# 2 Principles of Thermal Spraying

Thermal spraying requires a device that creates a high temperature flame or plasma jet. In the case of a plasma, such a device is called a plasmatron[1], i.e. a plasma generator powered by an arc or a high frequency discharge whose plasma is superposed by streaming gas. A metal, ceramic or even polymer powder is being injected into the fluid medium, melted during the very short residence time in the flame or plasma jet, and propelled towards a target where it solidifies and builds up a solid coating. Any material can be sprayed as long as it has a well-defined melting point, and does not decompose or sublimate during melting.

Figure 2-1 shows the organization of thermal spraying methods [1] divided into the two principal energy sources, *chemical energy* of the combusting gases that power the flame spray torches, and *electric currents* providing energy for the plasmatrons. The plasma spray methods are shown in Figure 2-2. The different techniques are distinguished here by the *surrounding atmosphere*, i.e. air for conventional air plasma spraying (APS) and high power plasma spraying (HPPS), as well as APS with an inert gas shroud to prevent oxidation of oxygen-sensitive powders (SPS), and plasma spray methods relying on special atmospheres, most importantly inert gas plasma spraying (IGPS), vacuum, i.e. low pressure plasma spraying (VPS and LPPS, respectively), and controlled atmosphere plasma spraying (CAPS).

The principal difference between flame spraying and plasma spraying is given by the maximum temperatures achievable. In flame spraying the temperature is limited by the internal heat of combustion of the plasma gases (acetylene, propane, butane). Conventional oxyacetylene torches reach temperatures of around 3 000 K; special devices such as Union Carbide Corporations's (now Praxair Surface Technology, Inc.) D-Gun and Jet Kote System are limited to about 3 500 K, whereas the present limit of the Hypervelocity Oxyfuel Gun (HVOF) seems to be below 3 200 K [1]. The advantage of the latter techniques lies in the exceptionally dense structure of the coatings.

Using electric energy as the source to create the plasma provides for theoretically

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[1] The terms plasma burner, plasma torch, plasma arc torch etc. should be avoided since they convey the inaccurate notion of something burning. Also, the term plasma gun should not be used for obvious reasons.
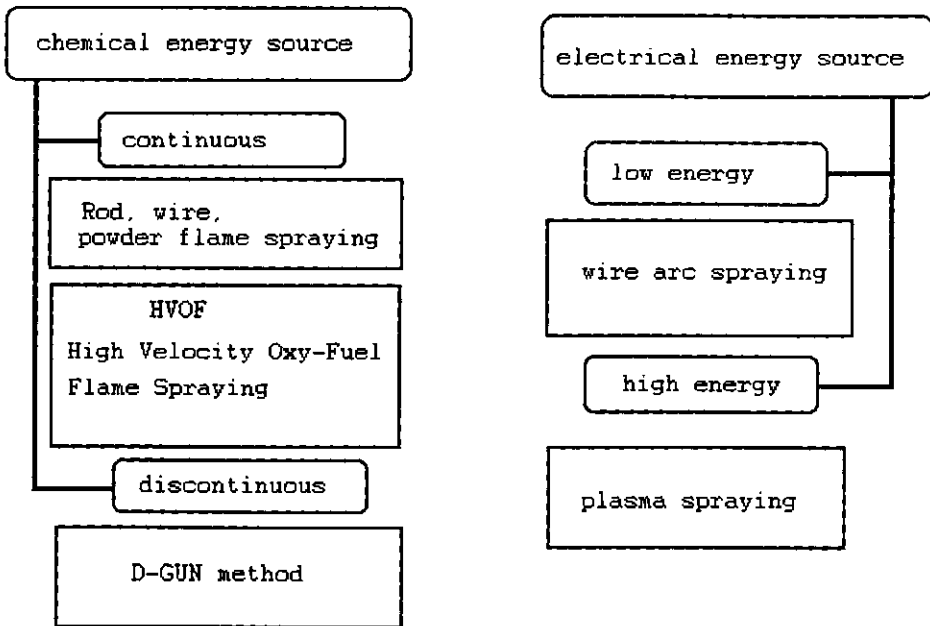
chemical energy source

continuous

Rod, wire,
powder flame spraying

HVOF
High Velocity Oxy-Fuel
Flame Spraying

discontinuous

D-GUN method

electrical energy source

low energy

wire arc spraying

high energy

plasma spraying

**Figure 2-1.** Thermal spray techniques divided by their principal energy sources (according to [1]).

The plasma spray methods

surrounding atmosphere

air

conventional
plasma spraying
(APS)

high power
plasma spraying
(HPPS)

shrouded plasma
spraying (SPS)

special
atmosphere

underwater
plasma spraying
(UPS)

inert gas
plasma spraying
(IGPS)

vacuum plasma
spraying (VPS)

controlled
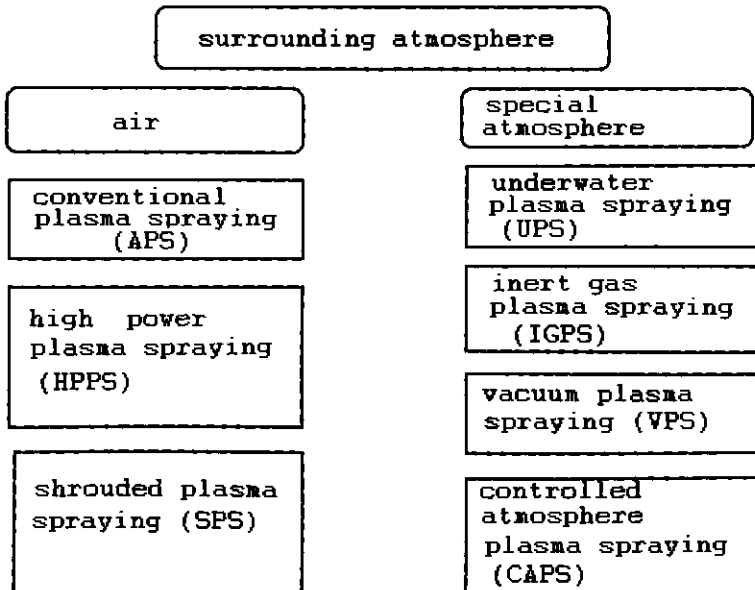atmosphere
plasma spraying
(CAPS)

**Figure 2-2.** Plasma spray techniques divided by their surrounding atmospheres (according to [1]).

unlimited temperatures that are controlled by the energy input. The maximum power supplied to the plasmatron depends on the cross-sectional area of the power leads between a d.c. or a.c. transformer and the device. Electric arc wire-spraying reaches arc temperatures of close to 6 000 K. APS temperatures are typically around 15 000 K depending on the type of the plasma gas used (argon, nitrogen, auxiliary hydrogen) and the powder input. Similar temperatures can be obtained by inductively-coupled radiofrequency plasmatrons and LPPS devices.

Thermal spraying is emerging as an active area of research and development. These worldwide activities include the development of new techniques and associated devices. Modern applications include underwater plasma spraying (UPS) [2] and laser spraying (LS) [3, 4]. A concise review of state-of-the-art spraying technology including a to-the-point description of flame torches and plasmatrons has been given recently [5].

Modern equipment is so versatile that a polymeric substrate can be coated with metal, or a metal substrate with plastic, just by changing the plasma or flamespray parameters. As simple as this sounds there are highly sophisticated requirements for selecting and controlling numerous intrinsic and extrinsic plasma spray parameters. Some researchers say that there are many hundreds of parameters which can potentially influence the properties of the coatings.

For economic (time requirements) and theoretical reasons (interdependence of parameters) it is not possible to control all possible parameter variations. In fact, only eight to twelve parameters are routinely controlled at pre-set levels, using principles of SDE and SPC (see Chapter 8). The most common control parameters are:

- power input,
- arc gas pressure,
- auxiliary gas pressure (helium, hydrogen, nitrogen),
- powder gas pressure,
- powder feed rate,
- grain size/shape,
- injection angle (orthogonal, downstream, upstream),
- surface roughness,
- substrate heating,
- spray distance,
- spray divergence, and
- spray atmosphere.

These parameters can control a variety of secondary parameters such as quench rate, residence time of particles in jet, gas composition of plasma jet, heat content etc. Some of the more important parameters are shown in Fig. 2-3 [6]. For economical reasons, one of the most important secondary parameter is the deposition efficiency. Figure 2-4 illustrates schematically the way in which specific variables affect deposition efficiency. Variables that can greatly influence efficiency include power input, arc gas flow, and spray (stand-off) distance. Variables with moderate effects are the powder feed rate and the powder gas flow rate within limits. Finally, changes in the traverse rate have little or no effect on deposition efficiency and coating density [7].
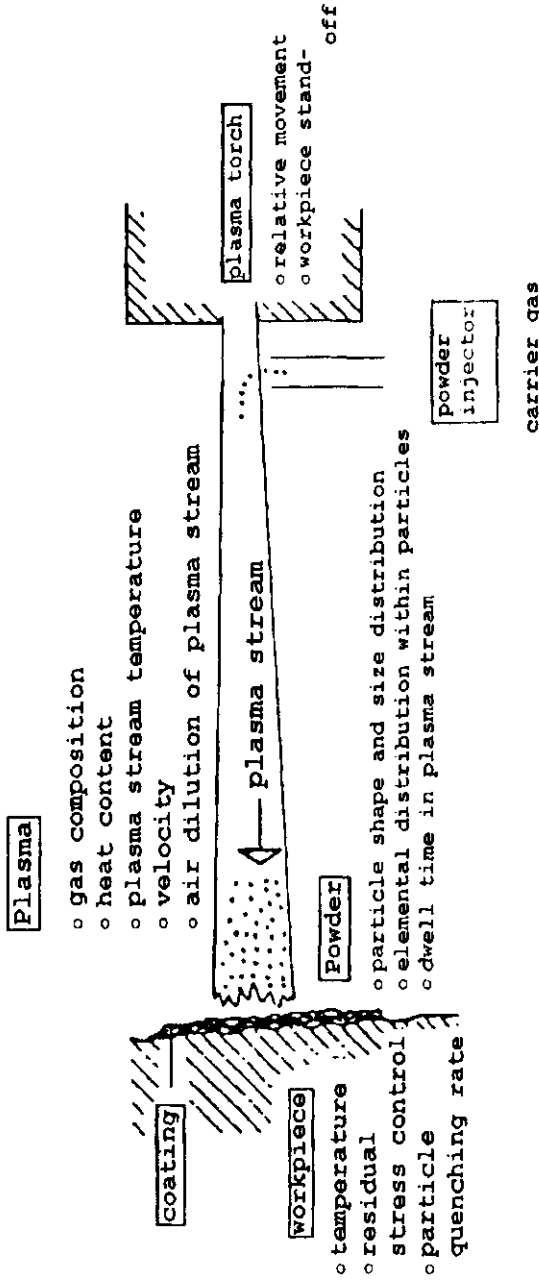
**Plasma**

o gas composition
o heat content
o plasma stream temperature
o velocity
o air dilution of plasma stream

**Powder**

o particle shape and size distribution
o elemental distribution within particles
o dwell time in plasma stream

**Coating**

**Workpiece**

o temperature
o residual
  stress control
o particle
  quenching rate

plasma torch

o relative movement
o workpiece stand-
  off

powder
injector

carrier gas

plasma stream

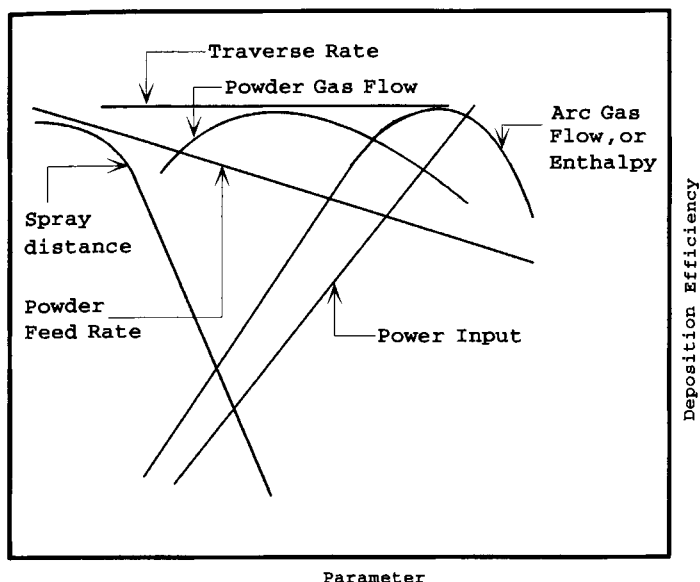**Figure 2-3.** Main plasma spray parameters controlled at preset levels [6].

Figure 2-4. Dependence of deposition efficiency on various plasma spray parameters [7].

# 2.1 Characterization of Flame versus Plasma Spraying

The main difference between these two techniques is that of the temperature of the powder melting. The temperature of a combustion flame is limited by the enthalpy of the chemical reaction that leads to the combustion of gases such as acetylene or propane in the presence of oxygen. While the flame velocity can be boosted in modern equipment (such as HVOF) to values near Mach 5, the temperatures achievable are limited to approximately 3 300 K. On the other hand, plasma jets have temperatures limited only by the amount of electrical energy supplied which in turn is a function of the cross-section of the power leads. Temperatures as high as 25 000 K can be easily generated. Thus, flame spray including HVOF systems are used mainly for the spraying of materials with lower melting points such as metals or metal–ceramic (cermets) composites, for example tungsten carbide–cobalt or chromium carbide–nickel–chromium composites. The high flame velocity of the HVOF system leads to dense, well-adhering coatings for a wide variety of applications in the resource and manufacturing industries. Thermal spraying of ceramics with high melting points, such as alumina (2 050 °C) or zirconia (2 680 °C) is the domain of plasma spray systems.

Figure 2-5 shows a comparison of various flame and plasma arc spray techniques with maximum temperatures indicated. Table 1.1 shows a comparison of combustion flame systems, HVOF (D-Gun, Jet Kote), air plasma spray (APS), inductive plasma spray (IPS), vacuum plasma spray (VPS) and radio-frequency (RF) spray in terms of gas temperatures, particle velocity, flame length, and particle injection mode [8].

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                    Flame spraying
(Temperature (T) limited by internal heat of gasses.)

Oxyacetylene torch                  (T = 2700 °C)
Detonation gun (D-gun)              (T = 3200 °C)
Jet Kote system                     (T = 3000 °C)
Hypervelocity oxyfuel gun           (T = 3000 °C)




                    Arc spraying
(Temperature (T) unlimited, controlled by energy input)

Electric arc wire-spraying
Air plasma spraying (APS)           (T = 15000 °C)
Inductive plasma (IPS)              (T > 15000 °C)
Reduced pressure ('vacuum')
      plasma spraying               (T > 15000 °C)
RF-Plasma spraying                  (T > 15000 °C)
Low pressure laser spraying (LPLS)(T = 10000 °C)
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**Figure 2-5.** Comparison of various flame and plasma arc spray techniques.

## 2.2  Concept of Energy Transfer Processes

The plasma spraying process can be conveniently described as a connected energy transfer process, starting with the transfer of electrical energy from an electrical potential field to the plasma gas (ionization and thus plasma heating), proceeding with the transfer of thermal energy and impulse (heat and momentum transfer) from the plasma to the injected powder particles, and concluding with the transfer of thermal and kinetic energy from the particles to the substrate to be coated. Figure 2-6 shows the three stages of this connected energy transfer process together with fundamental constituent parts of the plasma spray system [9].

## 2.3  Unique Features of the Plasma Spray Process

The plasma spray process is characterized by a set of uniques features. These are listed below [10].

1. With the process a wide range of materials, from metal to ceramics to polymers, and any combination of them can be deposited.

**Table 1-1.** Comparison of different spraying processes.

| | Flame | D-Gun | Jet Kote | APS | IPS | VPS | RFS |
|---|---|---|---|---|---|---|---|
| **Gas Temp. (°C)** | | | | | | | |
| $p = 1$ atm | 2700 | 3200 | 3000 | 14000 | 14000 | – | – |
| $p = 0.25$ atm | – | – | – | – | – | 10000 | 8000 |
| $p = 0.07$ atm | – | – | – | – | – | 5000 | – |
| **Particle velocity** | | | | | | | |
| **($m\,s^{-1}$)** | | | | | | | |
| **$Al_2O_3$–30 µm** | | | | | | | |
| $p = 1$ atm | 70 | 500 | 350 | 230 | 250 | – | – |
| $p = 0.25$ atm | – | – | – | – | – | 380 | 30 |
| $p = 0.07$ atm | – | – | – | – | – | 300 | – |
| **Flame length (cm)** | | | | | | | |
| $p = 1$ atm | <10 | – | <20 | <7 | <10 | – | – |
| $p = 0.25$ atm | – | – | – | – | – | <15 | <15 |
| $p = 0.07$ atm | – | – | – | – | – | <50 | – |
| **Particle injection** | axial | axial | axial | orthogonal to plasma jet downstream arc root | | | axial |

APS: air plasma spraying. IPS: inductive plasma spraying. VPS vacuum plasma spraying. RFS radio frequency spraying.

2. It is possible to deposit mixed ceramics and alloys containing components with widely differing vapor pressures without significant changes in coating composition.
3. Homogeneous coatings with time invariant changes in composition, i.e. without compositional changes across the thickness can be produced.
4. Microstructures with fine, equiaxed grain but without columnar defects can be deposited. This is in contrast to electron-beam deposition.
5. Graded coatings can be produced with the same type of equipment whereby the coating composition can be changed from that of a pure metal to that of a pure ceramics via continuously changing metal–ceramic mixtures.
6. High deposition rates of the order of $mm\,s^{-1}$ can be achieved with only modest investment in capital equipment.
7. Free-standing thick forms can be sprayed in near-net shape fashion of pure and mixed ceramics.
8. The process can be carried out in any conceiveable environment such as air, reduced pressure, inert gas, or underwater.

Despite these apparently simple and straightforward characteristics it must be emphasized that the underlying physical principles are complex and in many cases nonlinear. Achieving a coating with the desired mechanical or functional properties requires great care and stringent control of many plasma spray parameters that in a generally synergistic way influence the coating properties and thus performance.
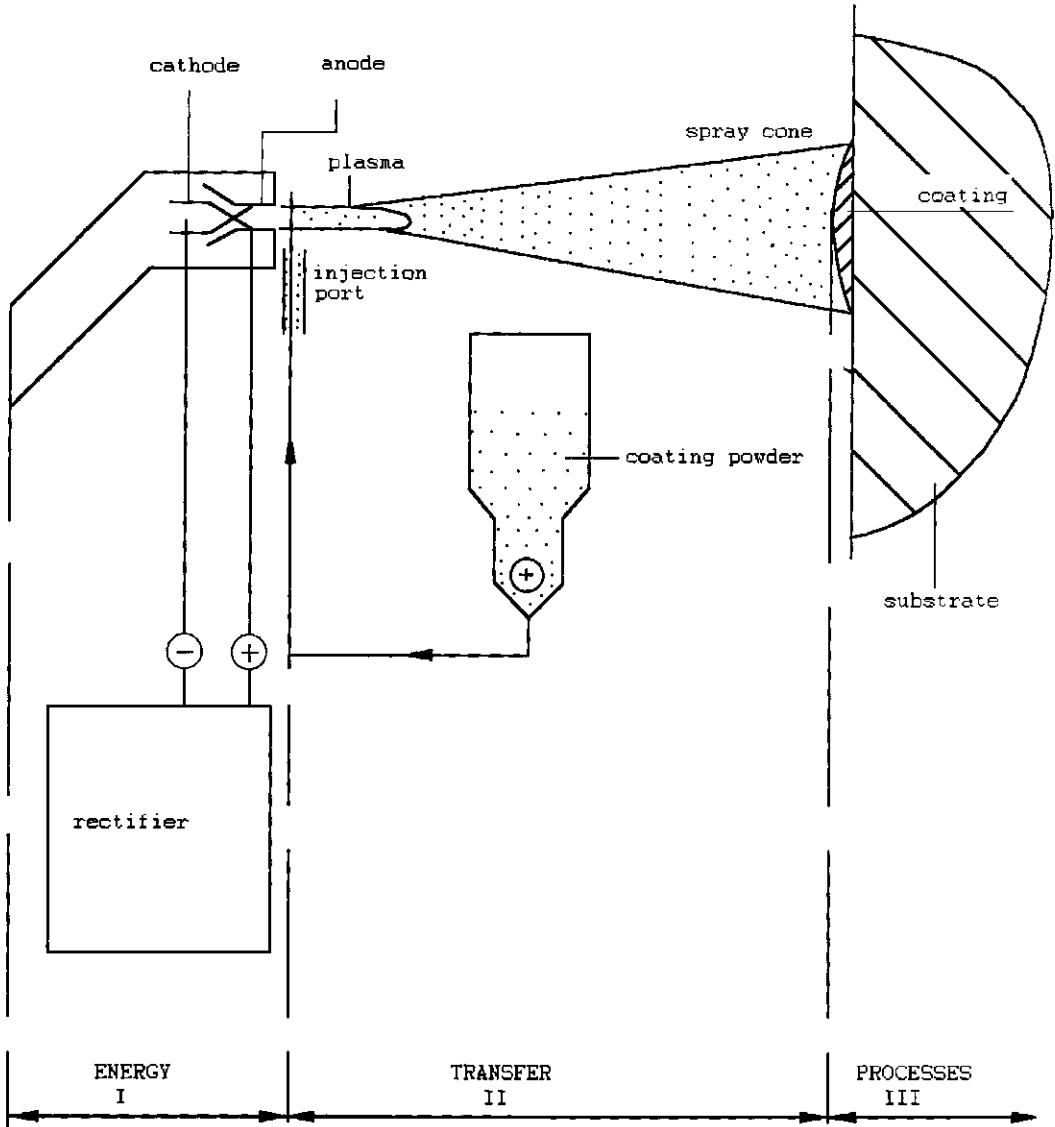
**Figure 2-6.** The three stages of the connected energy transfer process [9].

With automated technology such as robotics and adaptive statistical process control as well as the incipient development of on-line feedback control reproducibility and consistent coating quality can be achieved.

# References

[1] E. Lugscheider, *Technica*, **1992**, *9*, 19.
[2] E. Lugscheider, B. Bugsel, *Proc. 1st Plasma-Technik Symposium*, Lucerne, Switzerland, 18–20 May, **1988**, p. 55.
[3] F. Uchiyama, *et al.*, *Proc. 13th ITSC*, Orlando, Florida, 28 May–5 June, **1992**, p. 27.
[4] A. Petitbon, Guignot, U. Fischer, J.-M. Guillemot, *Mater. Sci. Eng.* **1989**, *A121*, 545.
[5] L. Pawlowski, Chapter 3 in *The Science and Engineering of Thermal Spray Coatings*, Wiley, Chichester, New York, Brisbane, Toronto, Singapore, **1995**, 28–50.
[6] A. R. Nicoll, *Thermal Spray* (CEI Course on High Temperature Materials and Coatings), Plasma-Technik AG, Wohlen, Switzerland, **1984**.
[7] D. R. Mash, N. E. Weare, D. L. Walker, *J. Met.* **1961**, (July), 473.
[8] M. I. Boulos, P. Fauchais, E. Pfender, *Fundamentals of Materials Processing Using Thermal Spray Technology* (CUICAC Short Course), Edmonton, Alberta, Canada, 17–18, October **1989**, p. 275.
[9] J. M. Houben, Relation of the adhesion of plasma sprayed coatings to the process parameters size, velocity and heat content of the spray particles. PhD Thesis, Technical University Eindhoven, The Netherlands, **1988**.
[10] H. Herman, C. C. Berndt, H. Wang, Chapter 5 in *Ceramic Films and Coatings* (Eds.: J. B. Wachtman, R. A. Haber), Noyes Publications, Park Ridge, NJ, USA, **1993**, p. 131–188.