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Review of the physicochemical properties and associated health effects of aerosols generated during thermal spray coating processes

James M Antonini, **Walter G McKinney**, **Eun Gyung Lee**, **Aliakbar A Afshari**

Health Effects Laboratory Division, National Institute for Occupational Safety and Health, Morgantown, WV, USA

Abstract

Thermal spray coating is a process that applies a molten metal product under pressure onto a surface. Although thermal spray processes have been used for decades, exposure to aerosols formed during thermal spray coating is an emerging risk. Reports indicate that high concentrations of aerosols composed of toxic metals (e.g. chromium) are generated in the workplace. A knowledge gap exists related to the physicochemical properties of thermal spray coating aerosols as well as any potential associated health effects. The objective of this manuscript was to review thermal spray coating and previous studies that have examined the aerosols produced from this process. A thermal spray coating generator and exposure system is also described that has recently been developed to further evaluate the physical and chemical properties of aerosols formed during thermal spray coating as well as to assess the possible health effects of this process in an effort to mitigate potential occupational health hazards related to the industry.

Keywords

Thermal spray coating; metals; particulates; particle size

History of thermal spray coating

Over 100 years ago in the early 1900s, Dr MU Schoop and colleagues developed processes and equipment for producing coatings using powder and molten metals (Degradation Group, 2020; International Thermal Spray Association, 2020). In 1912, they patented the first instrument used for spraying solid metal in wire form as a coating onto surfaces. The discovery was based on the principle that if a wire rod was fed into a concentrated flame, the wire rod would melt, and the resulting atomized molten metal could be propelled onto a surface by a stream of compressed gas to create a coating. The process was originally

Corresponding author: James M Antonini, Health Effects Laboratory Division, National Institute for Occupational Safety and Health, 1095 Willowdale Road, Mailstop 2015, Morgantown, WV 26505, USA. jga6@cdc.gov.

Authors' note

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Declaration of conflicting interests

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referred to as metallizing. Currently, the technique is known as thermal spray coating. In the 1950s and 1960s, other major thermal spray processes were developed, including wire spraying, detonation gun deposition, plasma spray, and high-velocity oxygen fuel (HVOF) (Degradation Group, 2020).

Description of thermal spray coating

Thermal spray coating is currently defined as a surface treatment process that enables different types of materials to be deposited on various substrates, including metals, metal alloys, plastics, and ceramics (ASM Thermal Spray Society, 2020). The process involves spraying a liquid or molten metal coating product that is melted by extremely high temperatures (e.g. 2600–16,000°C) and then sprayed under pressure onto a surface where it solidifies and forms a coating (Oerlikon Metco, 2016). The thermal spray processes include the substrate to be coated and the coating material. Suitable substrates are materials that can withstand intense propulsion processes that roughen the surfaces to be coated. The coating material can be in a wire or powder form and can be any material that will not degrade when melted. Most coating materials are composed of variety of metals or metal alloys (Table 1). When heated, the molten metal coating particles impact the roughened surface at high speeds, causing the particles to deform, flatten, and spread out over the substrate upon impact (Figure 1). The hot particles transfer heat to the cooler substrate, shrink, and solidify, forming a tight bond to the roughened base material.

Thermal spray processes are relatively simple to use, economical, and have coating properties that are beneficial to applications across all industrial sectors (Table 2) (ASM Thermal Spray Society, 2020). Important uses include coatings for wear prevention, repair and restoration, thermal insulation or conduction, corrosion and oxidation resistance, seals, decoration, and manufacture of freestanding components, spray-formed parts, and nano-enabled materials. Workplace exposure to aerosols formed during thermal spray operations is likely to increase from 6.5 billion dollars to 17 billion dollars from now to 2027 as the global thermal spray coating market expands (ASM Thermal Spray Society, 2020; Grand View Research, 2020). Increased need for corrosion-resistant coating in aerospace, automotive, and industrial gas turbines is expected to fuel global demand during the coming years. An estimated 146,350 workers were employed as coating and spraying machine setters and operators in 2019 (U.S. Bureau of Labor Statistics, 2019). The number of workers in the spray coating industry is expected to grow significantly as demand for thermal coating increases.

Thermal spray processes

There are two basic methods used to generate thermal spray coating—combustion and electric energy processes. The three common processes associated with combustion methods are flame spray, HVOF, and gun detonation. Detonation and HVOF spray coating result in high bond strengths and extremely dense microstructures (Oerlikon Metco, 2016). Plasma spray and arc wire spray are the two most common processes that use electric energy to melt consumables. Plasma spray coating methods result in high bond strengths and mostly dense oxide-free microstructures (Oerlikon Metco, 2016).

Combustion processes

Flame spray (wire/powder).—In this process (Figure 2(a) and (b)), a combustible gas, such as acetylene, propane, or hydrogen, serves a heat source that melts a coating material, either in wire or powder form, that is fed concentrically into a flame (ASM Thermal Spray Society, 2020; Oerlikon Metco, 2016). Compressed air directs the molten material toward the workpiece surface that is to be coated. Flame spray coating processes are characterized by efficiency, high deposition rates, ease of operation, and low equipment costs (ASM Thermal Spray Society, 2020). This process is often used for reclamation of worn parts, frequently using nickel-based, bronze, zinc, and tungsten carbide alloys.

High-velocity oxygen fuel.—In this process (Figure 3), fuel gases of propylene, propane, hydrogen, or natural gas, as well as liquid fuels such as kerosene, are mixed with oxygen and burned in a chamber (ASM Thermal Spray Society, 2020; Oerlikon Metco, 2016). The combustion products expand through the nozzle of a gun sprayer in which gas velocities become supersonic. Powder is added to the nozzle, heated, and then accelerated to a velocity of up to 700 m s^{-1} (ASM Thermal Spray Society, 2020; Oerlikon Metco, 2016).

Detonation.—In this process, a mixture of acetylene and oxygen, together with a pulse of powder, is added to a barrel and detonated by a spark. The high pressure and high temperature of the denotation wave moving through the barrel heats the powder above its melting point and accelerates the molten particles to a velocity in a range of 750–1000 m s^{-1} (ASM Thermal Spray Society, 2020). The detonation coating process has the highest bonds strengths and lowest porosities of the different thermal spray methods. Nearly all metallic and ceramic materials can be deposited using denotation coating processes.

Electric energy processes

Electric arc wire spray.—As opposed to other coating processes that use an external heating source, such as a gas flame or plasma, electric arc wire spray coating (Figure 4) uses an arc formed by contact of two electrically opposed, charged metallic wires, most often of the same material and usually of the same composition (ASM Thermal Spray Society, 2020; Oerlikon Metco, 2016). The arc melts the wire tips, and compressed air atomizes the melted material and accelerates it onto the substrate surface to be coated. The electric arc wire spray process is generally inexpensive with low energy requirements and is widely used for high volume, low cost applications (ASM Thermal Spray Society, 2020).

Plasma spray.—This process (Figure 5) uses superheated gas, such as argon, nitrogen, hydrogen, or helium, that flows between an anode and a tungsten cathode (ASM Thermal Spray Society, 2020; Oerlikon Metco, 2016). A high-frequency arc is formed and ionizes the gas that creates a high-pressure plasma plume that can reach temperatures as high as 16,000°C (Oerlikon Metco, 2016). The spray coating material is introduced into the plasma as a powder where it is melted and propelled onto the surface to be coated. The powder velocity in plasma spray coating deposition can range from 300 m s^{-1} to 550 m s^{-1} (ASM Thermal Spray Society, 2020). Plasma spray coating is widely used in the aircraft engine industry and can be used with nearly any metallic or ceramic material.

Cold spray.—This is a newer coating process that relies more on kinetic energy and high velocity compared to thermal energy like the other processes. Particle temperatures are generally lower, but the velocities are much higher, producing coating structures that more resemble the bulk manufactured material (ASM Thermal Spray Society, 2020). The distinguishing feature of the cold spray coating process compared to others is that its carrier gas temperature (0–700°C) is lower than the melting temperature of the coating particle material. It is a solid-state method as the generated coating particles are not molten during the spraying process. The adverse effects related to high-temperature thermal spray processes such as oxidation, recrystallization, evaporation, and residual stress are minimal with cold spray coating. Materials used during cold spray coating include metals (especially copper), ferrous and nonferrous alloys, cements, and other composites.

In all metal spray coating processes, large quantities of aerosols composed of mostly fine and ultrafine metal particles are generated, which likely present a serious risk to the operator who in many cases still performs the spraying process manually. The generated particles in thermal spray coating are often composed of potentially toxic metals, such as chromium, nickel, cobalt, zinc, and aluminum. Information about the physical (e.g. particle size and morphology) and chemical (e.g. metal composition, solubility, and surface chemistry) properties of the aerosols formed during different spray coating processes is lacking. Even less is known about the adverse health effects associated with exposure to aerosols generated during thermal spray operations.

Exposure concentrations and physicochemical properties of thermal spray particles

Exposure and particle size and morphology

Published studies examining the physical characteristics of aerosols formed during thermal spray coating are limited. Industrial hygiene groups in different metal industries have reported hexavalent chromium exposures “as high as they have ever measured (>500 μg/m^3) in an open air work area that approached 100 times the OSHA permissible exposure limit of 5 μg/m^3” (A. Siert, Xcel Energy, February, 2017; personal correspondence) and “measured to be 20-40 times higher than the permissible exposure limit for a 12-hr work shift” (L.P. Dutton, Work Environment Associates, June, 2008; personal correspondence).

Bemer et al. (2010) evaluated the emission rates and particle size distribution of aerosols generated by electric arc and flame spray processes. Extremely high emission rates were observed, especially for electric arc spray coating, that far exceeded those encountered during arc welding. Concentrations greater than 10^8 particles cm^{-3} were recorded inside a well-ventilated cabin. In agreement with this finding, Huang et al. (2016) observed a time-weighted average concentration of 34.2 mg m^{-3} with a highest total dust concentration measurement of 140 mg m^{-3} during HVOF spray coating in a workshop in China that far exceeded local exposure limits by 4 and 8 times, respectively.

In assessment of air quality in a thermal spray facility in Greece, portable air samplers using quartz fiber filters worn by workers for 8 h day^{-1} for 30 working days (not including weekends) indicated that total particle and specific metal concentrations were below the established Greek workplace limit of 10 mg m^{-3} for an 8 h day^{-1} (Petsas et al., 2007). The investigators believed this was most likely because of work using closed and well-ventilated systems. Average total suspended particle concentrations of 4.363 mg m^{-3} (range 0.192–96.129) and 2.175 mg m^{-3} (range 0.176–22.447) were measured from two different samplers, respectively. For the first sampler, there was one significant transgression (96.1 mg m^{-3}) of the exposure limit. This measurement was observed at a time when cleaning and maintenance activities were performed in the thermal spray booth. For the second sampler, there were two measurements over the exposure limit. One (22.447 mg m^{-3}) was recorded during maintenance and cleaning activities of the spray booth, whereas the other (12.405 mg m^{-3}) was recorded during at time period when spraying took place out of the booth, despite efforts to provide adequate ventilation.

Because of the high particle number, the aerosols were observed by Bemer et al. (2010) to be highly unstable due to coagulation, and the physical properties of the aerosol changed quickly during transport from the generation point to the sampling device. Similar observations have been demonstrated with welding fume as their physical characteristics have been shown to dynamically change based on time after particle formation (Zimmer and Biswas, 2001) as well as selection of processes and settings (Petsas et al., 2007). During thermal spray coating, Bemer and colleagues (2010) observed the aerosol using an electrical low-pressure impactor and condensation nucleus counter to be mostly in the submicron size range with 85–90% of the particles less than 100 nm. In agreement, Salmatonidis et al. (2019) observed 90% of the particles formed during HVOF and atmospheric spray of ceramic coatings using feedstocks of different compositions to be between 26 nm and 90 nm.

In a similar study, Viana et al. (2017) also observed significant ultrafine particle formation when examining workplace exposure during atmospheric plasma spray coating using micron-sized powders and suspensions containing submicron- or nano-sized particles as feedstock. Substantially elevated concentrations of particles less than 100 nm as high as 3.3×10^6 cm^{-3} and 8.3×10^5 cm^{-3} were measured inside the spraying chamber and in the worker area outside the chamber, respectively. Importantly, ultrafine particle generation was detected during the use of both micron-sized powders and suspensions containing different sized particles, suggesting that emissions formed during plasma spray coating were likely dependent on the process and not the material.

In a recent study, the morphology of particles generated during thermal spray process using scanning electron microscopy (SEM) was observed to be similar to that of welding fumes (Figure 6). In assessment of aerosols generated during electric arc spray coating using a stainless-steel wire (PMET 720; Polymet Corporation, West Chester, Ohio, USA), most particles were arranged as chain-like agglomerates of primary particles in the ultrafine or nanometer-size range (<100 nm). Much larger, more spherical particles and cylinder-like structures also were observed. Using a micro-orifice uniform deposit impactor (MSP Model 110; TSI, Incorporated, Shoreview, Minnesota, USA) to assess particle size distribution, the mass median aerodynamic diameter was found to be 0.35 μm with a geometric standard deviation of 2.2 during 2 min of spray coating (Figure 7). These observations were mostly confirmed previously by Bemer et al. (2010) as they observed both nanometer-size primary particles and micron-size agglomerates using SEM to assess particles formed during electric arc spray coating using a zinc wire. Also, Huang et al. (2016) observed that particle morphology varied with different sizes during HVOF spray coating. Particles greater than 5 μm in size mainly existed singly and were irregular in shape, whereas spray coating particles in the size range from 1 μm to 5 μm generally existed as aggregates composed of mostly spherical particles. The smaller HVOF spray particles below 1 μm in size were described as "flocculent agglomerates."

Examining different thermal spray coating processes in a worker exposure area, Salmatonidis et al. (2019) observed irregular-shaped, metal-containing particles as both single primary particles and aggregates that ranged in size from 5 nm to 200 nm. In a separate study, Salmatonidis et al. (2020) demonstrated that ultrafine particles smaller than 90 nm that were generated by different spray coating processes exhibited hygroscopic factors in a nonuniform way. They observed the formed particles were irregularly shaped at dry conditions and then underwent a shape change upon humidification. The hygroscopicity of the sampled spray coating particles was significantly lower than those of the ambient background particles present in the breathing air.

The observation that ultrafine or nanometer-size particles are formed during thermal spray coating process is important. Animal toxicology studies have shown that ultrafine particles of similar composition when compared on a mass basis were more pneumotoxic (Brown et al., 2001; Oberdörster et al., 1992) and have an elevated lung deposition (National Institute for Occupational Safety and Health, 2007; Oberdörster et al., 2005) compared to their larger-sized counterparts. Importantly, the individual metals associated with nanoparticles formed during welding have been observed to translocate from the lungs to the circulation and other organs, such as the liver, heart, kidney, spleen, and discrete regions of the brain (Antonini et al., 2010).

Particle metal composition

Preliminary studies indicated that the metal profile of the generated particles closely resembled the composition of metal feedstock that was consumed in the spray coating process, according to the manufacturer's specifications. The metal profile of the particles formed during electric arc spraying using PMET 720 stainless steel wire was 80% iron, 17% chromium, and 3% manganese with trace amounts of nickel and copper as determined by inductively coupled plasma–atomic emission spectroscopy. Changes in the metal profile ratio were observed when different spray coating processes and parameters were selected. Using energy dispersive X-ray analysis, Salmatonidis et al. (2019) confirmed the presence of specific metals that originated from the coating material in a separate study that examined different thermal spray coating processes and feedstocks, establishing a direct link between the spraying activity and exposure. These findings were similar to what was previously reported with welding fume characterization in which the ratio of specific metals (e.g. chromium and manganese) could be altered by changing the selections of different weld process parameters (Antonini et al., 2011; Keane et al., 2012; Sriram et al., 2015). In the assessment of valence state, Huang and associates (2016) observed by X-ray photoelectron spectroscopy that the metal elements of the spray coating particles in a thermal spray workshop were mostly in the form of oxides (e.g. Cr_2O_3, Fe_2O_3, and ZnO). In addition, intermetallic compounds also were observed in the formed particles, such as NiAl and FeAl, due to chemical reactions between specific elements and complex metal compounds generated during the spray coating process.

Health effects associated with exposure to aerosols from thermal spray coating

Documented information about the health effects related to exposure during thermal spray coating is lacking, although workers in the industry may be exposed to a variety of potentially toxic metals (Table 3). One death was reported in 2003 after a worker spent 2 days applying nickel- and chromium-based thermal spray coating at a temporary worksite in the state of Washington (Washington State Department of Labor and Industries, 2005). The worker developed progressive symptoms of cough, shortness of breath, and fatigue. He died a short time later, and a postmortem examination revealed severe lung damage associated with toxic metal inhalation. It was determined the victim was overexposed to chromium and nickel and had applied thermal metal sprays without using proper ventilation and an appropriate respirator.

In a biomonitoring investigation, Chadwick et al. (1997) used a cross-sectional design of 34 workers performing thermal spray coats at six worksites in the United Kingdom to determine exposure and biological uptake of metals during different metal spray activities. Exposure levels of chromium, nickel, and cobalt were highest when using plasma spray processes, and exposure at times exceeded local occupational exposure limits. However, metal exposure levels during electric arc spray and detonation gun coating processes were observed to be below local occupational exposure limits throughout the study period. Urinary levels of nickel and cobalt were highest in workers performing plasma spray coating and mimicked airborne workplace concentrations (Chadwick et al., 1997). Interestingly, urinary chromium concentrations were highest in workers using electric arc spray coating. The investigators concluded that this observation may reflect an increased body burden of chromium due to a longer history of exposure during thermal spray coating (Chadwick et al., 1997).

Because little is known about the associated health effects related to thermal spray coating as airborne levels for specific toxic metals generated during the process have been reported to be many times higher than established exposure limits, a computer-controlled, completely automated thermal spray coating generation and inhalation exposure system was designed and constructed to perform whole-animal studies that would mimic workplace exposure conditions (Figure 8). A rotary motor rotates the stainless steel pipe in circular and up-and-down directions to allow for continuous, sequential coating during specified periods of time within an enclosed chamber (Figure 9). Aerosols generated during thermal spray coating are delivered to an animal exposure chamber. Ports are used for gravimetric sampling pumps to determine particle concentration using cassettes with 47-mm filters installed inside the chamber. Additional ports are located on the top of the chamber and used to measure chamber pressure and to collect additional particle samples for size distribution, chemical composition, and electron microscopy analysis. The temperature and relative humidity inside the exposure chamber also are measured. The mass concentration in the chamber is monitored by a real-time aerosol monitor (DataRAM, MIE, Inc. Bedford, Massachusetts, USA). To maintain a constant particle concentration in the exposure chamber, programmed computer software takes readings from the DataRAM and automatically adjusts the time between each circular coat made on the steel pipe.

With this system, the generated aerosols from thermal spray coating processes are collected in the breathing zone of the laboratory animals and characterized. Importantly, standard lung function tests are performed to monitor exposed animals for changes in pulmonary function as well as assess adverse pulmonary and systemic effects (e.g. cardiovascular, neurological, and immune) associated with exposure to thermal spray aerosols. The findings from this study may impact thousands of workers by providing new information related to the possible health effects of thermal spray coating, which could possibly lead to interventions and, hopefully, mitigate potential occupational health hazards associated thermal spray exposure. Importantly, proper ventilation, including both local exhaust and general ventilation systems, is vital to preventing the respiratory hazards associating with thermal spray coating activities. Also, it is strongly recommended that a respiratory protection program is established that includes regular medical screening of workers, job training, and selection and fitting of appropriate respirators.

Conclusions

Exposure to aerosols formed during thermal spray coating is an emerging risk as significant numbers of workers are employed in a global market expected to equal 15 billion dollars in the coming years. A knowledge gap currently exists related to the physical and chemical characteristics of thermal spray coating aerosols and the associated health effects (Table 4). Respirable-size particles, many of which are in the nanometer or ultrafine size range, are generated during multiple spray coating processes that contain highly toxic and potentially carcinogenic metals. Excessively high airborne concentrations of these metals, that often exceed established workplace exposure limits, have been observed in a variety of occupational settings. Elevated levels of some of these metals (i.e. chromium, nickel, and cobalt) have been measured in biological samples of exposed workers.

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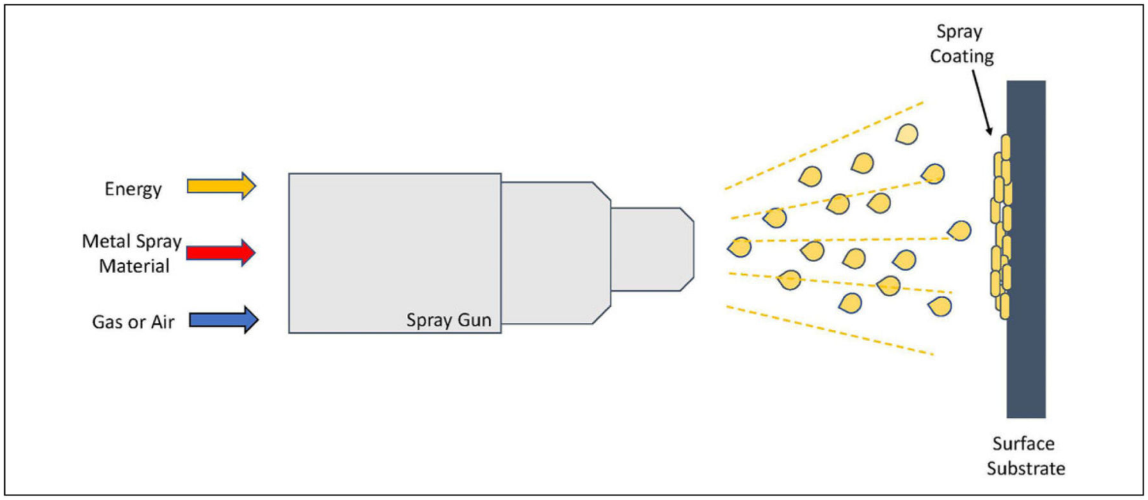

Figure 1.
Principle of thermal spray coating. The process involves spraying molten metal coating product under pressure onto a surface where it solidifies and forms a solid coating.

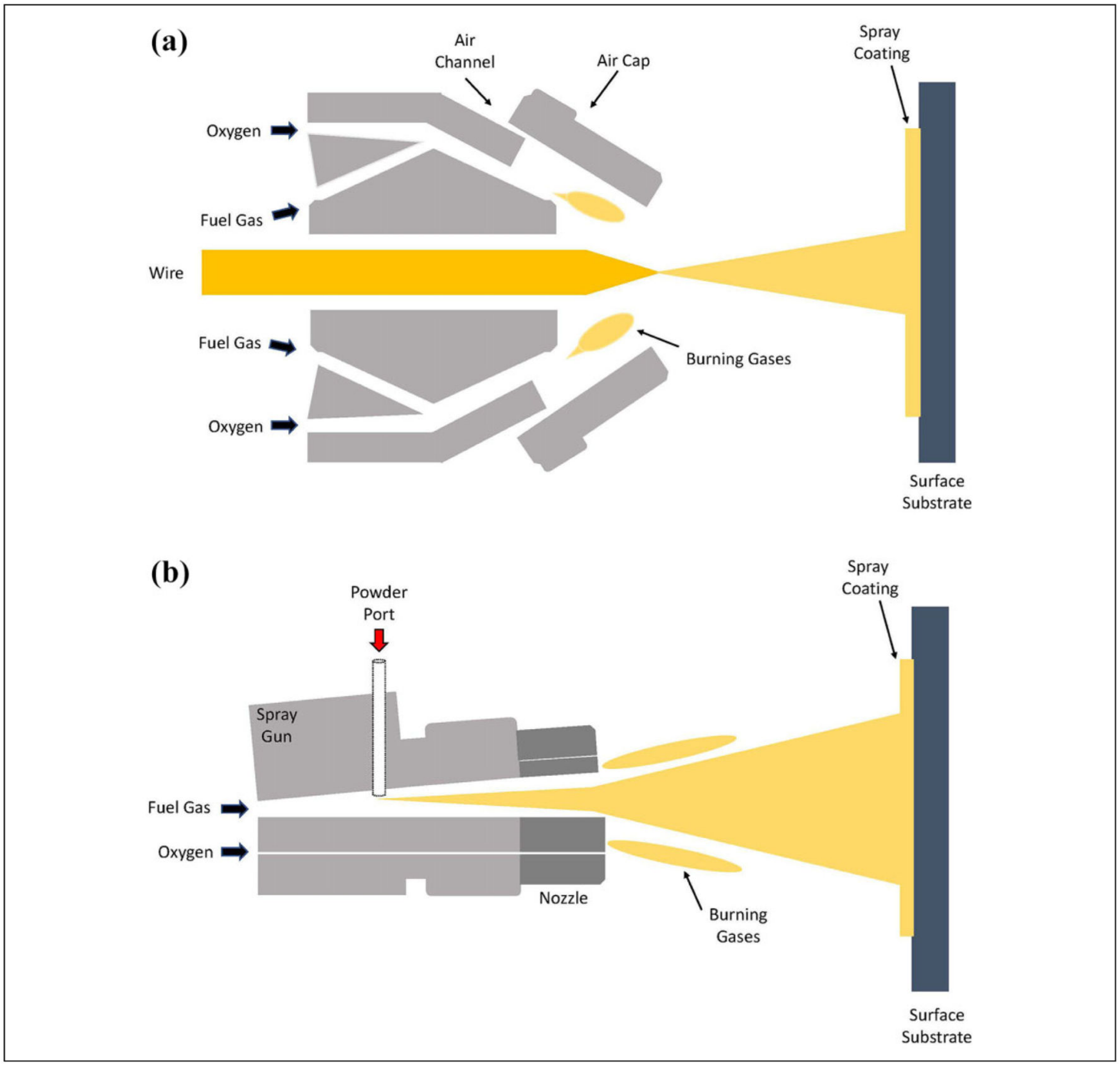

Figure 2.

Thermal spray process: Flame spray (a) wire and (b) powder. A combustible gas serves as a heat source that melts the metal wire (a) or powder (b) that is fed into a flame. Compressed air directs the molten material toward the surface to be coated.

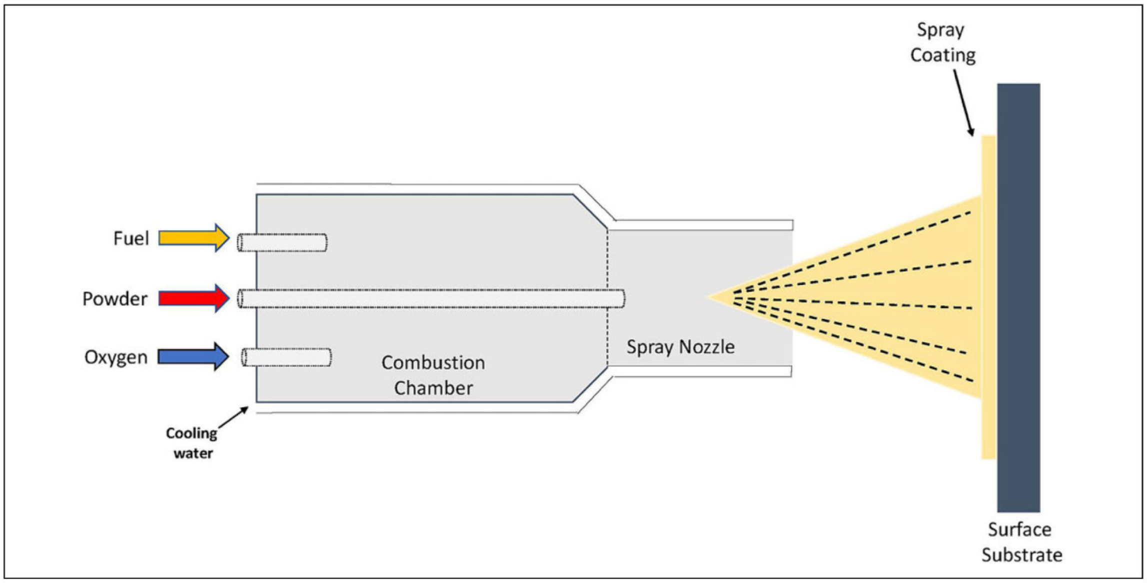

Figure 3.
Thermal spray process: High-velocity oxy-fuel. Fuel gases are mixed with oxygen and burned in a chamber, resulting in expansion of the combustion products through the nozzle of a spray gun and significantly increasing in gas velocity. Powder is added to the nozzle, heated, and then accelerated with the expanding combustion products.

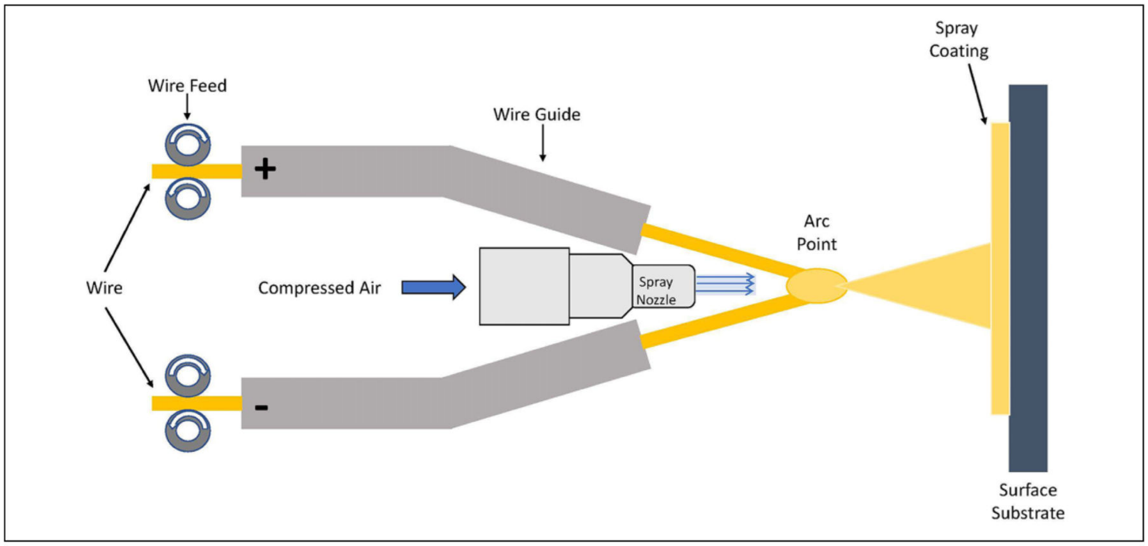

Figure 4.
Thermal spray process: Electric arc wire. An arc is formed by contact of two electrically opposed, charged metallic wires that melts the wire tips, and compressed air accelerates the molten metal onto the surface to be coated.

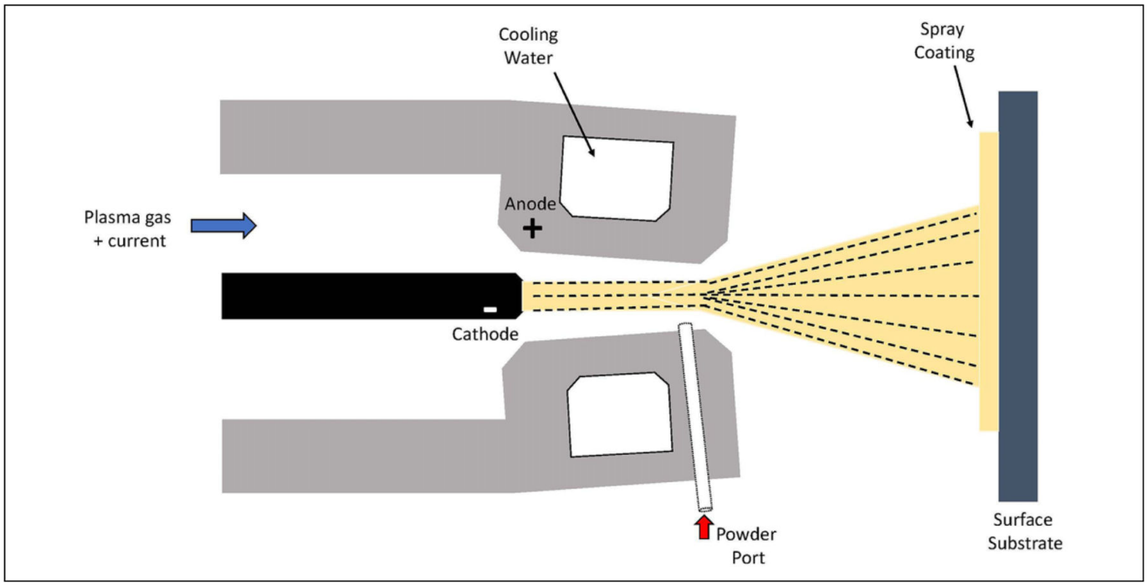

Figure 5.
Thermal spray process: Plasma spray. A high-frequency arc is formed as superheated gas flows between an anode and a tungsten cathode, creating a high-pressure plasma plume. The spray coating material is introduced into the plasma as a powder where it is melted and propelled onto the surface to be coated.

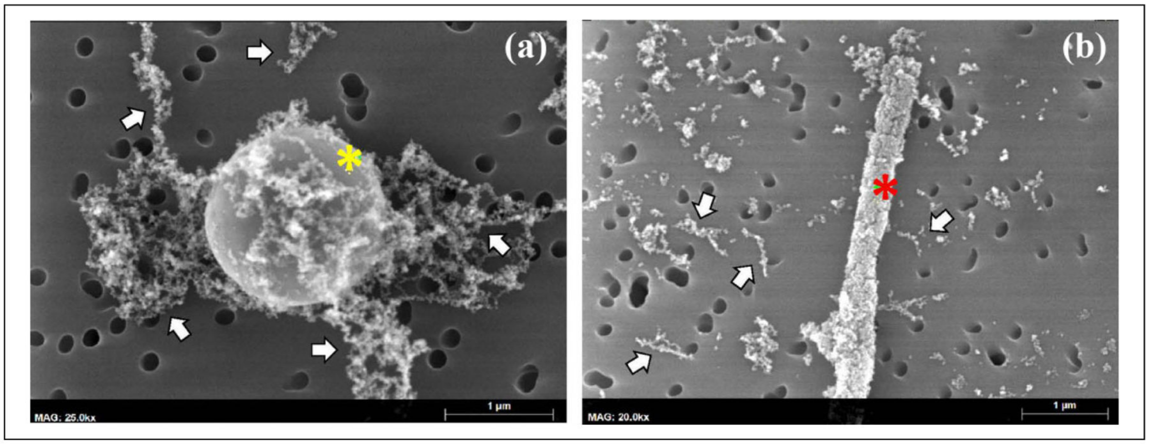

Figure 6.
Scanning electron micrograph of particles generated during electric arc thermal spray coating using a PMET 720 stainless steel consumable wire. The particles were collected on 47-mm filters mounted on aluminum stubs with silver paste and viewed using a Hitachi S4800 filed emission SEM (Bruker, Madison, Wisconsin, USA). In (a) and (b), particles were arranged as chain-like structures of nanometer-size primary particles that had agglomerated together (arrows). Much less numerous but significantly larger, more spherical particles (a) (yellow asterisk) and cylinder-like structures (b) (red asterisk) also were observed. SEM: scanning electron microscopy.

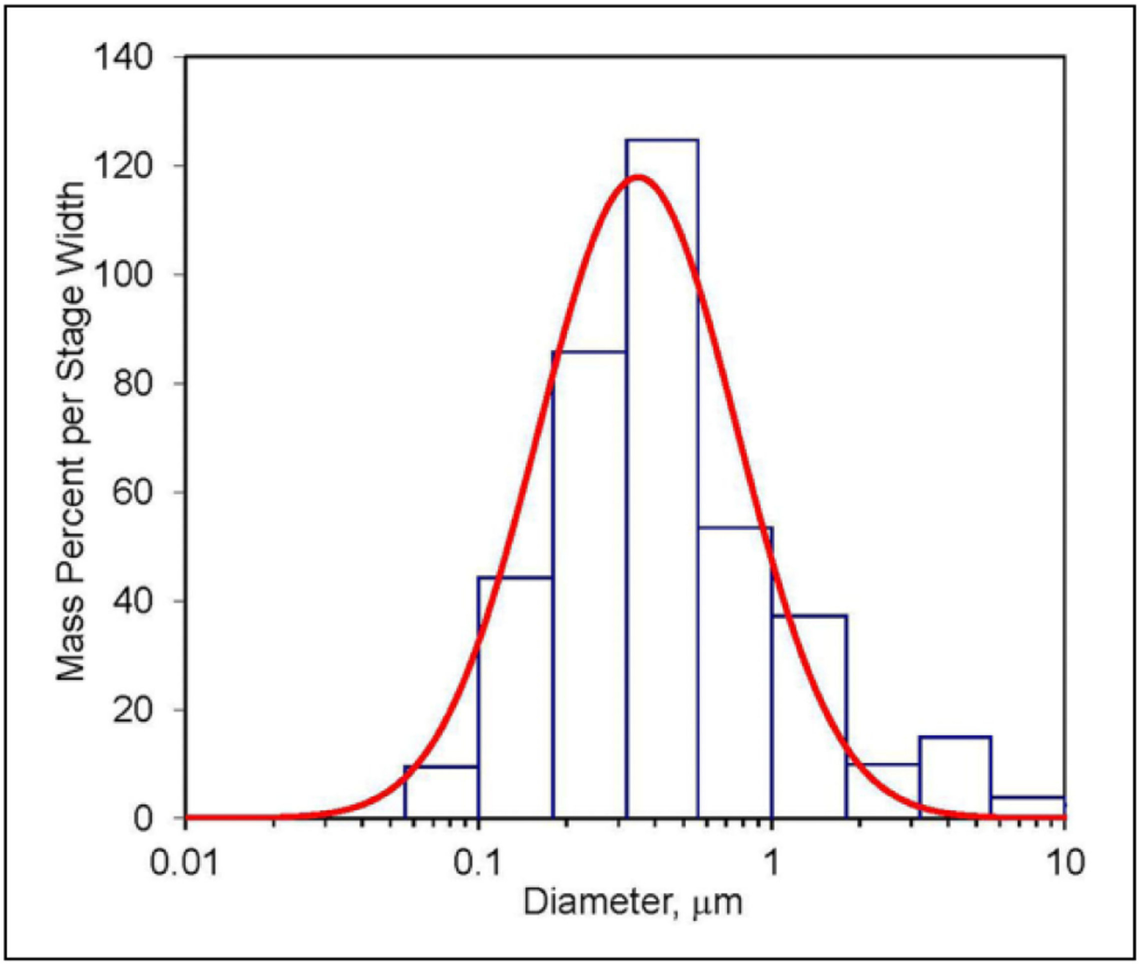

Figure 7.

Representative particle size distribution graph of generated particles during electric arc thermal spray coating using a PMET 720 stainless steel consumable wire. Particles were collected in the size range from 0.056 µm to 18 µm by an MOUDI particle sizer that were separated into eight fractions. The sampling period was for 2 min at 30 L/min (5 L/min of the chamber air and 25 L/min of the diluted air). MOUDI: micro-orifice uniform deposit impactor.

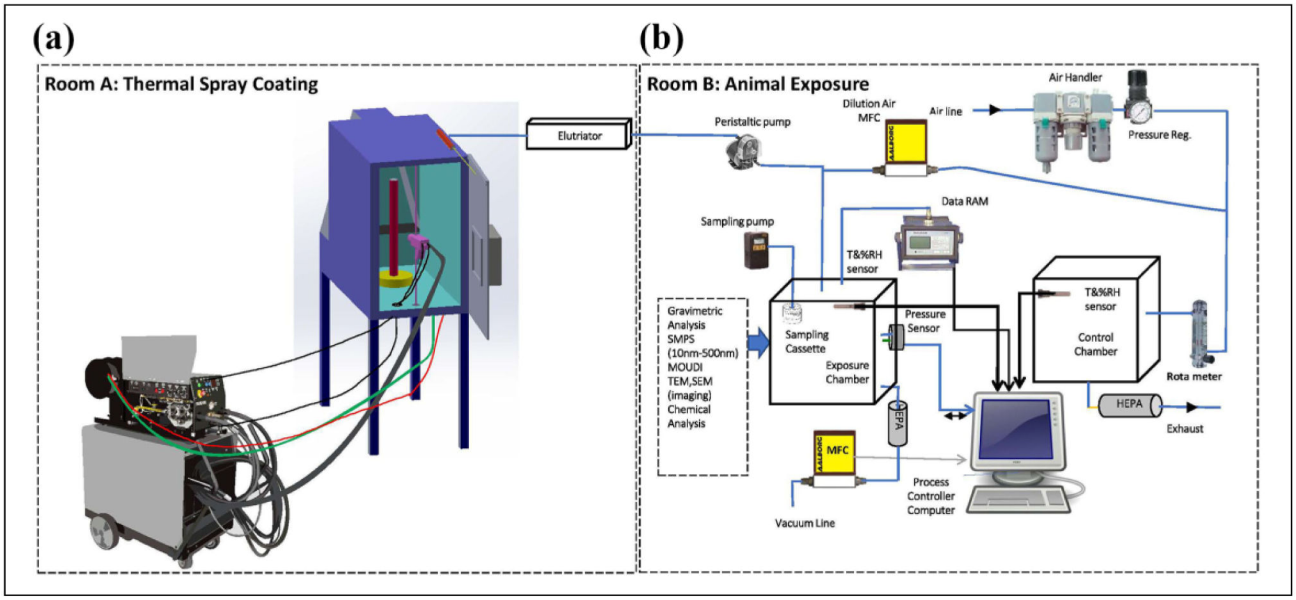

Figure 8.
Schematic design of the electric arc wire thermal spray coating aerosol generation and exposure system. Thermal spray coating will be performed in one room (a), and the aerosols transferred to an exposure chamber in a separate room (b) divided by shaded glass doors (b). Data Ram: real-time aerosol monitor; MOUDI: micro-orifice uniform deposit impactor; SEM: scanning electron microscopy; TEM: transmission electron microscopy; T: temperature; RH: relative humidity; SMPS: scanning mobility particle sizer; MFC: mass flow controller.

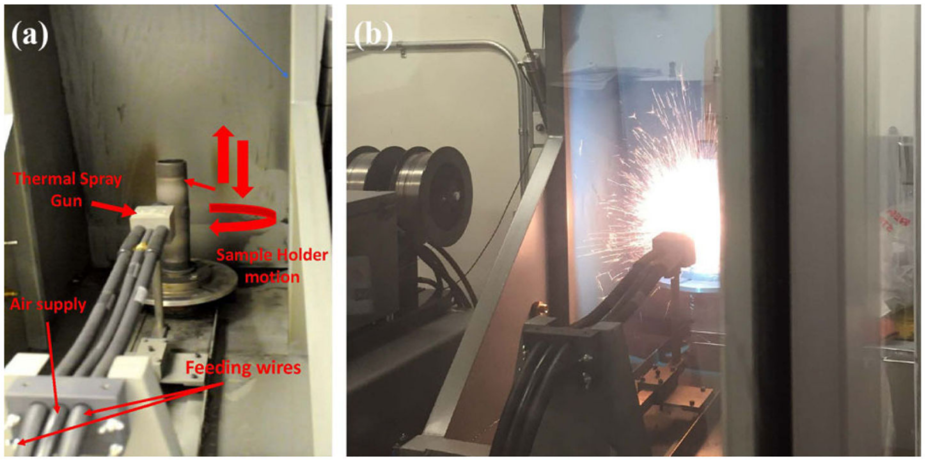

Figure 9.
Image of the steel pipe that will be coated during the thermal spray process, depicting the thermal spray gun, feeding wires, air supply, and directions of motion of the pipe (a). Image of the thermal spray coating process in operation (b). The process will take place in an enclosed hood. The hood is opened in both (a) and (b) to allow visualization of the system.

Table 1.

Common material used as coatings in thermal spray processing.

Materials	Characteristics	Composition examples
Pure metals	Corrosion protection, electrical and thermal conductivity	Zn, Cu, Ti, Al
Steels	Wear resistance, economical	Fe 35N 20Cr 2Si, Fe 28Cr 5C 1Mn, Fe 13Cr
Complex composition	High temperature, corrosion resistance	NiCoCrAlY, NiCrAlY, CoCrAlY
Self-fluxing alloys	High hardness coating, high fusion, wear resistance	NiCrBSiC, NiCoCrBSiC
Carbides	Wear and erosion protection	WC 12Ni, WC 10Ni 5Cr
Oxides	High hardness coating, oxidation and wear resistance	Al_2O_3, Cr_2O_3

Table 2.

Common industries that use thermal spray coating technology.

Industries	Coating application examples
Automotive	Engine and exhaust components
Gas/energy	Turbines
Medical	Orthopedic implants
Aerospace	Turbines, combustion chambers
Textile	Manufacturing machinery equipment
Printing/paper	Rollers
Steel	Rolls
Electronics	Sensors, antennas
Salvage/restoration	Repair
Consumer goods	Frying pans, iron plates

Table 3.

Potentially hazardous constituents of thermal spray coating processes.

Element	Potential hazard concern
Chromium	Lung carcinogen
Cobalt	Respiratory irritant
Copper	Metal fume fever
Iron	Siderosis
Manganese	Nervous system effects, respiratory irritant
Nickel	Lung carcinogen
Zinc	Metal fume fever

Table 4.

Studies of health effects and physicochemical properties of thermal spray coating processes.

Study findings	Study
Elevated urinary concentrations of chromium, nickel, and cobalt in workers during thermal spray coating processes	Chadwick et al. (1997)
Worker death due to severe lung damage caused by toxic metal inhalation during thermal spray coating	Washington State Department of Labor and Industries (2005)
Elevated particle concentrations were observed during cleaning and maintenance activities in a thermal spray coating booth	Petsas et al. (2007)
Emission rates for thermal spray coating process far exceeded those compared to arc welding	Bemer et al. (2010)
Total dust concentrations during spray coating exceeded local exposure limits by four to eight times	Huang et al. (2016)
Elevated ultrafine particle formation was observed inside and outside spray coating chamber	Viana et al. (2017)
Ninety percentage of particles formed during spray coating processes were less than 90 nm	Salmatonidis et al. (2019, 2020)