1 Introduction to Thermal Spray

Abbreviations

APS	Atmospheric Plasma Spraying
DC	Direct current
HVAF	High-velocity air fuel
HVOF	High-velocity oxy fuel
ICP	Inductively coupled plasma
IPS	Induction plasma spraying
LPPS	Low pressure plasma spraying
OEM	Original Equipment Manufacturer
PTA	Plasma transferred arc
RF	Radio Frequency
RF-TPS	Radio Frequency Induction Plasma Spraying
WAS	Wire arc spraying
YSZ	Yttria stabilized zirconia

1.1 Introduction

The motto of the Olympic games "*citius, altius, fortius*" (faster, higher, stronger) entices athletes to continuously establish new records. Similarly, there is a continuous push in every part of industry to set new performance standards for the improvement of one part of human life. These performance improvements can be summarized as better functional performance, longer component life, and lower component cost. Besides the geometrical design, it is the choice of materials that will determine the performance and cost of the component. Advanced materials such as specialty steels, super alloys, and advanced ceramics have been developed for exceptional functional performance in a large number of applications. The increasing demands for combined functional requirements such as the high-temperature resistance to corrosive atmospheres in addition to abrasive wear resistance and the added difficulty in machining some of the specialty alloys to the relatively complex final forms, while keeping the final cost of the part at an acceptable level, led to the ever-increasing demand for surface modification technologies which allows the decoupling of the surface properties of a part from its bulk and structural properties. Surface modification can generally be achieved through either:

- Surface transformation through physical or chemical treatment
- Surface coating with a compatible metallic or ceramic material

This book is devoted to a review of thermal spray technologies which is one of the leading surface coating technologies. In this chapter, a brief introduction is given to this rapidly developing fields giving highlights of the technology, its historical development over the past century, and examples of typical industrial applications. An outline of the book content is presented at the end of the chapter in order to guide the reader through its different parts and provide easy access to information and pertinent references.

1.2 Needs for Coatings

The motivation for coating structural parts can be summarized by the following needs:

- Improve functional performance by allowing, for example, tolerance to higher temperature exposure using thermal barrier coatings
- Improve component life by reducing wear due to abrasion, erosion, and corrosion
- Extend the component life by rebuilding worn parts to their original dimensions avoiding the need for replacing the entire component, e.g., a shaft or axle.
- Reduce component cost by improving functionality of a low-cost material with an appropriate coating

M. I. Boulos et al. (ed.), *Thermal Spray Fundamentals*, https://doi.org/10.1007/978-3-030-70672-2_1

Coating technologies can be divided into two broad groups based on coating thickness. These are:

Thin films have thicknesses of less than 20 μm, offering excellent enhancement of surface properties. These are mostly obtained using atomic level deposition technologies such as chemical vapor deposition (CVD) or physical vapor deposition (PVD) which can provide surfaces with unparalleled hardness or corrosion resistance [Goto and Katsui (2015)], [Ogawa et al. (2018)]. The results can be further improved when assisted by plasma [Harder et al. (2017), Thull and Grant (2001)], laser [Katsui and Goto (2017)], or electron beam [Singh and Wolfe (2005)]. Most of thin film technologies, however, require a reduced pressure environment and, therefore, are more expensive and impose a limit on the size and shape of the part to be coated. The exceptions are the super thin surface modification films of large polymer sheets which are made possible using atmospheric pressure non-equilibrium discharges to manufacture materials such as nanocarbon [Hatakeyama (2017)] or Teflon-like layers on cellophane surfaces [Cruz-Barba et al. (2003)].

Thick films have generally a thickness greater than 20–30 μm, up to several millimeters. They are required when the functional performance depends on the layer thickness. Thermal barrier coatings are a typical example where the level of thermal protection of the substrate depends on the coating thickness. Wear resistance coatings exposed to strong erosion and corrosion conditions are another example where the component life depends on the layer thickness. Thick coatings in excess of a few millimeters may also be required for such applications as the rebuilding of worn parts to their original dimensions. Thick film deposition methods include chemical/electrochemical plating, brazing, weld overlays, and thermal spray. Each of these methods offers certain advantages and has their limitations. Wet chemical methods suffer from environmental hazards; brazing and weld overlays have limitations regarding the materials that can be deposited and the shape of the substrate, while thermal spray may require a post-deposition treatment to reach full density or eliminate all open porosity.

1.3 Thermal Spraying

The definition of thermal spraying is given in the thermal spray terminology compendium [Hermanek (2001)] as: “Thermal Spraying comprises a group of coating processes in which finely divided metallic or nonmetallic materials are deposited in a molten or semi-molten condition to form a coating. The coating material may be in the form of powder, ceramic rod, wire, or molten materials.”

A block diagram of the principal components of a thermal spray system is illustrated in Fig. 1.1. The system is centered around the “spray torch” in which different sources of energy whether chemical (combustion) or electrical (electric discharge), depending on the spray process, are converted into a stream of hot gas in which the material to be sprayed is injected. The material introduced into the torch, whether as powder, wire, or other forms, is heated, melted, and entrained by the high-temperature, high-velocity gas stream toward the substrate on which the particle/molten droplet impact generating splats which piles up on the substrate forming the coating. The splats formed either through the lateral flow of the melted material or, as in cold spray process, the ductile deformation of the particle represent the building block for the formation of the coating. The form and properties of these splats depend on the nature of the material sprayed, particle/droplet size distribution, particle/droplet temperature, and velocity prior to its impact on the surface of the substrate as well as on the surface properties of the substrate.

A schematic representation of a typical atmospheric pressure DC plasma spray system is given in Fig. 1.2a. It consists essentially of five principal components:

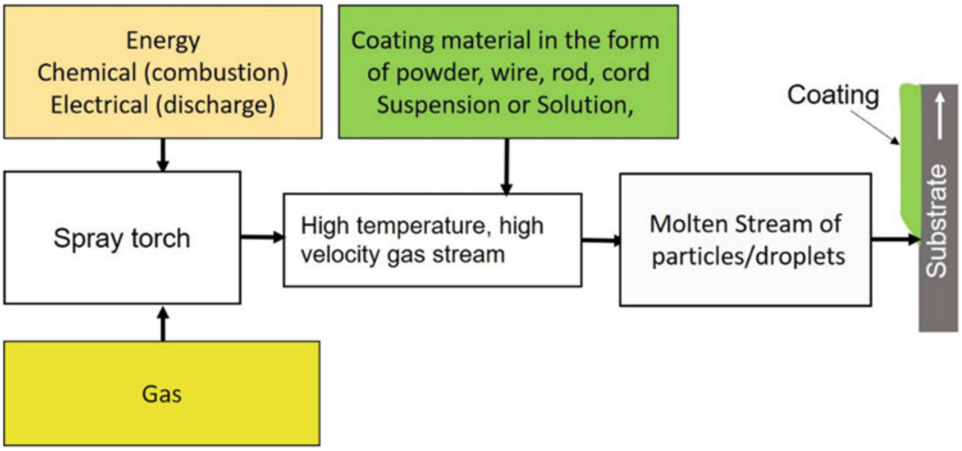

Fig. 1.1 Block diagram of a generalized thermal spray system

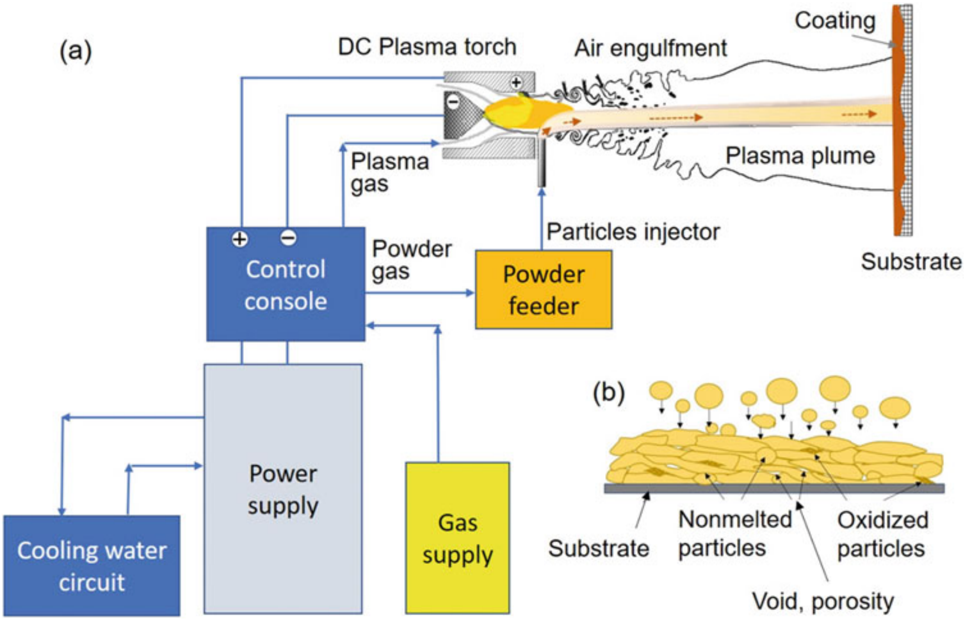

Fig. 1.2 (**a**) Schematic of a conventional DC plasma spray system. (**b**) Illustration of the coating building mechanism through the compilation of successive splat formation

Energy source, in the form of a DC electrical power supply

Gas supply, necessary for the operation of the plasma torch and the transport and injection of the material to be sprayed in powder form into the hot plasma stream

Powder feeder for the controlled feeding of the material into the plasma jet

Spraying torch and substrate manipulator, necessary for the movement of the spray torch and the substrate relative to each other to insure the control of the coating thickness

Control console, responsible for the monitoring and control of the different system components which are required for implementation of a reliable and safe coating processes

To these, it is necessary to add a broad range of ancillary equipment's and infrastructure services such as a cooling water circuits required for the protection of the different system components exposed to high-temperature plasma flow, exhaust gas cleaning and evacuation system, substrate preparation infrastructure which are necessary for optimal control of the spraying conditions, and, in certain cases, tooling for the post deposition finishing of the coating.

As illustrated in Fig. 1.2b, the coating is formed through the successive piling up of individual splats formed on impact of the particles/molten droplets on the surface of the substrate. The properties of the individual splats depend on the temperature and velocity of the particles/droplets prior to their impact on the substrate. The chemistry of the coating environment, the angle of projection of the particles/droplets on the substrate, and substrate surface preparation and its temperature can also be responsible for the creation of key features, or defects, in the coating as indicated in Fig. 1.2b. These could include non-melted or partially melted particles, oxidized particles, or poorly spread splats giving rise to the formation of voids/pores in the coating which, in turn, would affect the coating properties and its performance.

Substrate preparation has a critical impact on the quality of the coating since the adhesion of the coating to the substrate is directly related to its cleanliness, roughness, and sometimes the proper machining of the substrate. The presence of adsorbed contaminants on the substrate has also been reported to reduce the adhesion of the splat to the substrate. The effect is attributed to the heating and evaporation of the adsorbates and condensates present on the substrate during the splat formation step creating a localized high-pressure zone under the flattening particle and thus decreasing its contact with the substrate [Li and Li (2004)]. According to Fukumoto et al. (2006), such a situation can be avoided if the substrate is preheated over a critical transition temperature, T_t, which is in the range of 200–400 °C depending on the substrate material. To illustrate this point, micrographs given in Fig. 1.3. show splats of 58 μm diameter alumina particle plasma sprayed on a stainless steel substrate (ASI304) with a relative velocity of 138 m/s and an impact angle of 30°. The in-flight particle temperature prior to its impact on the substrate was reported as 2400 K. Micrograph given in Fig. 1.3a, obtained with a cold substrate, without substrate preheating, shows an elliptical shape with numerous fingers immerging from it, while that given in Fig 1.3b, which was obtained on a preheated substrate, has a pure elliptical shape with no visible fingers or splats. As will be discussed later in Part III of this book, the shape and properties of these splats have a significant impact on the overall properties of the coating.

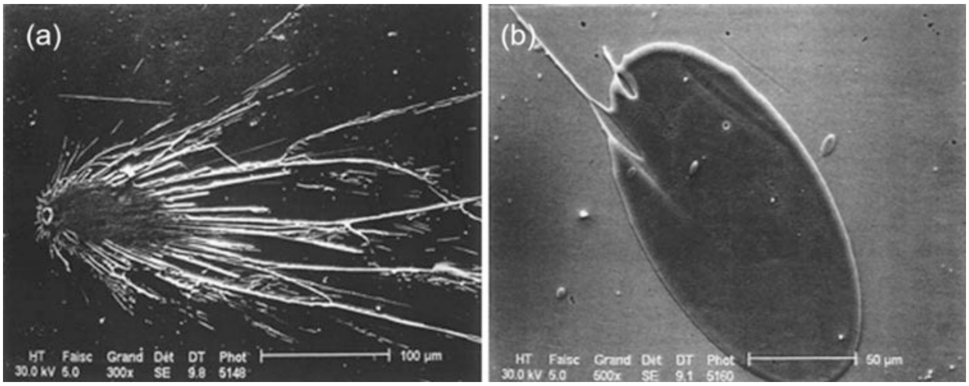

Fig. 1.3 Typical splats of plasma-sprayed alumina particles on an inclined stainless steel (ASI304) substrate at an impact angle of 30°. (**a**) Substrate at room temperature and (**b**) substrate preheated above transition temperature [Bianchi et al. (1997)]

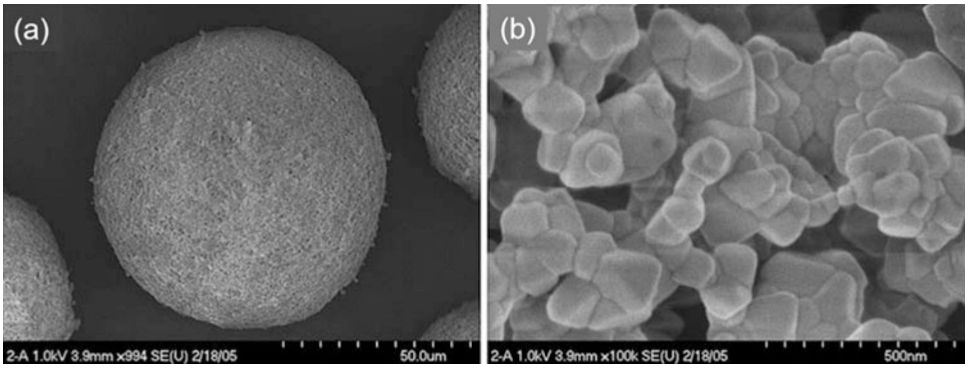

Fig. 1.4 (**a**) YSZ feedstock particle formed by the agglomeration (spray-drying) of individual nanosized particles (**b**) higher magnification micrographs of the constituent nanosized particles (30–130 nm) [Lima and Marple (2007)]

Another area where significant developments in the field of thermal spray have been made over the past few decades is the spraying of nanostructured coatings with the objective of improving the toughness of plasma sprayed coatings [Fauchais et al. (2011)]. McPherson in 1973 was one of the first to identify nanosized features in conventional thermal-sprayed alumina coatings. Subsequent studies in this area aiming at producing nanostructured coatings using nanopowders were greatly hindered by the difficulty of feeding them into a flame or plasma stream using carrier gas-based conventional powder feeding techniques. The challenges being the extremely small mass of the nanopowders and the difficulty to provide them with the momentum necessary to have them penetrate a fast-moving plasma stream. One approach proposed by Lima and Marple (2007) was to agglomerate the nanoparticles into micron-sized particles and feed them into the plasma using conventional techniques. Micrographs of yttria stabilized zirconia (YSZ) particles produced using this technique are given in Fig. 1.4a, with individual nanosized constituents integrated in the agglomerated shown in Fig. 1.4b. The thermal diffusivity of the nanostructured plasma-sprayed YSZ coating obtained using these agglomerated powders was found to be lower than those obtained using conventional YSZ coatings up to temperatures of 1200 °C (heating and cooling steps). These nanostructured YSZ coating had a thermal shock resistance 2–4 times higher than that of the conventional YSZ coatings. The challenge, however, remained in the fact that great care has to be exercised in the use of such agglomerated powders since their temperature during the spray process need to be maintained just below the melting temperature of the material in order to avoid their complete melting which would erase irreversibly all of their nanostructure features.

The growing need to manufacture coatings with enhanced properties for a wide range of applications [Fauchais et al. (2015)] has led to the emergence of alternate powder feeding techniques that could be used with nanopowders that would not require the particle agglomeration step. *Suspension* and *solution* plasma-spraying techniques are two such novel powder injection approaches which have been gaining wide acceptance in the scientific community.

Suspension plasma spraying was used for the first time by Bouyer et al. (1997), Gitzhofer et al. (1997) for the feeding of hydroxyapatite nanopowders in an RF inductively coupled plasma (RF-IPS)-spraying system. In this approach, the nanoparticles are maintained in a suspension which is injected and atomized into the plasma stream. The formed droplets of the suspension containing the nanoparticles are further fragmented in-flight and the liquid evaporated without affecting the nanostructure of the powder. The dried agglomerated powder particles entrained by the relatively colder plasma stream, integrating the evolved liquid vapors, are heated to a sufficiently high temperature to adhere to the substrate on impact without causing them to melt completely and lose their nanostructure feature. Occasionally the produced agglomerated particles will disintegrate releasing individual nanoparticles which are entrained by the plasma flow and deposited on the substrate. A micrograph of typical micro-splats formed using this approach is given in Fig. 1.5 for the suspension plasma-sprayed YSZ nanopowder using ethanol as liquid medium for the formation of the suspension. The substrate used in this case was smooth stainless steel, preheated over its transition temperature. Splats of molten particles are noted to be well flattened with a relatively low mean flattening degree of 2.1 (ratio of splat diameter to the original particle/droplet diameter) reflecting their relatively low impact velocity on the substrate.

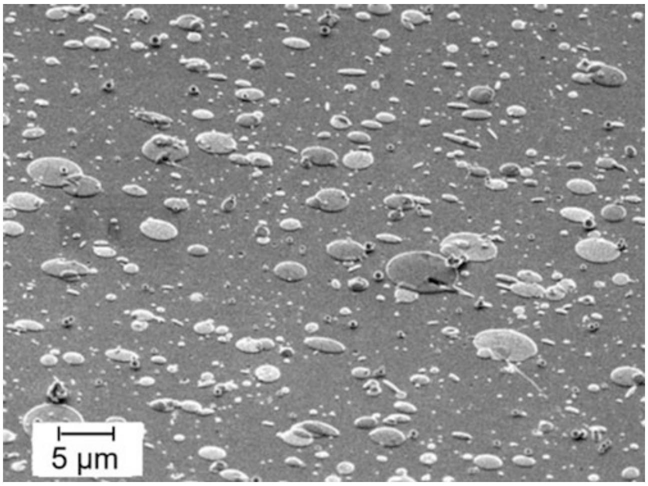

Fig. 1.5 SEM photography of YSZ splats resulting from suspension plasma spraying of nanosized particles on a preheated steel substrate [Fauchais et al. (2016)]

Solution spraying, on the other hand, is a technique in which the precursor material to be deposited is dissolved in an appropriate liquid, injected and atomized in the form of fine liquid droplet mist. As these droplets are entrained by the plasma stream, they are heated and evaporated producing fine nanoparticles, depending on the solute concentration in the liquid. The formed nanoparticles are further heated and partially or completely melted before their impact on the surface of the substrate forming corresponding micron-sized splats. The main advantage of solution spraying compared to suspension spraying lies in the efficient mixing at the molecular level of the chemical constituents allowing for an excellent chemical homogeneity of the feedstock material [Ravi et al. (2006)]. The success in forming the phase required for a given system depends on the decomposition characteristics of the different precursors. Once the solid particles have been formed, the situation is the same as that with suspensions. Several liquid precursors, such as complexes solutions/sols/polymerics, have been evaluated for different oxide systems [Gell et al. 2008)].

1.4 Classification of Thermal Spray Processes

A preliminary classification of thermal spray technologies according to the source of energy used in the process for the generation of the high-temperature, high-velocity gas stream is given in Fig. 1.6. These are grouped into two broad categories:

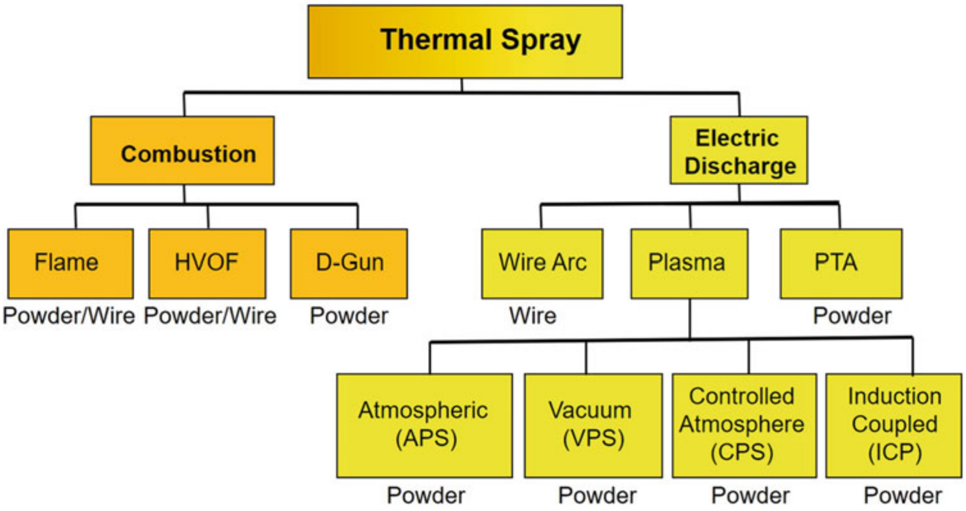

Fig. 1.6 Classification of thermal spray coating technologies

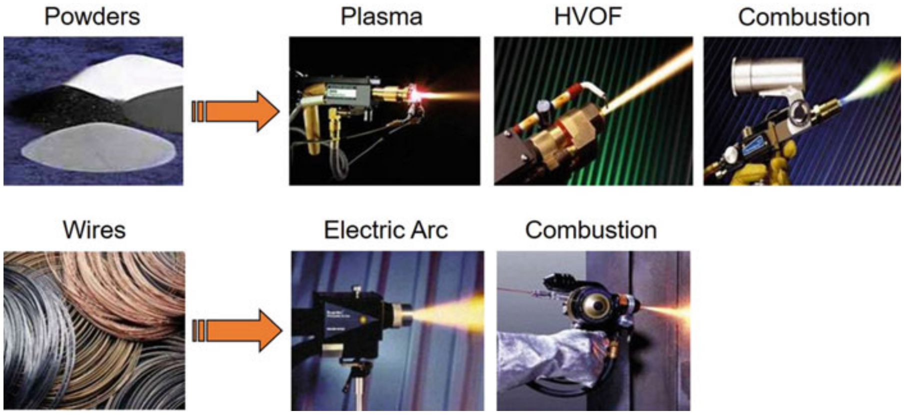

Fig. 1.7 Illustration of thermal spray processes using powders and wires. [Reproduced with kind permission of Oerlikon Metco Corp]

Combustion-based thermal spray processes, which historically represent the origin of the thermal spray technology, include *flame spraying*, *high-velocity oxy fuel (HVOF)*, or *high-velocity air fuel (HVAF)* and *detonation-gun*, or (*D-gun*), spraying processes. HVOF, in which the sprayed particle velocities can reach up to 650 m/s with temperatures in the range of 2000 °C, are used to spray metals, cermets, and a few ceramics. Attention must be given to avoid in-flight particle oxidation or partial decarburization which can significantly affect the quality of the coating. This can be achieved using HVAF due to the higher particle velocities and lower particle temperatures achieved compared to HVOF. The increased particle kinetic energy gives rise to increased particle plastic deformation with harder substrates compensating for the lower particle temperatures.

The second group, which evolved rapidly over the past few decades, is *electric discharge-based* technologies include *atmospheric and vacuum plasma spraying* (*APS and VPS*), wire arc spraying (WAS), and *plasma transferred arc (PTA)* deposition. The central part of these system is either a direct current (DC) or a radiofrequency (RF) induction plasma torch, which makes use of electrical energy for the generation of a high-temperature, high-velocity plasma stream which serves for the heating, melting, and atomizing the feed material in the spraying process.

Cold spray processes, which make use of a supersonic cold gas flow for the entrainment and acceleration of the spray material in the form of fine ductile particles to velocities between 300 and 1500 m/s, are also covered in this book. While this technology strictly does not belong to either the combustion or electric discharge groups, nor does it conform to the definition of thermal spraying, it is traditionally included as part of thermal spray technologies.

A second level for classification of the thermal spray processes is according to the form in which the coating material is introduced into the energy source, as powder, wires, or rods. As noted in Fig. 1.6 and illustrated in Fig. 1.7, the great majority of the thermal spray processes require that the material be sprayed in powder form. Wire arc spraying, developed in the 1960s for the protection of steel structures against corrosion [Steffens et al. (1990), Marantz and Marantz (1990)], is an exception in this regard since it is limited to the spraying of materials in the form of a wire with the tip of these wires molten by an electric arc struck between two wires, or between a single wire and a fixed hot electrode. A high-velocity gas flow across the arc constantly removes the molten material from the wire tips, breaks down larger droplets into smaller ones in a secondary atomization, and propels them toward the substrate. The wires need to be continuously fed to maintain a constant arc gap. Flame spraying and HVOF, which are combustion processes, are flexible enough to be able to use either powder or wire as feed material.

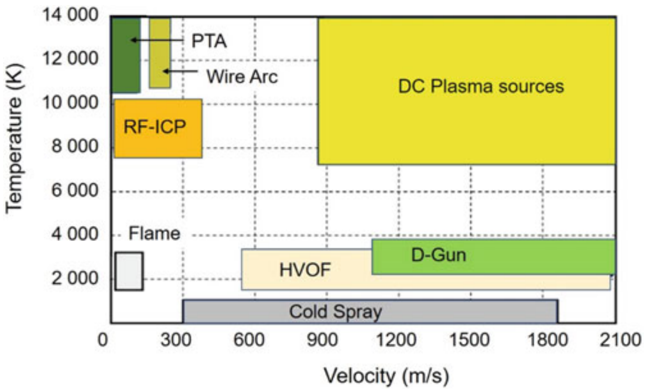

Fig. 1.8 Gas temperatures Vs velocity mapping associated with different thermal spray processes

A further classification of thermal spray processes can be made according to the predominant gas velocity and gas temperature levels in the energy sources used. These are illustrated in the velocity–temperature diagram given in Fig. 1.8. This shows DC plasma sources distinguished by their highest-velocities and highest-temperature range among all thermal spraying processes. Combustion sources, on the other hand, are temperature limited to 3000–400 K while being able to achieve velocities as high as 2000 m/s. RF induction plasma sources offers high temperatures in the 8000–10,000 K, with relatively lower velocities generally below 200 or 300 m/s. With the relatively large volume of RF discharges, they offer high residence time of the particles in the plasma region (of the order 10–15 ms), compared to less than 1 ms for DC sources, which allows for the heating and melting of relatively large particles (>100–200 μm) of most refractory materials ($T_m > 2000$ K). Wire arc spray and PTA are also recognized as being high-temperature sources ($T > 12{,}000$ K) with relatively low-gas velocities.

One must keep in mind, however, that:

- Different materials require different deposit conditions
- Specific coating properties (high density or desired porosity) may require specific particle velocity/temperature characteristics
- The heat fluxes to the substrate vary for the different coating methods and for some substrates the heat flux need to be minimized to eliminate or reduce residual stresses in the substrate
- Substrate preheating and temperature control during spraying strongly influence coating adhesion and residual stresses
- Frequently a trade-off needs to be made between coating quality and process economics

A comparative review of the different thermal spraying processes as part of the broad field of surface modification technologies is presented in Chap. 2. It is clear, however, that every process has some unique features that make it particularly suited for a specific coating application. This makes different thermal spray processes to a large extent complementary rather than competitive for optimum product performance.

1.5 Historical Evolution of Thermal Spray Technology

The invention of thermal spray is credited to M Schoop and his collaborators, who received several patents on various aspects of thermal spray process and successfully commercialized the technology on an industrial scale [Schoop (1910), Schoop 1911, Schoop (1915)]. His impact on thermal spray is well described by Berndt (2001) and Knight (2005) who point out his unique vision of this field at that time and anticipated future developments. In his early patents, Schoop M. U. (1910) describes the atomization of liquid metals by a high-pressure air or inert gas stream, the use of metallic or ceramic powders heated by a flame [Schoop (1911)], the use of wires or rods of various materials in a patent by [Morf (1912)], or a description of the twin wire arc spray process [Schoop (1915)]. It should also be mentioned that Schoop was the first to recognize the importance of the droplet velocity and temperature on the coating formation, e.g., by commenting in anticipation of HVOF and cold spray: "At a gas pressure of 20 atmospheres, for example, coatings are produced, the density and hardness of which are above normal values; at a gas pressure of only 5 atmospheres the density and hardness are below normal values" [Schoop (1910)]. While thermal spray technology was developed in the beginning of the twentieth century, the technology was limited essentially to flame spraying. In the mid-1950s, the first plasma spray torch was developed by Thermal Dynamics Corporation, followed by Metco and Plasmadyne, who developed the basis of the torch designs currently used in this field. Figure 1.9 [courtesy of Oerlikon Metco] illustrates

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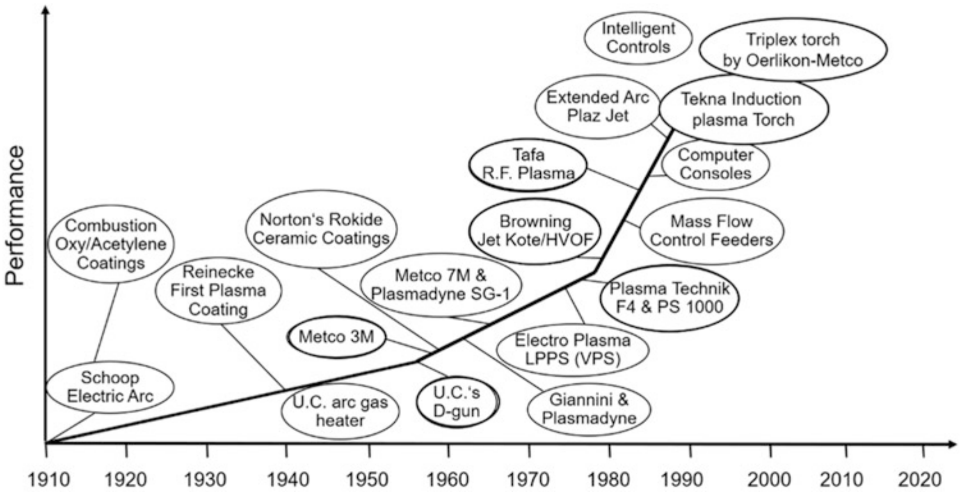

Fig. 1.9 Milestones in the development of the thermal spray industry. [Reproduced with kind permission of Oerlikon Metco Corp]

the evolution of thermal spray technology turning points in plasma torch designs used in the thermal spray industry over the past 100 years.

The requirements for new materials in the aeronautical and space industries led to a rapid development of thermal spray technology in the 1960s. Since then there has been an accelerating pace of developments for spray coating devices and processes, materials, process diagnostics and controls, and new applications. The 1970s saw the development of low-pressure plasma spraying and of induction plasma spraying, of HVOF, and of many process improvements. A trend was pursued to extend the process conditions to higher particle velocities and lower particle temperatures, through the introduction of HVAF and eventually that of cold spray. The use of coatings spread to more and more industries, and the increased requirements for improved process reliability led to an increase in research and development activities. At the same time, robotic systems were developed for the coating of complex shapes. Thermal spray technology became a truly interdisciplinary field, with research in plasma diagnostics, fluid dynamic modeling, new developments in describing plasma heat transfer, awareness of transient phenomena (instabilities), diagnostics for describing the in-flight properties of individual particles, and lastly the description of the coating formation. This research stimulated the development of more robust torches, as well as sensors, which can characterize properties of particles and of the substrate in the harsh environment of spray booths. These sensors not only allowed unprecedented gathering of information on the influence of process parameters on the particle states; they also set the stage for developing effective online control systems. Among the new torch developments, the torches with multiple cathodes [Zierhut et al. (1998), Barbezat and Landes 2000] or multiple anodes should be mentioned [Dzulko et al. (2005)] as well as the central injection torch [[Moreau et al. (1995), Burgess (2002)]. Induction plasma spraying, or as more commonly known as vacuum induction plasma spraying (VIPS), has attracted increasing attention over the past three decades. At the same time, cold spray technology became part of the family of industrially accepted coating technologies [Gärtner et al. (2006), Irissou et al. (2008)], and strong developments of this technology are continuing. This low temperature deposition process avoids the formation of oxides, and the properties of the deposited films are close to those of the wrought material. The discovery of the special properties of materials consisting of nanometer-sized grains (nanophase materials or nanomaterial) has led to developments of depositing coatings of such materials, either by using powders consisting of nanoparticle agglomerates or by using newly developed techniques of suspension spraying, where droplets of a suspension of nanoparticles are injected into the plasma, or solution spraying, where precursors of nanoparticles are injected as a liquid into the plasma where nanoparticles then nucleate [Fauchais et al. (2011)]. A separate chapter in this book is devoted to these new developments.

1.6 Thermal Spray Applications

A survey of thermal spray applications in Europe in 2002 is presented in Fig. 1.10 [Ducos and Durand (2001)]. This shows that the earlier domination of aerospace applications (around 50%) is challenged by a significant increase of the use of thermal spray in the automotive and chemical process industries. Such an extension from high added value products, to high-volume production items, is a clear indication of the maturity of the technology and its competitiveness for the opening new markets [Vardelle et al. (2015)]. While such diversification of applications is likely to increase, the main pillars of users of thermal spray are expected to remain the aerospace, automotive, power, and chemical industries [Vardelle et al. (2016)].

One of the main areas in which thermal spray offers significant advantages is substitutions of steel with lighter weight materials such as Al or Mg. The use of aluminum engine blocks in automobiles to reduce the weight is an example for how thermal spray technology can respond to an industrial/societal need. Spray torches have been developed to coat the inside walls of the Al alloy cylinder blocks with materials withstanding the high temperatures and corrosive environment of the internal combustion chamber [McCune Jr. et al. (1993) and Barbezat (2001)]. Another strong driver for expanding thermal spray technology is the need for replacement of wear-resistant hard chrome coatings [Wasserman et al. (2001)]. The main advantages of thermal spray coatings being:

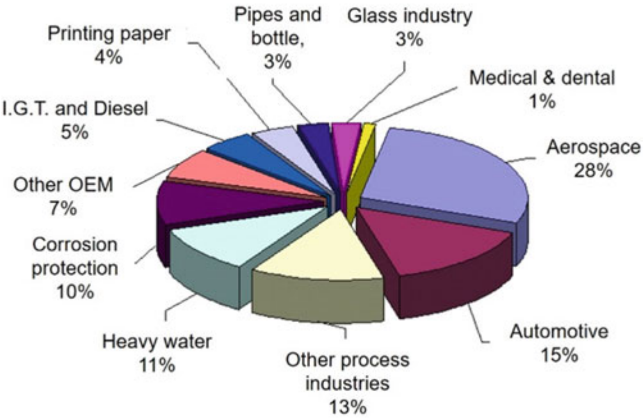

Fig. 1.10 Industrial applications of thermal spray technology in Europe in 2001, after Ducos and Durand (2001). Reprinted with permission of ASM International. All rights reserved

- Reduction of environmental concerns associated with exposure to hexavalent chromium
- Allowing for the deposition of thicker coatings
- Offering improved corrosion resistance and higher fatigue life

cost savings because of higher process productivity, and wider range of materials that can be deposited, having no limitations on the size of the part to be coated, and providing longer life of the coated part.

A comparison of wear resistance of chrome-plated surfaces with surfaces coated by HVOF or plasma spraying demonstrated the advantages of the thermally sprayed coatings in applications in the paper and textile industries. However, it is the large variety of materials that can be chosen for the coatings that are responsible for the continued diversification of the thermal spray market. Ceramic coatings can offer, besides good wear resistance, good tribological properties reducing friction, or can have high acceptance of color ink for printing presses [Wewel et al. (2002)]. Hip or knee or dental implants rely on biocompatible or bioactive coatings that increase the speed of connecting with the bone tissue.

According to Read (2003), the thermal spray market in 2003 was estimated at 3.5 billion USD. Details market distribution given in Table 1.1 show that the service of providing the coatings constitutes 40% of that market, with OEMs another 40% and 20% of the market related to powder sales. It should be pointed out, however, that in several applications, the coating is the "enabling technology" for components with a much larger market value than its actual cost.

Dorfman (2018) point out that a key feature of thermal spray coatings is that they can provide a functional surface to protect or modify the behavior of a substrate material and/or component. A substantial number of the world's industries utilize thermal spray for many critical applications. Key application functions include restoration and repair; corrosion protection; various forms of wear such as abrasion, erosion, and scuff; heat insulation or conduction; oxidation and hot corrosion; electrical conductors or insulators; near-net-shape manufacturing; seals, engineered emissivity; abradable coatings; decorative purposes; and more. Figures 1.11, 1.12, 1.12, 1.13, 1.14, 1.15 and 1.16 provide examples of the diversity of the technology and its industrial applications. Figures 1.11 and 1.12 show the multitude of parts that are coated using thermal spray technology in a jet engine and the automobile industry [Walser (2003)]. Figure 1.13 shows the spray deposition of a coating on a turbine blade and the assembly of coated blades in a gas turbine. Typically, such a blade is coated with at least two layers of different materials. Figure 1.14 illustrates the coating of a large drum used in the paper manufacturing industry, and Fig. 1.15 shows spray-coated spindles used in the textile industry, both coated for reducing wear. Figure 1.16 shows a plasma-coated hip implant which represents a rapidly

Table 1.1 Estimated thermal spray market size in 2003 as compiled by J. Read (2003), reproduced with kind permission of ITSA-Spraytime

OEM/end users	1400 M$ US
Large coating service companies	800 M$ US
Small coating companies	600 M$ US
Powder/equipment sales	700 M$ US
Estimated total market	3500 M$ US

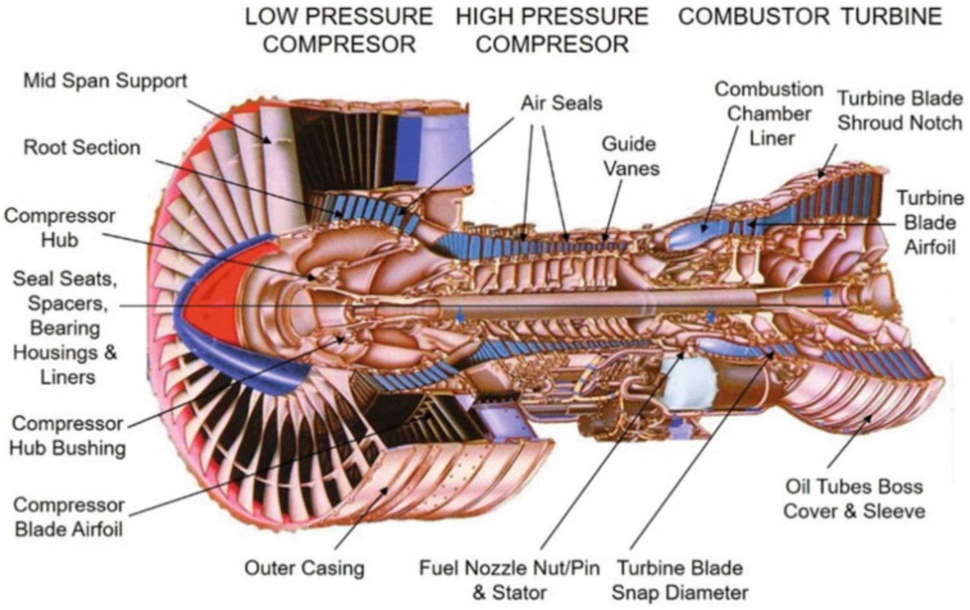

Fig. 1.11 Thermal-sprayed coatings on aircraft turbine engine parts. [Reproduced with kind permission of Oerlikon Metco Corp]

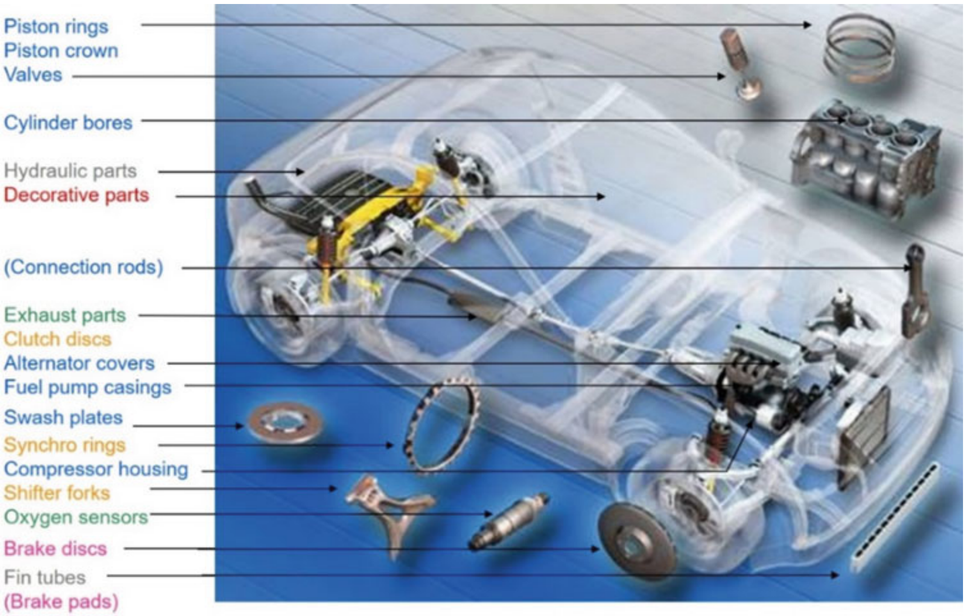

Fig. 1.12 Thermal spray components in the automotive industry. [Reproduced with kind permission of Oerlikon Metco Corp]

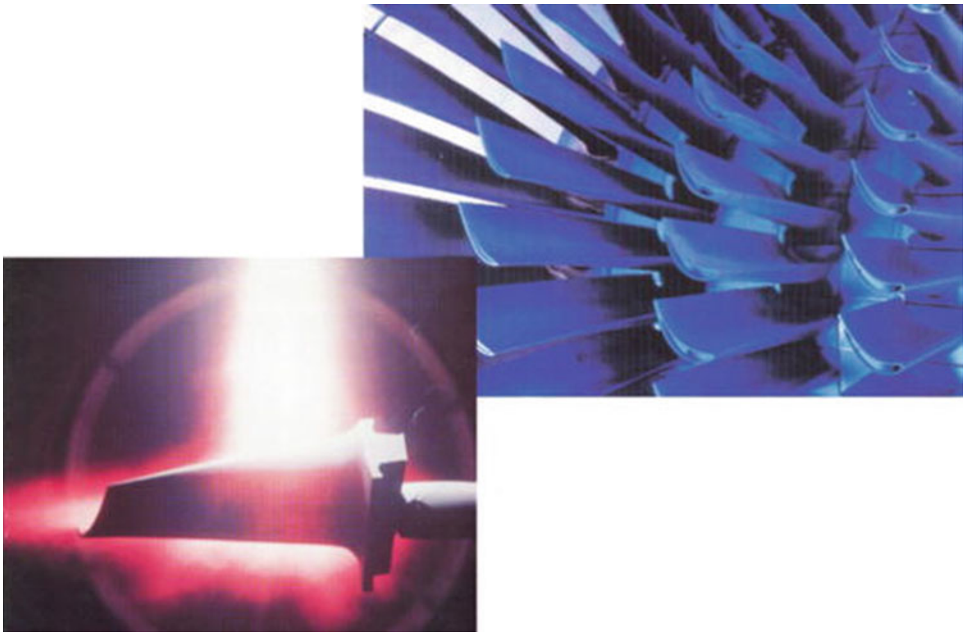

Fig. 1.13 Plasma-sprayed turbine blade coating. [Reproduced with kind permission of Oerlikon Metco Corp]

growing market. A detailed discussion of industrial applications of thermal spray and process economics is presented in Part IV of this book.

1.7 Overview of Book Content

Optimal integration of a thermal spray coating process into an industrial production line requires a fundamental understanding of the basic phenomena involved in the different stages of the process from the initial preparation of the coating material as a powder or wire to the final finishing step of the coated part. In this book, all issues related to producing a part that has the desired surface properties and performance characteristics are discussed. The book is divided into four distinct parts.

Part I covers essentially the fundamental aspects of the technology, with Chaps. 1 and 2 providing respectively brief introduction to thermal spraying and an overview of the vast field of surface modification technologies. Chapter 3 is

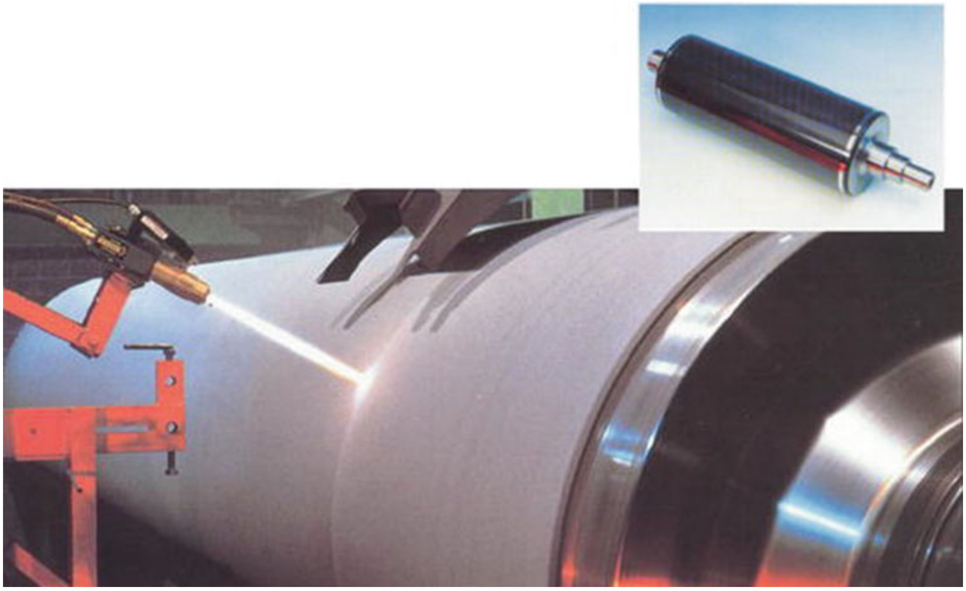

Fig. 1.14 Plasma spray applications in the paper and printing industry. [Reproduced with kind permission of Oerlikon Metco Corp]

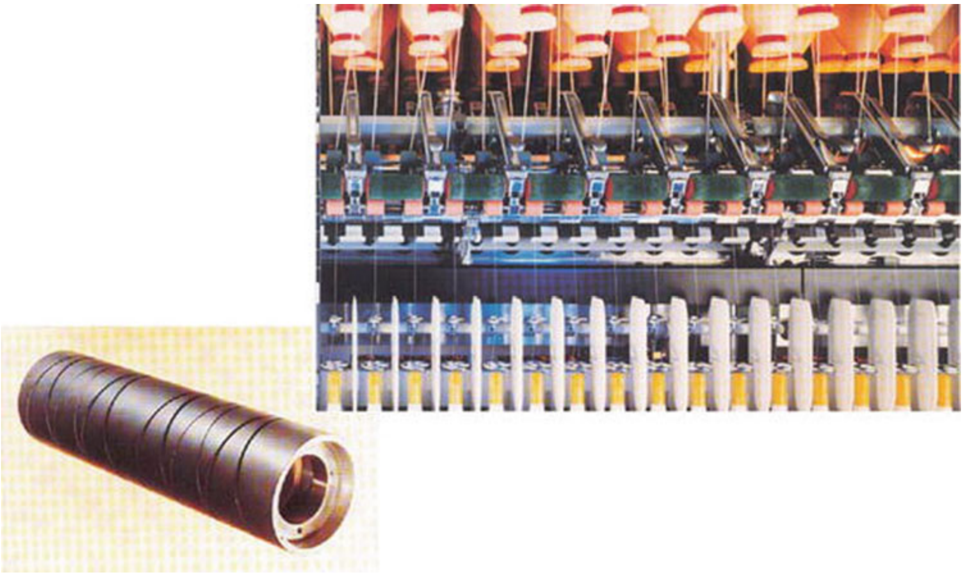

Fig. 1.15 Applications of plasma spray technology for the coating of spools and high wear parts in the textile industry. [Reproduced with kind permission of Oerlikon Metco Corp]

devoted a review of the fundamentals of combustion and thermal plasma generation and its thermodynamic and transport properties. Chapters 4 and 5 deal with the important field of transport phenomena under plasma conditions and plasma–particle interactions which are at the core of the thermal spray process in order to insure the proper entrainment and in-flight heating and melting of the coating materials in the combustion or plasma stream prior to its impact on the substrate. Examples are provided to understand and control the particle trajectories and their thermal histories in a flame or plasma-spraying operations.

Part II of this book is devoted to a detailed description of the different thermal spray deposition techniques. In Chap. 6, an overview is given of the "cold spray process" which while not being a "thermal spray process" is included in this book because of its complementarity to other thermal spray coating processes. Combustion-based thermal spray processes are described in Chap. 7, while atmospheric and vacuum DC and RF induction plasma-spraying technologies are described in great details in Chaps. 8, 9, and 10. Wire arc spraying (WAS) and plasma transferred arc (PTA) deposition are presented in Chaps. 11 and 12, respectively.

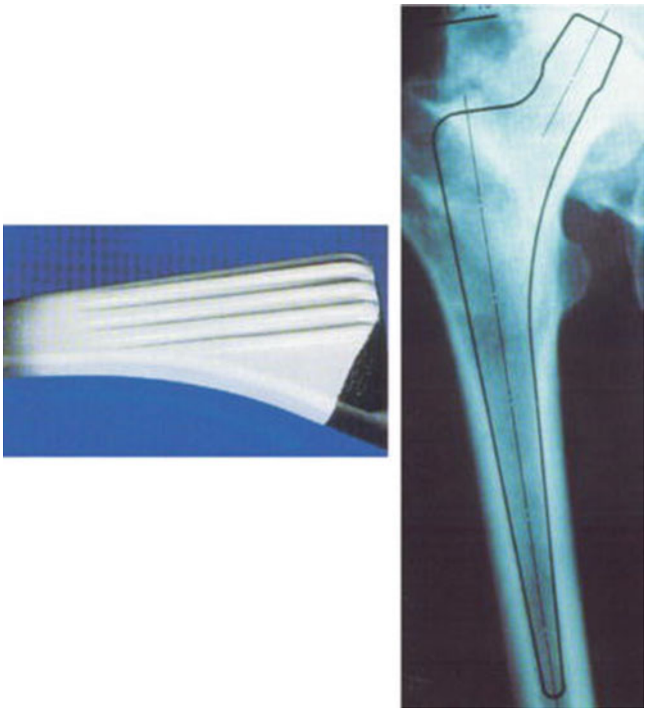

Fig. 1.16 Medical applications of plasma spray technology for the coating of hip and dental implants. [Reproduced with kind permission of Oerlikon Metco Corp]

Part III is devoted to a detailed discussion of coating formation and characterization, with Chaps. 13 and 14 dealing, respectively, with the important issues of preparation of the coating material to be used in the spraying process and substrate surface preparation. Over the past decade, significant progress has been made in understanding the details of the coating formation process, through modeling and sophisticated experimental studies. A detailed review of process fundamentals is provided in Chap. 15 including splat formation and coating buildup. The relatively new area of the spraying of nanostructured coatings using either agglomerated nanoparticles, suspension, or solution plasma-spraying techniques is discussed in Chap. 16. Chapter 17 is devoted to a review of various analysis techniques used to characterize the coatings and to describe both their material and functional properties.

Part IV, the final part of this book, is devoted to process integration and industrial applications. A description of ancillary equipment's such as spray booth design, powder feeders, and robotics for spray torch and substrate manipulation needed for the safe and efficient operation of the process in an industrial environment is presented in Chap. 18. This chapter also covers the important topic of health and operator safety concerns and a brief discussion of coating post treatment and finishing steps. Process instrumentation and online controls which have been the subject of significant developments in recent years are discussed in Chap. 19, while Chap. 20 is devoted to an overview of present and potential industrial applications of thermal spray technology including criteria for the selection of the coating process and materials as well as preliminary process economic analysis.

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