Chapter 22
Detonation Sprayed Coatings for Aerospace Applications

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Abstract This chapter presents a concise overview of detonation spray technology and the associated principles and applications for the aerospace industry. The most popular feedstock powders for obtaining a wide variety of coatings with varying composition and properties are emphasized. The strategies for obtaining improved structure–property combinations via spray process optimization are discussed, and also the utilization of novel powders for enhanced protection. The typical microstructural features as a key to achieving the required mechanical, tribological and corrosion properties are briefly illustrated with specific examples.

Keywords Detonation sprayed coatings · Processing · Wear resistance · Thermal barriers

22.1 Introduction

In the modern world many materials are expected to deliver multi-functional properties and performances. The available choice window often becomes narrow and therefore encourages non-conventional materials processing routes.

An important example is the development of thermal spray coatings. This technology has expanded especially over the last few decades in such a way as to significantly broaden the otherwise narrow material selection window. In fact, thermal spray technologies have become essential for enhancing the service life of various engineering components, and have therefore become an integral part of the manufacturing process. For example, almost all aircraft landing gear manufacturers have one or more thermal spray systems as part of the regular manufacturing line.

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In view of the large number of thermal spray technologies employed for various industrial applications, including aerospace, this chapter focusses mainly on one of the most important thermal spray technologies known as detonation spraying.

The detonation spray coating (DSC) technology (also known with popular trade names such as D-Gun, Super D-Gun) primarily depends upon the kinetic energy of particles-in-flight, rather than the thermal energy transferred to the particles (e.g. unlike plasma spraying). In view of the lower thermal energy input the feedstock undergoes skin melting or plasticizing. Therefore the oxidation tendency and solidification stresses (tensile) are minimal. The detonation causes the particles to bombard the substrate with high kinetic energy, leading to formation of a coating with uniformly dense microstructure (porosity < 0.5 %) and excellent inter-splat bonding and adhesion to the substrate.

In the aerospace industry detonation sprayed coatings are used mainly on aircraft gas turbine components. Some of these are illustrated in this chapter and are from the authors' institute.

22.2 Detonation Spraying

22.2.1 The Spraying Process

While most thermal spray techniques deposit coatings continuously, DSC is a '*pulsed*' process in which oxygen and acetylene are injected in pre-measured quantities into the combustion chamber of a long water-cooled stainless steel barrel. This is shown schematically in Fig. 22.1. The oxy-fuel mixture is ignited explosively using a spark plug, and the combustion products expand rapidly owing to their high specific volume and the high temperature generated by the explosion.

Upstream of the combustion process, and assisted by a nitrogen carrier gas, metered quantities of powder (usually 5–45 μm size) are fed into the zone of reduced barrel inner diameter where detonation waves are generated, as shown in

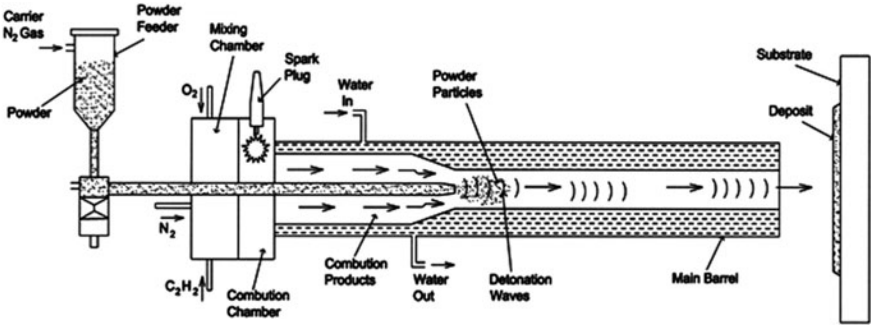

Fig. 22.1 Schematic representation of the detonation spray coating process

Fig. 22.1. The powder particles interact with the surrounding combustion products and undergo physico-chemical changes while travelling towards the open end of the barrel.

The thermal and kinetic energy transport rate primarily depends upon the relative ratio of oxygen to fuel (acetylene) and the total volume of the gas mixture. The particles are accelerated to supersonic velocities that can be as high as 1200 m/s. The temperature and velocity of the particles exiting the barrel depend upon the size, density and thermo-physical properties of the particles.

The particles ejected in each detonation cycle impact the substrate to form layer-by-layer coatings. By manipulating the movement of the barrel (and the part being coated), a uniformly thick coating can be deposited. More details about the process fundamentals and coating formation mechanisms are described in Refs. [1–3].

One interesting feature which distinguishes the DSC process from most other thermal spray methods is its ability to spray metals, ceramics and cermets very effectively by way of creating neutral, oxidizing or reducing environments, simply by altering the relative oxygen/fuel ratio.

22.2.2 Equipment Characteristics

The DSC technology was proprietary until the last decade. However, commercial systems based on the original design from the former Soviet Union are now available. The typical water-cooled stainless steel barrel illustrated in Fig. 22.1 is 1350 mm long and has a 22 mm internal diameter, see Fig. 22.2 also.

A variety of powder feeder designs are available, based on the application needs. For instance, multiple powder feeder systems may be used to allow spraying different powders; or sequential spraying that permits formation of coating layer gradients with varied composition in each layer.

The spray process is usually controlled and monitored remotely via a panel located outside the spray booth, which is sound- and dust-proof. A typical spray booth is shown in Fig. 22.2b.

22.3 DSC Technology Compared with Other Thermal Spray Techniques

Although DSC was initially meant for depositing wear-resistant carbide coatings, its ability to deposit dense ceramic coatings has enabled it to secure an equivalent position with respect to high velocity oxy-fuel spray coating (HVOF). Also, the thermo-kinetic energy transport of powder particles is better controlled in the DSC

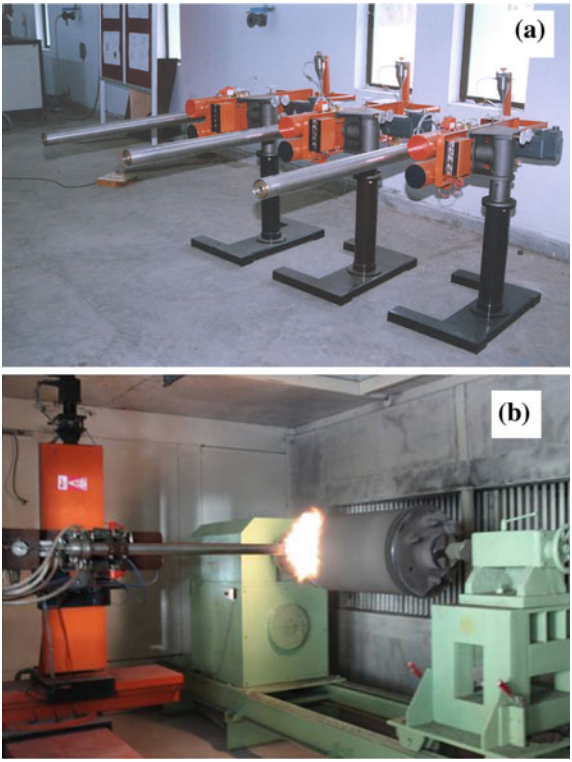

Fig. 22.2 **a** Typical configuration of DSC systems and **b** spraying in progress

process than in the well-established thermal spray technologies APS and VPS (air and vacuum plasma spraying).

HVOF is the chief alternative to DSC. The HVOF combustion gases are discharged through a confined cooled nozzle at high gas flow (up to Mach 3 velocity), and the resultant particle velocities, especially for carbide powders, are similar to those of DSC (up to 1200 m/s). The HVOF coatings also have similar densities to those produced by DSC: both types of coating are much denser than plasma sprayed coatings.

In fact, most wear-resistant carbide coatings are sprayed using either the HVOF or DSC systems with identical aerospace quality specifications. This demonstrates wide acceptance of these techniques as being equivalent. (However, since DSC is only recently commercially available, HVOF has been the only option for depositing dense, wear-resistant carbide coatings on a large variety of aircraft and helicopter components.)

DSC is very versatile: it can accommodate a wide variety of spray grade powders including metals, alloys, ceramics, cermets and composites with low melting point binders [4–9]. Also, the number of spray grade powders being formulated and manufactured has steadily increased, such that a wide variety of DSC coatings is potentially available.

Although DSC can deposit almost any material that melts without decomposition, the size of the gun prevents complete internal coatings. Internal cavities connected to the outer surface can be coated only via line-of-sight. Therefore, utilizing the 45° angle of deposition, it is possible to provide internal coating of a cylindrical object to a length equal to its diameter.

Other competing technologies are powder flame spraying, wire flame spraying and wire arc spraying. These find limited use at present, although they have the advantages of moderate equipment costs and are portable for on-site repairs and refurbishments. Recent developments such as the introduction of solid ceramic rods as feed in wire arc spraying systems have increased their potential for relatively non-critical and corrosion-resistant aerospace applications.

22.4 DSC Coating Applications in Aerospace

22.4.1 Tungsten Carbide/Cobalt (WC–Co) Coatings

Tungsten carbide/cobalt (WC–Co) coatings are the main thermal spray coatings used in aerospace. These coatings possess a unique combination of extreme hardness (12–14 GPa), high modulus (350–400 MPa), high indentation toughness (5–7 $\mathrm{MPa}\sqrt{\mathrm{m}}$) and low porosity (0.5 %), and have excellent resistance to fretting wear, corrosion and rolling contact fatigue. Such wide-ranging properties are attributed mainly to a uniform distribution of extremely hard (24 GPa) WC cuboids in the softer (2.5 GPa) cobalt matrix, which typically constitutes 20 vol% of the coating [10]. The cuboids have a typical size range of 0.5–6 μm.

Unlike plasma spraying, both the HVOF and DSC processes can maintain reducing atmospheres within the combustion gas stream, making these techniques particularly suited to depositing carbide-based coatings. The DSC process has some advantages over HVOF in (i) its flexibility to employ a wide range of oxy-fuel ratios while maintaining a reducing atmosphere, and (ii) the use of a much longer barrel that enables better thermo-kinetic energy transfer to the particles. Thus DSC coatings are often preferred to HVOF coatings, especially when close control over the final coating microstructure is essential.

An illustration of the DSC flexibility is given in Fig. 22.3: using the same WC–12Co feedstock powder, the DSC technique can significantly alter the coating microstructure simply by varying the oxy-fuel ratio [10].

***Decarburization*:** Whichever technique is used, a common issue is the decarburization of WC cuboids during spray deposition. On the one hand, the powder particle temperature during spraying needs to be sufficiently high to attain cobalt melting and therefore achieve higher inter-splat cohesion. But on the other hand, higher particle temperatures lead to decomposition or decarburization of WC, whereby W and C dissolve into the cobalt matrix [11]. Therefore the temperature and oxidation potential of the gas stream needs to be balanced to achieve a practical

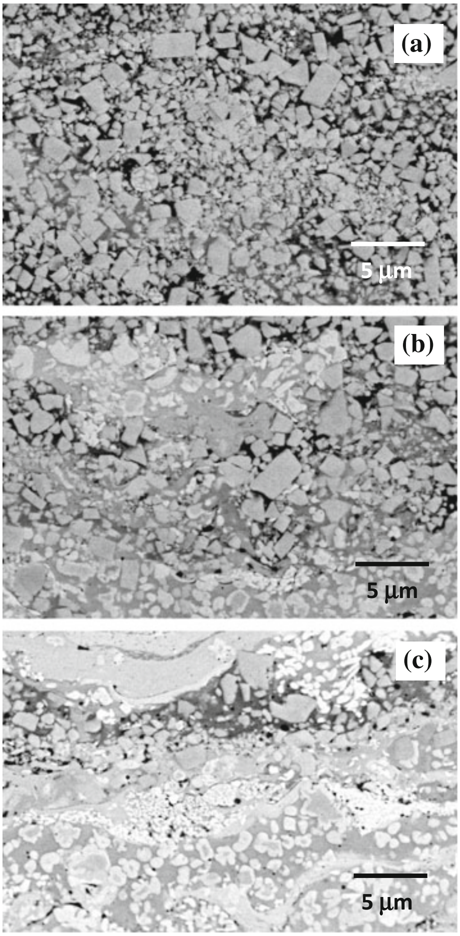

Fig. 22.3 WC–12Co coatings deposited by DSC at various oxy-fuel ratios. **a** 1.16 **b** 1.5, **c** 2.0

balance of these opposing phenomena. Also, the finer the WC-cuboid size in the WC–Co powder, the greater is the extent of decarburization during the coating process, while too-large cuboids lead to relatively poor cohesion with the cobalt matrix [12].

***Particle changes during deposition*:** It is noteworthy that decarburization cannot be completely eliminated, since the Co matrix has to melt to impart sufficient inter-splat bonding. At the same time, formation of the harder W_2C phase (30 GPa—harder than WC itself) should be minimal because W_2C embrittles the coating, see Ref. [10]. The presence of W_2C can be easily identified in the coating microstructure by the formation of typical W_2C shells around the WC cuboids [10, 11]. Since the solid solubility of both W and C in the Co matrix decreases rapidly as the splat cools down, precipitation of W_2C around the WC cuboids and

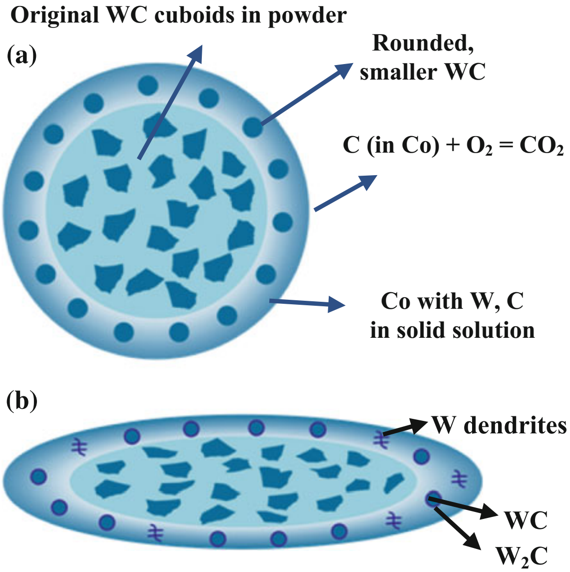

Fig. 22.4 Schematic illustration of physico-chemical changes in WC–Co powder particle **a** during spraying, **b** during splat solidification: Refs. [12, 13]

W in dendritic form can be observed in the coating microstructure, as schematically illustrated in Fig. 22.4b.

Also, while the primary goal is to retain the typical composite structure of WC cuboids distributed in the Co matrix, the cuboids will eventually reduce in size, and the shape changes to non-cuboidal (with rounded edges) due to WC loss from the sharp edges, as also indicated in Fig. 22.4.

It should be noted that the extent of retention of dissolved C in Co is determined by the rate at which C is lost from the Co matrix owing to the formation of CO_2/CO during the rapid solidification when the particles impact the substrate [14].

In view of the above-mentioned physico-chemical changes that are likely to happen during spray deposition of WC–Co coatings, it is very important to understand the influence of all possible interacting factors to arrive at the optimum process parameters, including the inter-splat cohesion. Any compromise in inter-splat cohesion will have a deleterious effect on the fracture toughness and wear resistance of the coatings. Experience has shown that an oxy-fuel ratio of 1.3–1.5 is the optimum for obtaining the best property combinations.

Wear resistance: As already mentioned, WC–Co coatings have excellent resistance to wear and rolling contact fatigue. They also have a high erosion resistance: erosive media, e.g. sand, usually have grain sizes much larger than the WC cuboids, and so the WC–Co composite modulus provides a high resistance to erosion damage. This can be explained with the aid of Fig. 22.5 [15]. This shows the formation of lips on the WC–Co coating surface, implying a ploughing mechanism, which is a common feature of ductile materials undergoing and resisting erosion.

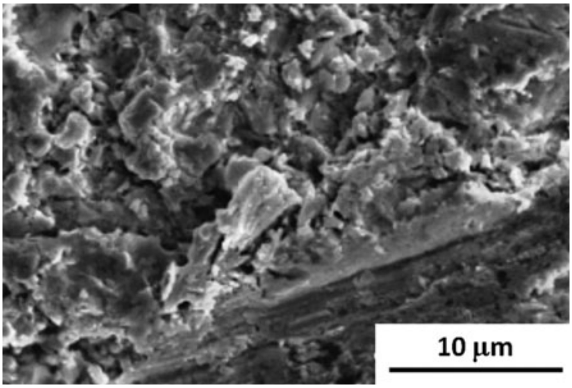

Fig. 22.5 Eroded surface of WC–Co coating showing lip formation [15]

WC–Co coatings also provide excellent protection under abrasive and sliding wear modes [16–19]. In addition, these coatings significantly enhance service life by resisting fretting wear, erosion–corrosion and rolling contact fatigue [20, 21], as was also mentioned earlier.

Gas turbine applications**:** The exceptional combination of properties obtainable from WC–Co coatings has resulted in numerous applications in aircraft gas turbines. In the turbine section these include actuator piston rods and fuel pump impellers in the afterburner; combustion chamber positioning pins; gear box support pins, bushings and lugs; labyrinth seal fins and seal teeth; gears; oil pump scavenge and breather tubes; bearing housings and seal assemblies; and exhaust fairing pins and bushings.

In addition, WC–Co coatings are used to meet the functional requirements of numerous parts in the compressor section, e.g. bevel gears; gear box drives; bleed manifold expansion joint liners and sleeves; fan and compressor blades; case flanges; hubs; discs; rotor tubes and sleeves; diffusers; impellers and vane sectors; and variable vanes.

Figure 22.6 depicts some aircraft parts that have been coated with the two most popularly employed coatings, viz., WC–12Co and WC–17Co.

Helicopter applications**:** WC–Co coatings to combat wear, corrosion, fretting and sliding wear damage are applied to a wide selection of helicopter components including main rotor shafts, rotor blade extension sleeves, blade bolts, transmission gears, damper housings, swash plates, tail rotor hubs, pinion gears, blade radius rings, cylinder assembly plungers, inner race bearings, spur gears, bearing retaining nuts, bevel drive gears, and conical and input gears.

Fig. 22.6 **a** WC–17Co coated compressor disc and **b**–**c** WC–12Co coated nozzle parts

22.4.2 *Modified Tungsten Carbide/Cobalt (WC–Co–Cr) Coatings*

A slightly modified WC–Co coating chemistry is the WC–10Co–4Cr composition, which is recognized as an actual and potential replacement for hard chrome electroplating [22], thereby avoiding the environmentally hazardous chemicals used in the plating process.

Although WC–Ni and WC–Ni–Cr coatings have also been extensively studied, the WC–Co–Cr coatings demonstrate superior corrosion and erosion resistance. Also, these coatings are superior to hard chrome electroplate with respect to pitting, spalling and cracking under stress [23, 24]. Further, it should be noted that these coatings are more rapidly deposited via DSC/HVOF routes as compared to the electroplating process.

Owing to their superior erosion and corrosion resistance, the WC–Co–Cr coatings are now used to effectively provide functional property enhancement of numerous landing gear components; piston rods and swash plate sliders; low- and high-pressure turbine shafts; pinch locks; bearing housings; and front- and rear-compressor hubs of aircraft and helicopter gas turbines.

22.4.3 Cr_3C_2–NiCr Coatings

Besides WC-based coatings, DSC-deposited Cr_3C_2–NiCr coatings are widely used to provide high thermal stability, excellent resistance to wear [25], oxidation, fretting, corrosion and high temperature wear, especially in the harsh operating conditions of an aircraft engine. Also, the solid particle erosion resistance at low angles of impingement is better than that of special grade stainless steels, and the coatings are well-bonded to the substrate (bond strength ~70 MPa [26]).

The relative proportion of NiCr ranges from 20–40 at.%, although Cr_3C_2–25NiCr (50:50 at.% Ni–Cr solid solution) is the most popular spray grade powder [27]. The Cr_3C_2–NiCr coating exhibits a typical plate-like lamellar structure oriented roughly parallel to the substrate, as shown in Fig. 22.7. The microstructure is characterized by a dense skeletal network of fine chromium carbide (Cr_3C_2) and chromium oxide (Cr_2O_3) bound within the NiCr ductile matrix [28]. With such a microstructure and a coating hardness in the range of 750–950 HV, the high temperature wear resistance up to 980 °C is excellent, especially under moderate load, dry frictional conditions [25, 29].

Owing to the above-mentioned specific properties, the Cr_3C_2–NiCr coatings are being used for seals, flaps, nozzle segments and spray bars of afterburner sections; sealing rings, spacers, air seals, shrouds, blades and vanes in turbine sections; clamps, liners, nozzle nuts and fuel swirlers in combustion sections; and seal seats and spacers of bearings. As an illustration, a Cr_3C_2–NiCr coated turbine blade is shown in Fig. 22.8.

It should be noted that the Cr_3C_2 phase in Cr_3C_2–NiCr powder undergoes decarburization during the spraying process. Hence a proper selection of the spraying parameters is essential. Decarburization of the Cr_3C_2 phase leads to

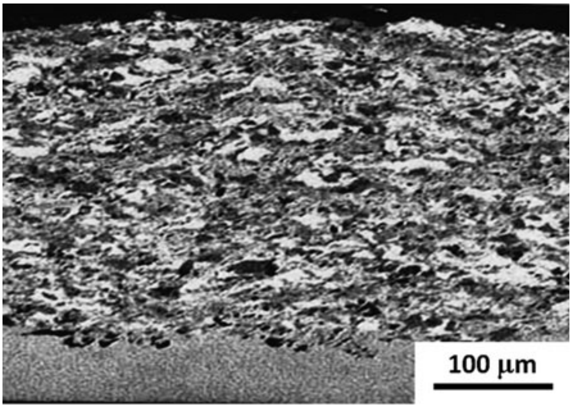

Fig. 22.7 Typical lamellar microstructure of a 325-m-thick Cr_3C_2–NiCr coating deposited by the DSC process

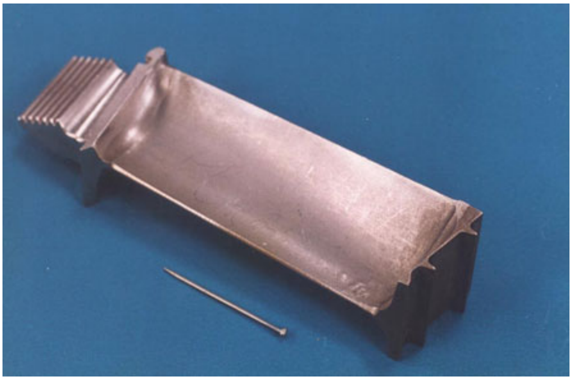

Fig. 22.8 Aircraft engine turbine blade coated with Cr_3C_2–NiCr for corrosion, oxidation and fretting wear resistance

formation of lower carbides such as Cr_7C_3 and $Cr_{23}C_6$ phases, thereby negatively influencing the coating properties [25].

22.4.4 Abradable Coatings

Abradable coatings are mostly deposited by vacuum plasma spraying and HVOF processes. The DSC process is also capable of depositing abradable coatings, and owing to its better thermal management during spraying it is used for specialized abradable applications on various aeroengine components.

Unlike wear-resistant coatings, abradable coatings should preferentially wear away, and the debris should not damage the mating surfaces. Besides good abradability these coatings should have high resistance to gas and particulate erosion, good thermal properties, be self-lubricating, and have minimum affinities with the substrate materials. In view of these requirements, abradable coatings are mostly combinations of metals (e.g. Al–Si and MCrAlYs, where M=Ni, Co, Fe or a combination of these elements) with polyester and solid lubricants such as hexagonal boron nitride (h-BN), bentonite or graphite [30].

Al–Si–polyester, Ni–graphite and Ni–Cr–Al–bentonite can withstand engine operating temperatures up to 325, 450 and 815 °C, respectively [31]. The abradability requirements are met by introducing controlled porosity in the coating microstructure, thereby reducing the overall cohesive strength; while the substrate–coating bond strength is designed to be higher than the inter-splat cohesive strength.

22.4.5 Thermal Barrier Coatings (TBCs)

Components such as blades, vanes, combustion chambers, liners and domes in the hottest parts of gas turbines are usually provided with thermal barrier coatings

(TBCs) to better resist corrosion, oxidation or excessive heat loads [32]. The most used TBC, yttria-stabilized zirconia (YSZ) containing 7–8 wt% Y_2O_3, serves as a functional topcoat, and is usually deposited by plasma spray or electron beam physical vapour deposition (EB-PVD) [33].

EB-PVD provides the most sophisticated TBC, since it builds up a columnar YSZ microstructure that has better strain tolerance and resistance to cracking and spalling. However, the success of TBCs also relies on a good bond coat between the YSZ and the substrate. The bond coat provides the main resistance to high temperature oxidation and corrosion.

Bond coats are MCrAlYs, and are deposited by thermal spray variants such as vacuum plasma spray (VPS), low pressure plasma spray (LPPS), air plasma spray (APS), HVOF or DSC [34]. Sufficient aluminium content in the MCrAlY bond coat allows formation of a thin Al_2O_3 layer (thermally grown oxide, TGO) between the bond coat and YSZ topcoat: the TGO hinders further oxidation of the bond coat.

A NiCoCrAlY TGO-forming bond coat is the most generally used, since it provides the best cyclic oxidation resistance. Recent research has shown that a DSC-deposited NiCoCrAlY bond coat outperforms a similar HVOF-sprayed bond coat under cyclic oxidation testing [35].

22.4.6 *Coating Refurbishments*

Refurbishment of previously coated and damaged or worn components by thermal spraying is most important, since it extends the service lives of many expensive parts and assemblies, notably in aircraft gas turbines. Refurbishing usually entails completely stripping away the original coating by mechanical or electrochemical means (or both), followed by surface preparation (e.g. grit blasting) and recoating.

The versatility of DSC technology enables it to be used for refurbishing various parts. For example, Fig. 22.9 shows a refurbished blade and the entire assembly of a low pressure compressor module, where the faces of the snubber abutments (interlocking mid-span supports) have been DSC sprayed with a WC–17Co coating.

Other examples are given in Fig. 22.10, which shows high-pressure compressor spacers after refurbishing with a *plasma sprayed* NiCr bond coat and DSC Al_2O_3 top coat as abradable coating.

22.5 Other Coating Processes

Combustion flame spray: This process, with its flame temperature of 3000 °C and relatively lower particle velocity (90–180 m/s), is used for depositing metallic coatings (molybdenum) and self-fluxing coatings.

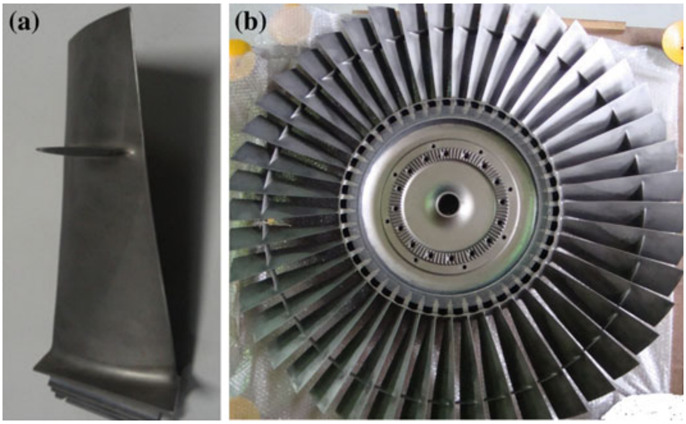

Fig. 22.9 Refurbished compressor module. **a** individual blade with snubber abutment face coated with DSC-sprayed WC–17Co coating, and **b** the assembled module

***Plasma spraying*:** This is performed via three principal techniques: air plasma spraying (APS); argon-shrouded plasma spraying (ASPS); and vacuum plasma spraying (VPS) or low pressure plasma spraying (LPPS).

The principal limitation of the APS technique is the incorporation of air in the plasma jet, thereby slowing it and simultaneously causing some oxidation of metallic or alloy powders, resulting in higher oxide contamination in the coating. The particle velocities are higher in the VPS technique (400–600 m/s), leading to formation of relatively denser coatings with good adhesion and significantly reduced oxide content.

Typical uses of VPS–LPPS in aeroengines include M–Cr–Al–Y systems (overlays and thermal barrier bond coats), hot gas path seal systems, TBC coatings on afterburner liners, seals, flaps, nozzle segments and numerous combustion chamber parts [31]. Apart from these applications, TBCs are also employed on a wide variety of high pressure turbine blades and vanes, whereby both the bond coat and the TBC YSZ topcoat are applied via plasma spray.

***EB-PVD*:** With the advent of EB-PVD technology, many of the critical applications have been shifted from plasma coating to EB-PVD bond coat + EB-PVD topcoat, while the bond coat market is also popularly shared with platinum–aluminide coating by chemical vapour deposition (CVD) [36, 37]. Figure 22.11 shows a high-pressure turbine vane with a CVD platinum–aluminide bond coat and EB-PVD topcoat.

***Ion vapour deposition*:** Another popular process in the aerospace industry is ion vapour deposition (IVD) of aluminium as a replacement for cadmium plating [38–40]. The largest use of IVD aluminium is for corrosion protection of low-alloy steel parts such as cylinders, retainers, caps, retainer rings, spacers, strikers, springs, bolts, brackets, standoffs, links, flap tracks, rings, outboard actuators, strut

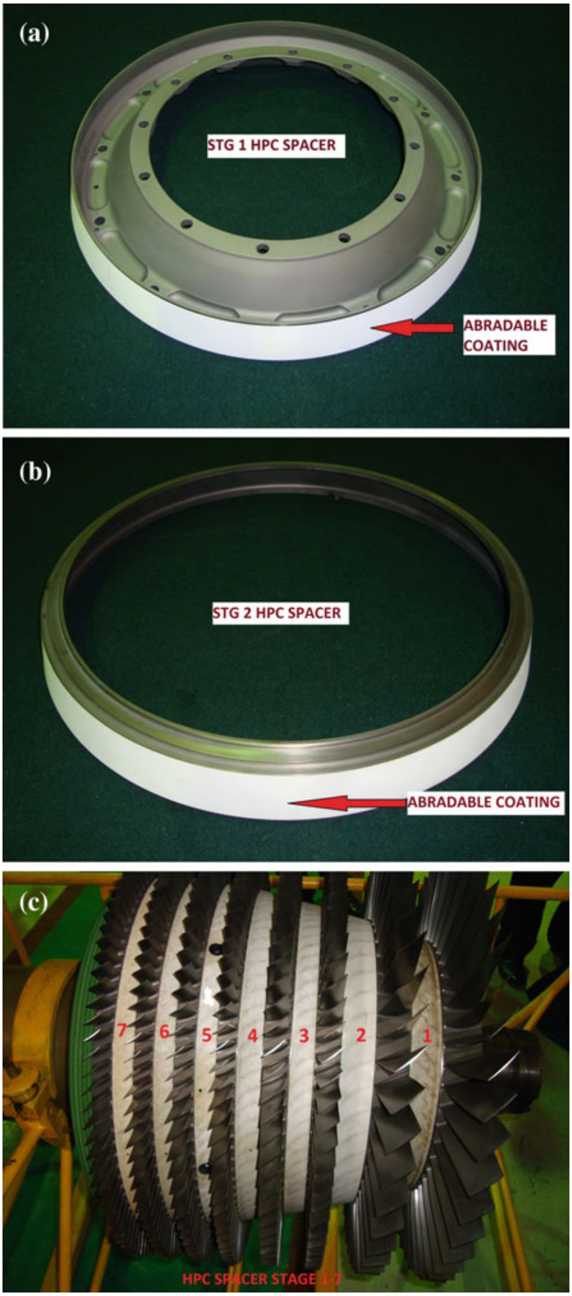

Fig. 22.10 High-pressure compressor spacers pertaining to **a** stage-1, **b** stage-2 and **c** 7 spacer stages in an assembled module

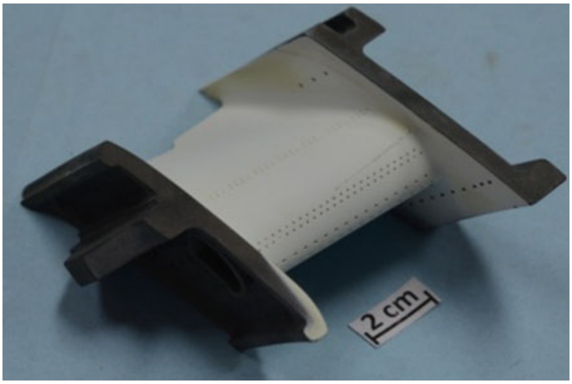

Fig. 22.11 High pressure turbine vane with platinum–aluminide bond coat and EB-PVD TBC YSZ topcoat

terminals, blower impellers, stops, screw assembly ball nuts, plates, housings leg bolts, fasteners, nuts, covers, housings, etc.

Selected aluminium alloys are also IVD aluminium-coated for corrosion protection and to eliminate a fatigue debit associated with anodizing aluminium parts: anodizing high-strength aluminium alloy parts can cause surface pits that nucleate fatigue cracks.

22.6 Summary and Concluding Remarks

Engine design concepts are moving towards greater thermal and propulsive efficiency. Materials and especially coatings will continue to play an important role in advancing performance, efficiency and reliability. Future engines are expected to operate at much higher temperatures and speeds; hence the need for extended component lives as well as reduced costs will grow [41]. With respect to coatings, reduced costs need to be realized via a compatibility and commonality of coating processes and compositions, and also the ease of coating repair and refurbishment.

Processing methodologies will be essential in creating new generation coating systems. For a given coating system it will be necessary to have more rigorous optimization schemes, such that even minor improvements in coating properties should be seen as an important opportunity. Sub-systems should also be developed to incorporate new and modified coatings with minimal alterations in existing production facilities.

As an example, Fig. 22.12 shows that Cr_3C_2–NiCr powders of almost identical median size (20 ± 5 μm) but manufactured via different routes give DSC coatings with widely differing porosity levels and hardness [25]. Although Fig. 22.12 shows that the blend (B) powder delivers the best combination of porosity and hardness, further refining or re-optimizing the process parameters may enable higher coating hardness from pre-alloyed and blended powders. In any event, the data in

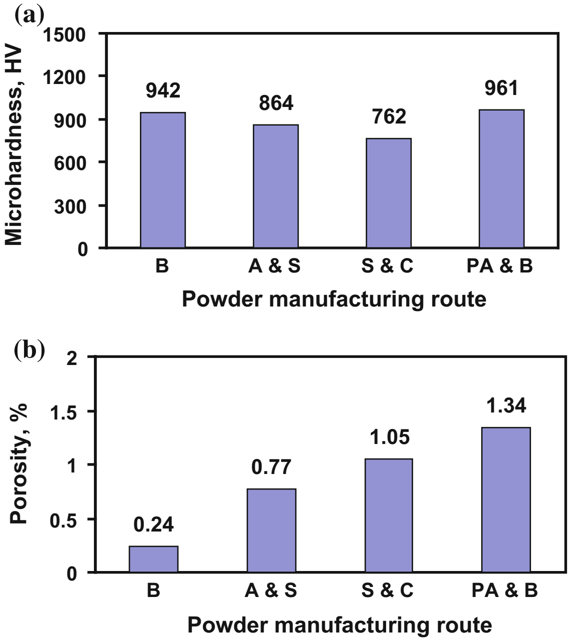

Fig. 22.12 Variation in **a** hardness and **b** porosity of Cr_3C_2–NiCr coatings deposited using powders manufactured via different routes *B* blended; *A&S* agglomerated and sintered; *S&C* sintered and crushed; *PA&B* pre-alloyed and blended

Fig. 22.12 highlight the need to optimize the process parameters separately for each powder.

An altogether new set of properties is achieved from composite coating structures, see Ref. [2]. Thermal spray systems and in particular the DSC and HVOF technologies should be evaluated with respect to achieving through-thickness graded or layered coating architectures. Recent world-wide R&D activities in developing multiple powder feeding systems indicate the interest in such coatings.

Finally, spray system automation to enhance the robustness of the processes needs to be increased. For example, the present authors have recently taken the initiative to completely replace all the mechanically moving parts of earlier designed DSC systems by using advanced flow metres and process controls. This is being done to improve the deposition efficiency, deposition rate, coating integrity and overall process reliability [42].

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References

1. Sundararajan G, Srinivasa RD, Sivakumar G, Joshi SV (2013) Detonation spray coatings. In: Wang J, Chung W (eds) Encyclopedia of tribology. Springer Science + Business Media, Berlin, Germany, pp 736–742
2. Rao DS, Sivakumar G, Sen D, Joshi SV (2015) Detonation sprayed coatings and their tribological performances. In Roy M, Davim J (eds) Thermal sprayed coatings and their tribological performances, IGI Global, Hershey, PA, USA, pp 294–327. doi:10.4018/978-1-4666-7489-9.ch010
3. Kadyrov V, Margarita Y, Sen D, Rao DS, Rao KP, Saibaba AV (1993) Detonation coating process. Trans PMAI 20:1–5
4. Fauchais PL, Heberlein JV, Boulos MI (2014) Thermal spray fundamentals Springer, New York, USA
5. Pawlowski L (1995) The science and engineering of thermal spray coatings. John Wiley & Sons Ltd, Chichester, UK
6. Wang J, Chung W (eds) (2013) Encyclopedia of tribology. Springer Science+Business Media, Berlin, Germany
7. Roy M, Davim J (eds) (2015) Thermal sprayed coatings and their tribological performances. IGI Global, Hershey, PA, USA: doi:10.4018/978-1-4666-7489-9
8. The basic principles of detonation coating (1974) In: Chapman BN (ed) Science and technology of surface coating. Academic Press, London, UK
9. Tucker RC Jr (1994) Thermal spray coatings. In: Cotell CM, Sprague JA, Smidt FA Jr (eds) ASM Handbook, vol. 5: Surface engineering, ASM International, Materials Park, OH, USA, pp 497–509
10. Suresh Babu P, Basu B, Sundararajan G (2008) Processing-structure-property correlation and decarburization phenomenon in detonation sprayed WC-12Co coatings. 56:5012–5026
11. Verdon C, Karimi A, Martin JL (1998) A Study of high velocity oxy-fuel thermally sprayed tungsten carbide based coatings. Part 1: Microstructures. Mater Sci Eng 246:11–24
12. Stewart DA, Shipway PH, McCartney DG (2000) Microstructural evolution in thermally sprayed WC-Co coatings: comparison between nanocomposite and conventional starting powders. Acta Mater 48:1593–1604
13. Du H, Hua W, Liu J, Gong J, Sun C, Wen L (2005) Influence of process variables on the qualities of detonation gun sprayed WC-Co coatings. Mater Sci Eng A 408:202–210
14. Suresh Babu P, Basu B, Sundararajan G (2013) A comparison of mechanical and tribological behavior of nanostructured and conventional WC-12Co detonation-sprayed coatings. J Therm Spray Technol 22:478–490
15. Suresh Babu P, Basu B, Sundararajan G (2011) The influence of erodent hardness on the erosion behavior of detonation sprayed WC-12Co coatings. Wear 270:903–913
16. Sundararajan G, Rao DS, Prasad KUM, Joshi SV (1998) A comparative study of tribological behavior of plasma and D-gun sprayed coatings under different wear modes. J Mater Eng Perform 7:343–351
17. Suresh Babu P, Rao DS, Rao GVN, Sundararajan G (2007) Effect of feedstock size and its distribution on properties of detonation sprayed coatings. J Therm Spray Technol 16:281–290
18. Suresh Babu P, Basu B, Sundararajan G (2010) Abrasive wear behavior of detonations sprayed WC-12Co coatings: Influence of decarburization and abrasive characteristics. Wear 268:1387–1399
19. Sundararajan G, Suresh Babu P (2009) Detonation sprayed WC-Co coatings: unique aspects of their structure and mechanical behavior. Trans Indian Inst Met 62:95–103
20. Ahmed R, Hadfield M (1997) Rolling contact fatigue performance of detonation gun coated elements. Tribol Int 30:129–137
21. Souza VAD, Neville A (2007) Aspects of microstructure on the synergy and overall material loss of thermal spray coatings in erosion-corrosion environments. Wear 263:339–346
22. Murthy JKN, Rao DS, Venkataraman B (2001) Effect of grinding on the erosion behaviour of WC-Co-Cr coatings deposited by HVOF and detonation gun spray process. Wear 249:592–600

23. Karimi A, Verdon C (1993) Microstructure and hydroabrasive wear behaviour of high velocity oxy-fuel thermally sprayed WC-Co Cr) coatings. Surf Coat Technol 57:81–89
24. Berget J, Rogne T, Bardal E (2007) Erosion–corrosion properties of different WC–Co–Cr coatings deposited by the HVOF process—influence of metallic matrix composition and spray powder size distribution. Surf Coat Technol 201:7619–7625
25. Somaraju KRC, Sivakumar G, Rao DS, Sundararajan G (2000) The influence of powder characteristics on the properties of detonation sprayed Cr_3C_2–25NiCr coatings. In: Thermal Spray 2000: Proceedings of the 1st international thermal spraying conference, Berndt CC (ed), ASM International, Materials Park, OH, USA, pp 309–316
26. Quets JM, Walsh PN, Srinivasan V, Tucker RC Jr (1994) The high temperature fatigue characteristics of an erosion-resistant detonation gun chromium carbide coating. Surf Coat Technol 68(69):99–105
27. Rao DS, Sen D, Somaraju KRC, Kumar SR, Ravi N, Sundararajan G (1998) The influence of powder particle velocity and temperature on the properties of Cr_3C_2-25NiCr coating obtained by detonation-gun. In: Thermal spray 1998: Meeting the challenges of the 21st century, ASM International, Materials Park, OH, USA, pp 385–393
28. Wang J, Zhang L, Sun B, Zhou Y (2000) Study of the Cr_3C_2-NiCr detonation spray coating. Surf Coat Technol 130:69–73
29. Lindgren JR, Johnson WR (1987) Friction and wear behavior of chromium carbide coatings. Surf Coat Technol 32:249–260
30. Talib RJ, Saad S, Toff MRM, Hashim H (2003) Thermal spray coating technology—a review. Solid State Sci Technol 11:109–117
31. Jones TNR (1990) Thermally sprayed coating systems for surface protection and clearance control applications in aero engines. Surf Coat Technol 43(44):402–415
32. Altun O, Boke YE (2009) Effect of the microstructure of EB-PVD thermal barrier coatings on the thermal conductivity and the methods to reduce the thermal conductivity. Arch Mater Sci Eng 40:47–52
33. Yuan FH, Chen ZX, Huang ZW, Wang ZG, Zhu SJ (2008) Oxidation behavior of thermal barrier coatings with HVOF and detonation-sprayed NiCrAlY bondcoats. Corros Sci 50:1608–1617
34. Miramontes JAC, Tiburcio CG, Calderon A, Lopez FHE, Basulto GKP, Salas CAP (2014) Parameter studies on high-velocity oxy-fuel spraying of CoNiCrAlY coatings used in the aeronautical industry. Int J Corros. doi:10.1155/2014/703806
35. Rao DS, Janardhan GR, Krishna V, Joshi SV (2011) Processing–structure–property relationships in EB-PVD yttria stabilized zirconia (YSZ) coatings. J Vacuum Sci Technol A 29:031501–031508
36. Das DK, Laxmi SG, Rao DS, Bhanumathi S, Singh AK (2011) Microstructure, texture and thermal cycling performance of EB-PVD TBCs deposited under different processing conditions. J High Temp Mater Processes 30:539–548
37. Jie S, Dan Z, Lili Z, Yong T (2011) Thermal corrosion behavior of NiCoCralY coatings prepared by different thermal spraying methods. Mater Sci Forum 686:686–691
38. MacDonald D, Jodoin B, Gaydos S, Pollack M, Falkowski J, (2013) Study on the restoration of aluminum aerospace IVD coatings using cold gas dynamic spray. In: Proceedings of international thermal spray conference and exposition: innovative coating solutions for the global economy, ITSC, 13–15 May 2013, Busan, South Korea, Code 107529
39. Alanazi NM, Leyland A, Yerokhin AL, Matthews A (2010) Substitution of hexavalent chromate conversion treatment with a plasma electrolytic oxidation process to improve the corrosion properties of ion vapour deposited AlMg coatings. Surf Coat Technol 205:1750–1756
40. Voorwald HJC. Peres MP, Costa MYP, Cioffi MOH, Evaluation on fatigue strength of AISI 4340 steel aluminum coated by electroplating and IVD processes. J Mater Sci 45:6094–6100
41. De MJT, Gupta DK (1994) Protective coatings in the gas turbine engine. Surf Coat Technol 68(69):1–9
42. Nirmala S, Sivakumar G, Joshi AS, Aruna N, Rao DS, Sundararajan G (2013) A Computer—based approach for developing functionally graded and layered coatings with detonation spray coating process. J Sci Ind Res 72:477–480