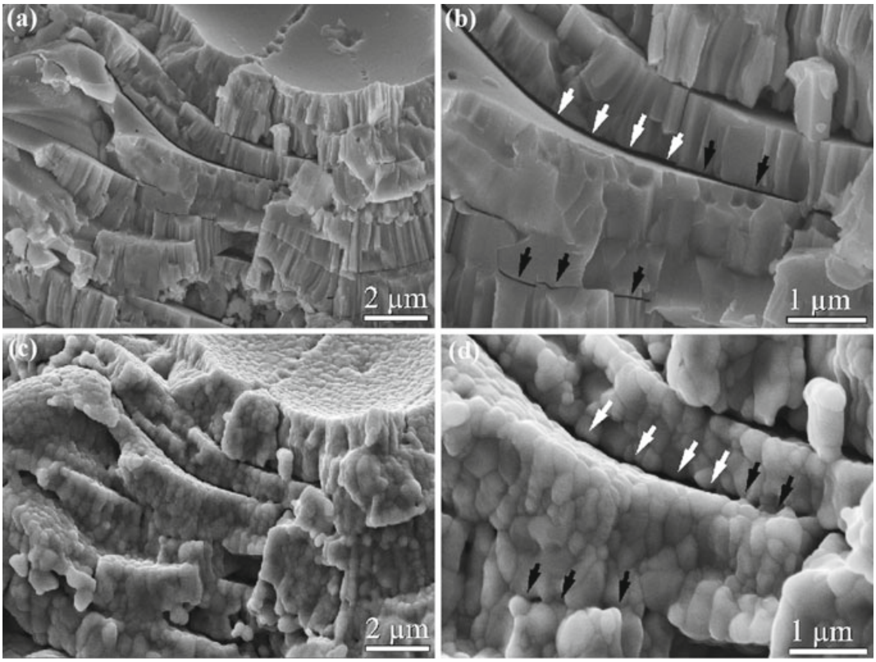

Fig. 14.5 Morphological investigation of LZO thermal spray coating **a**, **b** as sprayed **c**, **d** thermal exposer at 1300 °C for 2 h [43]

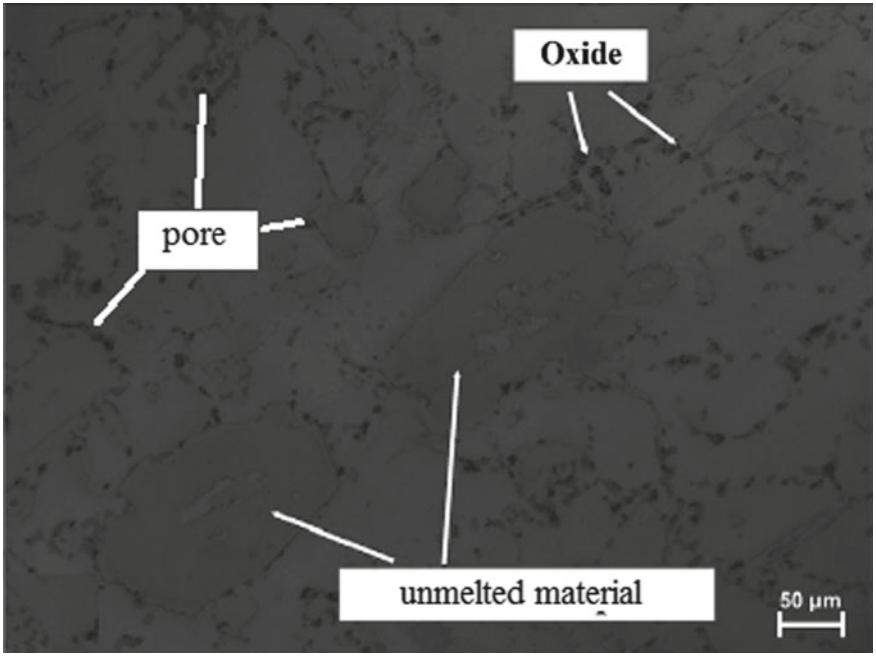

Fig. 14.6 Microstructure of coated Babbitt alloy [65]

the coating. The voids formed due to cracking may be responsible for accelerated oxidation of the specimen [61].

14.3.2.3 Unmelted Coating Material

The high melting point material or large size coating material doesn't melt completely and gets deposited on the substrate surface. Another reason may be the refractoriness of the material which reduces the heat transfer from the source to the material or the low-temperature heat source [62–64]. These unmelted particles cause stress concentration in the coating. The localized oxidation had also been observed at the site of unmelted particles shown in Fig. 14.6. The unmelted particles strike the lamellar with a high impact compared to the fully molten material. This results in increased microhardness and density of the coating [65].

14.3.2.4 Oxidation

The atmospheric contamination observed mainly in a metallic coating known as oxidation. The oxidation of substrate or coating may occur at different stages of thermal spray coating. The uncleaned substrate may prove to a carrier for the initial oxidation at the interface of the substrate and coating. The coating material came across an elevated temperature which increases the rate of oxidation. The coating material sprayed over the substrate may react with the carrier gas and cause oxidation. The lamellar sites proved to be one of the very common locations for oxidation [67–69]. The oxidation of particles continues thereafter at the sites such as pores or cracks, where the atmospheric gasses could react with the substrate material. The mechanical, chemical, electrical, thermal properties etc. had been hugely affected by oxidation [70, 71].

14.4 Conclusions

The thermal spray coating has very wide applications right from mechanical components to aerospace applications, automobile, medial equipments, electronics and electrical etc. The effectiveness of coating not only depend on the substrate or coating material alone, but also on the microfeatures like morphological characteristics of coating material and coating obtained.

The morphology of coating material affects its followability through the nozzle, heat transfer rate, melting of the particle, impact velocity, mass flow rate etc. All these have some impact on some splat formation and other properties of the coating. The splat formation and shape have a major impact on the solidification and lamellar formation.

The coating gets deposited over the surface in the form of multi-layer lamellar and the density of coating enhances when the depositing layer strikes the previously deposited lamellar. There are some characteristics like voids, porosity, delamination, spalling, interface contamination, cracks, unmelted particles, pull-outs, oxidation, metal inclusion observed in the thermal spray coating, each having an impact on the various properties of the thermal spray coating.

References

1. Martins, R., Amaro, R., Seabra, J.: Influence of low friction coatings on the scuffing load capacity and efficiency of gears. Tribol. Int. **41**, 234–243 (2008)
2. Kamps, T.J., Walker, J.C., Wood, R.J., Lee, P.M., Plint, A.G.: Reproducing automotive engine scuffing using a lubricated reciprocating contact. Wear **332–333**, 1193–1199 (2015)
3. Goyal, T., Walia, R.S., Sidhu, T.S.: Surface roughness optimization of cold sprayed coatings using Taguchi method. Int. J. Adv. Manuf. Technol. **60**, 611–623 (2012)
4. Priest, M., Dowson, D., Taylor, C.: Predictive wear modelling of lubricated piston rings in a diesel engine. Wear **231**, 89–101 (1999)
5. Mierbach, A., Hildyard, M., Parker, D., Xu, H.: Piston ring performance modelling. In: T&N Technical Symposium Paper (1995)
6. Tyagi, A., Walia, R.S., Murtaza, Q., Pandey, S.M., Tyagi, P.K., Bajaj, B.: A critical review of diamond like carbon coating for wear resistance application. Int. J. Refract. Metals Hard Mater. **78**, 107–122 (2018)

7. Miguel, J.M., Vizcaino, S., Lorenzana, C., Cinca, N., Guilemany, J.M.: Tribological behavior of bronze composite coatings obtained by plasma thermal spraying. Tribol. Lett. **42**, 263–273 (2011)
8. Torres, B., Garrido, M.A., Rico, A., Rodrigo, P., Campo, M., Rams, J.: Wear behaviour of thermal spray Al/SiCp coatings. Wear **268**, 828–836 (2010)
9. Spencer, K., Fabijanic, D.M., Zhang, M.X.: The use of Al-Al_2O_3 cold spray coatings to improve the surface properties of magnesium alloys. Surf. Coat. Technol. **204**, 336–344 (2009)
10. Wilden, J., Schnick, T., Wank, A., Materials, C.: Performance of HVOF nanostructured diboride composite coatings. In: Proc. Int. Therm. Spray Conf. Essen, Ger., pp. 1033–1037 (2002)
11. Tyagi, A., Walia, R.S., Murtaza, Q.: Tribological behavior of temperature dependent environmental friendly thermal CVD diamond coating. Diamond Related Mater. **96**, 148–159 (2019)
12. Vignesh, S., Shanmugam, K., Balasubramanian, V., Sridhar, K.: Identifying the optimal HVOF spray parameters to attain minimum porosity and maximum hardness in iron based amorphous metallic coatings. Def. Technol. **13**, 101–110 (2017)
13. Pandey, S.M., Walia, R.S., Murtaza, Q.: Effect of NiCr on dry sliding wear of high carbon iron-molybdenum composite plasma spray coating. Int. J. Precis. Technol. **8** (2018)
14. Pandey, S.M., Murtaza, Q., Walia, R.S.: Study of dry wear behavior and morphological characteristic of 60%Mo-20%NiCr-10%Mo+Fe based alloy coating by atmospheric plasma spray technique. Adv. Mater. Process. Technol. **3**, 393–406 (2017)
15. Tyagi, A., Pandey, S.M., Walia, R.S., Murtaza, Q.: Characterization and parametric optimization of tribological properties of Mo blend composite coating. Mater. Res. Express **6** (2019)
16. Jiang, C., Xing, Y., Zhang, F., Hao, J.: Microstructure and corrosion resistance of Fe/Mo composite amorphous coatings prepared by air plasma spraying. Int. J. Min. Met. Mater. **19**, 657–662 (2012)
17. Kobayashi, K., Yano, S., Inoue, A.: Fe-based metallic glass coating produced by smart plasma spraying process. Mater. Sci. Eng. B **148**, 110–113 (2008)
18. Kishitake, K., Era, H., Otsubo, F.: Characterization of plasma sprayed Fe-17Cr-38Mo-4C amorphous coatings crystallizing at extremely high temperature. J. Therm. Spray Technol. **5**, 283–288 (1996)
19. Tyagi, A., Walia, R.S., Murtaza, Q.: Tribological behavior of HVOF carbon coating for wear resistance application. Mater. Res. Express **6**, 67–77 (2019)
20. Muthu, S.M., Arivarasu, M.: Investigations of hot corrosion resistance of HVOF coated Fe based superalloy A-286 in simulated gas turbine environment. Eng. Fail. Anal. **107**, 104224 (2020)
21. Wu, J., Zhang, S., Sun, W., Gao, Y., Wang, J.: Enhanced corrosion resistance in Fe based amorphous coatings through eliminating Cr-depleted zones. Corros. Sci. **136**, 161–173 (2018)
22. Zhang, C., Chan, K., Wu, Y., Liu, L.: Pitting initiation in Fe-based amorphous coatings. Acta Mater. **60**, 4152–4159 (2012)
23. Berman, D., Narayanan, B., Cherukara, M.J., Sankaranarayanan, S.K.R.S., Erdemir, A., Zinovev, A., Sumant, A.V.: Operando tribochemical formation of onion-like-carbon leads to macroscale superlubricity. Nat. Commun. **9**, 1164 (2018)
24. Cheng, D., Xu, Q., Lavernia, E.J., et al.: The effect of particle size and morphology on the in-flight behavior of particles during high-velocity oxyfuel thermal spraying. Metall. Mater. Trans. B **32**, 525–535 (2001)
25. de Villiers Lovelock, H.L.: Powder/processing/structure relationships in WC-Co thermal spray coatings: a review of the published literature. J. Therm. Spray Technol. **7**, 357–373 (1998)
26. Tucker, R.C.: ASME Handbook: Thermal Spray Technology, vol. 5A (2013)
27. Technology, T.S., Tucker, R.C.: Introduction to Coating Design and Processing, vol. 5 (2013)
28. Nouri, A., Sola, A.: Powder morphology in thermal spraying. J. Adv. Manuf. Process. **e10020**, 1–19 (2019)
29. Nayak, H., Krishnamurthy, N., Shailesh, R.A.: Studies on plasma sprayed thermal barrier coating with increase in coating thickness. Tribol. Ind. **40**(3), 420–432 (2018)

30. Siao, A., Ang, M., Berndt, C.C., Siao, A., Ang, M., Berndt, C.C.: A review of testing methods for thermal spray coatings: a review of testing methods for thermal spray coatings **6608** (2014)
31. Pawlowski, L.: The Science and Engineering of Thermal Spray Coating. Wiley, Hoboken (2008)
32. Fauchais, P.L., Heberlein, J.V.R., Boulous, M.I.: Thermal Spray Fundamentals from Powder to Part. Springer, Berlin (2014)
33. Davis, J.R.: ASME Handbook of Thermal Spray Technology (2004)
34. Ben Ettouil, F., Mazhorova, O., Pateyron, B., Ageorges, H., El Ganaoui, M., Fauchais, P.: Predicting dynamic and thermal histories of agglomerated particles injected within a d.c. plasma jet. Surf. Coat. Technol. **202**, 4491–4495 (2008)
35. Bouneder, M., Ageorges, H., El Ganaoui, M., Pateyron, B., Fauchais, P.: Direct current plasma spraying of mechanofused alumina-steel particles, October 2009
36. Ghadami, F., Aghdam, A.S.R.: Improvement of high velocity oxy-fuel spray coatings by thermal post-treatments: a critical review. Thin Solid Films **678**(February), 42–52 (2019)
37. Schneider, K.E., Belashchenko, V., Dratwinski, M., Siegmann, S.: Thermal Spraying for Power Generation Components. Wiley, Hoboken (2007)
38. Rokni, M.R., Nutt, S.R., Widner, C.A., Campagne, V.K., Harbe, R.H.: Review of relationship between particle deformation, coating review of relationship between particle deformation, coating microstructure, and properties in high-pressure cold spray. J. Therm. Spray Technol. (2017)
39. Rad, D.T.M.R., Hussain, A.M.T.: Beyond Traditional Coatings: A Review on Thermal-Sprayed Functional and Smart Coatings, vol. 28, no. 4. Springer, US (2019)
40. Mikli, V., Kafrdi, H., Kulu, P., Besterct, M.: Characterization of powder particle. Proc. Estomian Acad. Sci Eng. **7**, 22–34 (2001)
41. Gu, S., Kamnis, S.: Bonding mechanism from the impact of thermally sprayed solid particles. Metall. Mater. Trans. **40**, 2664–2674 (2009)
42. Picas, J.A., Punset, M., Baile, M.T., Martin, E., Fom, A.: Effect of oxygen/fuel ratio on the in-flight particle parameters and properties of HVOF WC-CoCr coating. Surf. Coat. Technol. **205**, S364–S368 (2011)
43. Chi, W., Sampath, S., Wang, H.: Ambient and high-temperature thermal conductivity of thermal spray coatings. JTTEE **5**, 773–778 (2006)
44. Siao, A., Ang, M., Berndt, C.C., Siao, A., Ang, M., Berndt, C.C.: A review of testing methods for thermal spray coatings. Int. Mater. Rev. **59**, 179–223 (2014)
45. Sun, S.D., et al.: Microstructure, abrasive wear and corrosion characterisation of laser metal deposited Fe-30Cr-6Mo-10Ni-2C alloy. Wear **438–439**, 203070 (2019)
46. Zhang, J., Guo, X., Jung, Y., Li, L., Knapp, J.: Microstructural non-uniformity and mechanical property of air plasma-sprayed dense lanthanum zirconate thermal barrier coating **1**, 11–16 (2014)
47. Si, C, Duan, B., Zhang, Q., Cai, J., Wu, W.: Wear-resistance properties of subsonic flame sprayed amorphous Fe–Mo–Cr–Co coating with extremely high amorphous rate. Integr. Med. Res. 1–12 (2020)
48. Xiao, J., Liu, Q., Li, J., Guo, H., Xu, H.: Microstructure and high-temperature oxidation behavior of plasma-sprayed Si/Yb_2 SiO_5 environmental barrier coatings. Chin. J. Aeronaut. **32**(8), 1994–1999 (2019)
49. Coatings, P.: Porosity and its significance in plasma-sprayed coatings. Coatings **9**, 1–19 (2019)
50. Thirumalaikumarasamy, D., Shanmugam, K., Balasubramanian, V.: Establishing empirical relationships to predict porosity level and corrosion rate of atmospheric plasma-sprayed alumina coatings on AZ31B magnesium alloy. J. Magnes. Alloys **2**, 140–153 (2014)
51. Mancini, C.E., Berndt, C.C., Sun, L., Kucuk, A.: Porosity determinations in thermally sprayed hydroxyapatite coatings. J. Mater. Sci. **36**, 3891–3896 (2001)
52. Konyashin, I.Y., Chukalovskaya, T.V.: A technique for measurement of porosity in protective coatings. Surf. Coat. Technol. **88**, 5–11 (1997)
53. Curran, J.A., Clyne, T.W.: Porosity in plasma electrolytic oxide coatings. Acta Mater. **54**, 1985–1993 (2006)

54. Mutter, M., Mauer, G., Mücke, R., Guillon, O., Vaßen, R.: Correlation of splat morphologies with porosity and residual stress in plasma-sprayed YSZ coatings. Surf. Coat. Technol. **318**, 157–169 (2016)
55. Ekberg, J., Ganvir, A., Klement, U., Creci, S., Nordstierna, L.: The influence of heat treatments on the porosity of suspension plasma-sprayed yttria-stabilized zirconia coatings. J. Therm. Spray Technol. **27**, 391–401 (2018)
56. Son, S.-H., Lee, H.-J., Park, Y.-J., Kim, J.-H.: Preparation of conducting polymer composites: effects of porosity on electrical conductivity. Polym. Int. **46**, 308–312 (1998)
57. Khal, H.E., Cordier, A., Batis, N., Siebert, E., Georges, S., Steil, M.C.: Effect of porosity on the electrical conductivity of LAMOX materials. Solid State Ionics **304**, 75–84 (2017)
58. Al-Fadhli, H.Y., Stokes, J., Hashmi, M.S.J., Yilbas, B.S.: HVOF coating of welded surfaces: fatigue and corrosion behaviour of stainless steel coated with inconel-625 alloy. Surf. Coat. Technol. **200**, 4904–4908 (2006)
59. Padilla, A., Velasquez, J.A., Berrios, E.S., Cabrera, P.: Fatigue behavior of a 4140 steel coated with a NiMoAl deposit applied by HVOF thermal spray. Surf. Coat. Technol. **150**, 151–162 (2002)
60. Liu, T., Luo, X., Chen, X., Yang, G., Li, C., Li, C.: Morphology and size evolution of interlamellar two-dimensional pores in plasma-sprayed $La_2Zr_2O_7$ coatings during thermal exposure at 1300 °C. J. Therm. Spray Technol. Ref 12 (2015)
61. Voorwald, H.J.C., Souza, R.C., Pigatin, W.L., Cioffi, M.O.H.: Evaluation of WC-17Co and WC-1OCo-4Cr thermal spray coatings by HVOF on the fatigue and corrosion strength of AISI 4340 steel. Surf. Coat. Technol. **190**, 155–164 (2005)
62. Zhang, C., Guo, R.Q., Yang, Y., Wu, Y., Liu, L.: Influence of the size of spraying powders on the microstructure and corrosion resistance of Fe-based amorphous coating. Electrochim. Acta **56**, 6380–6388 (2011)
63. He, J., Ice, M., Dallek, S., Lavernia, E.J.: Synthesis of nanostructured WC-12 pct Co coating using mechanical milling and high velocity oxygen fuel thermal spraying. Metall. Mater. Trans. A **31A**, 541–553 (2000)
64. Wu, Y., Lin, P., Chu, C., Wang, Z., Cao, M., Hu, J.: Cavitation erosion characteristics of a Fe–Cr–Si–B–Mn coating fabricated by high velocity oxy-fuel (HVOF) thermal spray. J. Mater. Lett. **61**, 1867–1872 (2007)
65. Roberto, P., Alcover, C., Geraldo, A., Pukasiewicz, M.: Tribology international evaluation of microstructure, mechanical and tribological properties of a Babbitt alloy deposited by arc and fl ame spray processes. Tribiol. Int. **131**, 148–157 (2019)
66. Matikainen, V., Koivuluoto, H., Vuoristo, P.: A study of Cr_3C_2-based HVOF- and HVAF-sprayed coatings: abrasion, dry particle erosion and cavitation erosion resistance. Wear **446–447**(January), 203188 (2020)
67. Kiilakoski, J., Langlade, C., Koivuluoto, H., Vuoristo, P.: Surface & coatings technology characterizing the micro-impact fatigue behavior of APS and HVOF-sprayed ceramic coatings. Surf. Coat. Technol. **371**(October 2018), 245–254 (2019)
68. Thirumalaikumarasamy, D., Shanmugam, K., Balasubramanian, V.: Corrosion performance of atmospheric plasma sprayed alumina coatings on AZ31B magnesium alloy under immersion environment. J. Asian Ceram. Soc. **2**, 403–415 (2014)
69. Khan, Z.S., et al.: Thermal cycling behavior and hot corrosion performance of the plasma sprayed $Er_2Si_2O_7$ coatings deposited on Cf/SiC composites. J. Asian Ceram. Soc. **3**(1), 123–129 (2015)
70. Wang, Y., Zhou, C.: Hot corrosion behavior of nanostructured Gd_2O_3 doped YSZ thermal barrier coating in presence of $Na_2SO_4 + V_2O_5$ molten salts. Prog. Nat. Sci. Mater. Int. **27**(4), 507–513 (2017)
71. Zro, M.C.Y.O., Singh, J., Kumar, S., Mohapatra, S.K.: An erosion and corrosion study on thermally sprayed WC-Co-Cr powder. Wear **438–439**(January), 102751 (2019)