

# Industrial plasma torches and applications

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Plasma technology has given a new direction and impetus to many industrial operations by opening up a new range of mechanical, chemical and metallurgical processing techniques. The high temperatures together with the high reactivity due to the presence of free ions and radicals, make the plasma a powerful medium to promote high heat transfer rates and chemical reactions. This paper focuses on atmospheric plasmas known as thermal-plasmas produced by plasma torches. Conventionally, as in plasma cutting, welding, melting or spraying operations, the plasma torch acts as a source of highly concentrated thermal energy and the plasma-forming gas provides an inert atmosphere and helps to prevent undesirable reactions, thus ensuring the purity of the operation and the product. In contrast, the emerging trend is to use reactions, where the plasma gas enters the reaction scheme. Some of the above issues are reviewed and illustrated with examples of plasma torches developed and experiments carried out at Bhabha Atomic Research Centre (BARC), Mumbai.

## Introduction

PLASMA technology has in recent years emerged as a novel technique for the manufacture of newer and better materials. Plasmas of technological interest can be broadly divided into two categories: thermal-plasmas and non-equilibrium plasmas. Thermal-plasmas are atmospheric-pressure plasmas characterized by high enthalpy content and temperatures around 2000–20,000 degrees. Non-equilibrium plasmas are low-pressure plasmas characterized by high electron temperatures and low ion and neutral temperatures. This paper focuses on thermal-plasma, which is a source of concentrated energy, positive and negative ions, highly active radicals and intense radiation. Thermal-plasma devices operate from a few tens of watts to a few MW (Table 1). The use of low power thermal-plasma devices in industrial operations like cutting, welding, spraying has been known over three decades. The medium and high power devices in the range of hundreds of kW are used for plasma processing and metallurgical applications. There have been a number of comprehensive reviews over the last three decades on selected topics in the field of thermal-plasmas and arc devices<sup>1–7</sup>.

## Plasma torches

Thermal-plasmas are produced by plasma torches also known as plasmotrons. Depending on the primary source, which can be direct current, alternating current at mains frequency, or at radio frequency, they are known as dc, ac or rf torches. A conventional dc plasma torch consists of a tungsten rod cathode and a water-cooled copper anode, shaped in the form of a nozzle (Figure 1). The two electrodes are separated by an insulator, which also has an inlet for plasma gas. When a gas is introduced in the electrode gap and a dc arc is established between the electrodes, the arc is pushed through the nozzle resulting in a high temperature, high velocity flame. Electromagnetic forces and gas stabilization constrict the arc column and heat the plasma to nearly 20,000 degrees. The body of the torch consists of cooling chambers for cathode and anode. The torch is supplied with water and power through water-cooled cables which are in turn coupled to the main power supply and water headers. There are several variations of the torch based on differences in the stabilization of the arc, electrode geometry, plasma gas, electrode cooling and the type of gas flow. The plasma jet can be operated in a transferred/non-transferred arc mode (Figure 1 *a* and *b*) depending on whether the arc is electrically transferred to the work piece or not. The arc normally passes from the cathode through the nozzle orifice to the anode/ground as it represents the path of least resistance.

## Arc stabilization

An arc is a self-sustaining discharge with a voltage drop of a few volts near the electrodes. The current density in the arc is high ( $A/mm^2$ ). The arc is characterized by a high luminosity and emission of radiation. It is a highly turbulent discharge phenomenon and a disturbance from equilibrium is undesirable, as it will tend to extinguish the arc. Under these circumstances, the stabilizing mechanism should come into play. The word 'stabilize' means to create and maintain boundary conditions, which will enable the arc to remain in a steady state. Stabilization also provides for the constriction of the arc column to enable the steady passage of the electric current. The free burning or the open arcs are stabilized only by natural convection. The other types of stabilization involve external stabilizing mechanisms like gas or water flow, chamber wall and external magnetic fields. A plasma

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torch is a device that stabilizes the arc. In other words, it constricts the arc, efficiently cools the outer layers and defines the path of the arc.

Gas-flow stabilization is the simplest and the most common technique (Figure 2). In this technique, a flowing external cold layer of a gas surrounds the arc column and constricts it. The flow can be vortex or axial, depending on the mode of injection. In the former case, the vortex flow creates centrifugal forces, which drive the cold gas towards the walls of the chamber. The axial component of the flow replenishes the cold gas flow. The vortex-stabilization is extremely effective in constricting the arc, increasing the energy density and the temperature. Plasma torches used for cutting or spraying applications are normally vortex-stabilized. The arc lengths are short, but the arc itself is more intense. The axial flow-stabilized arcs have a laminar flow and the cold gas tends to surround the hot core and consequently the arcs are longer. They are used for metal-processing applications.

The principle of wall stabilization utilizes the constriction of the arc by means of cold surfaces like the wall of the confining chamber. The cold walls effectively cool the plasma, thereby constricting the arc and confining the discharge to the central portion. The arc will be coaxial within the tube. This arrangement can give high arc voltages and high power levels at low currents. This type of stabilization is used in arc lamps where the envelope of the bulb stabilizes the arc. Arc heaters for space simulation facilities rated at tens of MW are based on wall-stabilized torches. Another technique

for arc stabilization is through the use of an axial magnetic field. This prevents the expansion of the arc column, increases the temperature and stabilizes it. These are used in hollow-electrode gas heaters.

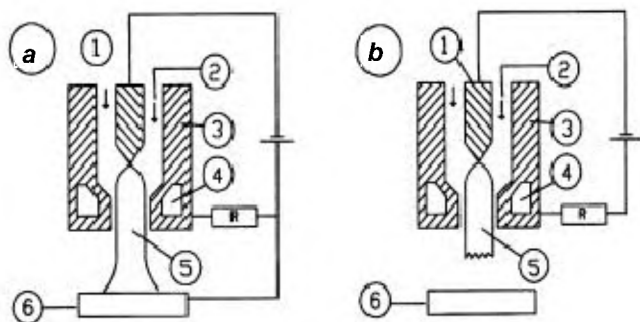
### Plasma gases

The plasma gas flow rate and the electric power to the plasma torch must be properly balanced in order to get a stable arc. The gas flow must be carefully metered as the current is built up in the arc stream, so as not to blow out the arc nor fail to cause the necessary thermal pinch effect to force the arc down through the nozzle. Improper sequencing can cause catastrophic failure of the electrodes. The most commonly used gases in the generation of plasma are argon, helium, nitrogen, air and hydrogen. The choice of the plasma gas is based on gas enthalpy, reactivity and cost. The energy content of nitrogen and hydrogen, which are diatomic is considerably higher than that of argon or helium. This is due to the dissociation reaction in the case of nitrogen and hydrogen prior to ionization. If a completely inert gas atmosphere is required argon is usually preferred. The inert gas should be extremely pure, especially when material-processing operations are being carried out. Reactive gases like hydrogen, oxygen (air), chlorine and nitrogen can be used to impart reducing, oxidizing, chloriding or nitriding effects to the plasma.

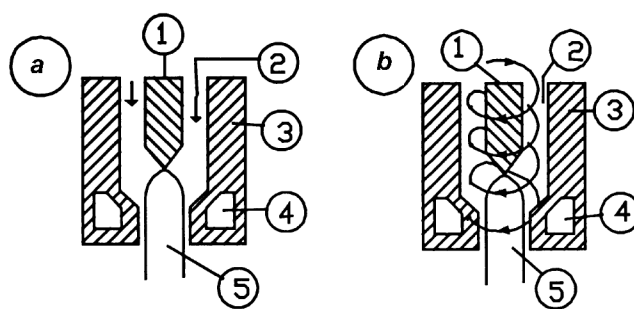
Argon is the gas used in several plasma equipment. It is used for producing the plasma, as a heat-transfer medium and for forming an inert-shield gas layer. It needs a low voltage to sustain the arc column. The low thermal conductivity helps in forming a narrow constricted column and hence forms a hotter arc. If argon is used also as a shielding gas, the arc column will expand, become less concentrated and intense. Without argon as a shield gas, a tight arc column is maintained, since the surrounding air containing oxygen and nitrogen is not easily ionizable. Hydrogen is primarily used as a reducing or deoxidizing agent. Its physical properties make it an excellent medium for increasing the heat content and

**Table 1.** Rating of plasma devices

Power level in kW	Device application
0.1–1	Welding of foils, bellows
1–10	Welding thin sheets, cutting thin plates
10–100	Plasma cutting, welding, spraying, machining, material processing
100–1000	Underwater cutting, plasma processing, plasma metallurgy, space simulation
> 1000	High enthalpy source, wind tunnels, plasma heaters



**Figure 1.** Plasma torch in (a) transferred and (b) non-transferred arc mode of operation. 1, Cathode; 2, Gas flow; 3, Anode; 4, Cooling channel; 5, Plasma jet; 6, Substrate.



**Figure 2.** Plasma torch gas-stabilization schemes: a, Axial flow-stabilized; b, Vortex flow-stabilized. 1, Cathode; 2, Gas flow; 3, Anode nozzle; 4, Cooling channel; 5, Plasma jet.

heat transfer. In welding or melting applications, hydrogen helps in improving the pool fluidity and in maintaining penetration. It also helps in system clean-up by removing residual oxygen.

### Plasma torch voltages

The plasma jet can be operated in a transferred or non-transferred arc mode, depending on whether the arc is electrically transferred to the work piece or not. The transferred arc mode torches operate with low gas flows and high torch voltages (Table 2). The non-transferred arc mode torches need high operating currents and have comparatively lower efficiencies.

The total arc voltage ( $V_{\text{arc}}$ ) is the sum of the individual voltage drops in different regions, like the cathode-fall region ( $V_c$ ), pre-nozzle region ( $V_{\text{cn}}$ ), nozzle region ( $V_n$ ), post-nozzle region ( $V_{\text{an}}$ ), and anode-fall region. The cathode and anode fall voltages form only a small part of the total arc voltage. With tungsten cathode,  $V_c$  is around 5–8 V and with copper anode  $V_a$  is also around the same value. The electric fields in the pre-nozzle and nozzle regions are nearly constant. In the nozzle region, the arc column is cylindrical, and the arc diameter of the electrically conducting arc cylinder is less than the nozzle diameter. Beyond the nozzle, the diameter of arc column increases, which corresponds to a lower temperature and jet velocity than in the nozzle. The following general observations can be made.

- (i) The plasma arc voltage depends on nozzle dimensions (diameter, length, cathode distance, etc.), arc current, composition and flow rate of gases and the distance of nozzle from work piece.
- (ii) For the same gas, the intensity of the arc column increases with increase in arc constriction. The degree of arc constriction increases with reduction of nozzle passage or with increase of gas flow rate.
- (iii) For a given current, arc voltages will be higher for a diatomic gas because, in view of higher enthalpy content greater power must be supplied.
- (iv) At the same gas temperature, the arc losses will be nearly the same and hence a molecular gas with higher enthalpy content will be more efficient.

### Torch electrodes

The cathode is the source of electrons for maintaining the arc discharge. It derives its heat from the arc and the

electrons are emitted thermionically. The cathode spot or the location at which the arc terminates at the cathode depends on the cathode material, its cooling and arc current. When the cathode is a refractory metal and sufficiently cooled, the arc constricts and the cathode current densities are as high as  $100 \text{ A/mm}^2$ , so that heating of the tip results. In other types of cathodes the arc is shifted over the cathode surface by a magnetic field or by the vortex flow, and the cathode is intensely water-cooled. Typical cathode materials are tungsten, thoriated tungsten, graphite, copper, zirconium/zirconia. Tungsten electrodes are the most common. However, tungsten has to be operated in an inert atmosphere like argon or nitrogen. In torches with low power outputs, the electrode tip is cone-shaped and is truncated for high outputs. For air-operated torches, hafnium or zirconium electrodes are used. With these electrodes, an oxide film is formed on the surface, which at normal temperatures is insulating. So, a high operating temperature is desirable, almost close to the melting point of the oxide when it becomes conducting. The non-thermionic cathodes are used for operation at high power levels in oxidizing or reactive environment. These are hollow, ring or flat cathodes and the cathode spot is made to move over the surface through fluid dynamic or magnetic means. The arc stability is comparatively low and the arc voltages are high.

The heat generated at the anode is quite large in plasma torches. The heat flux at the nozzle can be as high as  $160 \text{ W/mm}^2$ . The obvious choice of the material for anode is high-purity copper possessing excellent thermal conductivity. Other materials like graphite and refractory metals have also been used. Any other heat-resistant material with lower thermal conductivity used separately or as an insert reduces the nozzle life. The nozzle orifice is designed on the basis of stabilization of plasma column, and its diameter determines the power density. The technique for increasing the efficiency of the plasma torch is by increasing the constriction. This effectively increases the current density and also the electric fields. There are, in general, two types of nozzles: those with small  $L/D$  ratio ( $\sim 1$ ) and those with large  $L/D$  ratio (greater than 1). The first type of nozzle has a larger diameter and is suitable for transferred type torches. The second type of nozzle has higher intensity and is suitable for non-transferred devices.

### Torch efficiency

Consider a transferred arc plasma torch where the anode is the work piece. If  $P_{\text{arc}}$  ( $V_{\text{arc}} \cdot I_{\text{arc}}$ ) is the electric power to the arc, it is the sum of the power transferred to cathode, power radiated and convected from plasma column, power transferred to the nozzle and the power transferred to anode work piece. The effective efficiency of a plasma torch in heating the work piece is

$$\eta = (P_{\text{work-piece}})/(V_{\text{arc}} \cdot I_{\text{arc}}).$$

**Table 2.** Arc voltages (volts) in the cutting and spraying applications

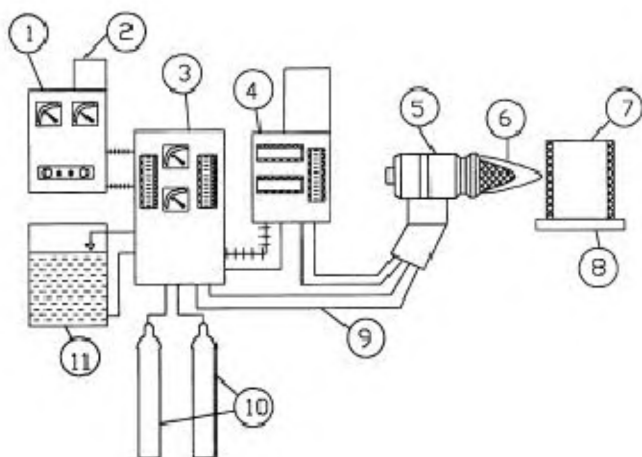
Gas	Transferred arc mode (cutting)	Non-transferred arc mode (spraying)
Argon	110–300	25–50
Nitrogen	150–400	60–100
Argon/hydrogen	130–350	80–100
Nitrogen/hydrogen	150–400	90–150

For a transferred arc-plasma torch, the efficiency of heating the work piece is normally 70–80% of the input power. Under optimum conditions, this can be made considerably higher. For a non-transferred arc-plasma torch the efficiency, defined as the capacity for heating the plasma gas, is only 40–50%.

Extensive experiments carried out at the Institute of Novosibirsk have resulted in the following empirical formula to calculate the torch thermal efficiency  $\eta$  for torches with rod-type cathodes<sup>4</sup>

$$\frac{1-\eta}{\eta} = 5.85 \times 10^{-5} \left[ \frac{I^2}{Gd} \right]^{0.265} (p.d)^{0.3} \left[ \frac{G}{d} \right]^{-0.265} \left[ \frac{l}{d} \right]^{0.5},$$

where  $I$  is the arc current in A,  $G$  the mass flow rate in kg/s,  $d$  the diameter,  $l$  the length of the nozzle in m and  $p$  the pressure in the arc chamber in Pa. The formula is valid for a large range of operating conditions: 5 mm <  $d$  < 80 mm; 1 atm <  $p$  < 50 atm; 5 g/s <  $G$  < 5000 g/s; 5 kW <  $P$  < 50 MW; and  $I$  < 6000 A.



**Figure 3.** Schematic of plasma spray facility. 1, DC power source; 2, HF unit; 3, Control console; 4, Powder feeder; 5, Plasma torch; 6, Plasma flame; 7, Job; 8, Job-handling system; 9, Cabling; 10, Gas supply; 11, Cooling-water supply.

### Industrial plasma facility

An industrial plasma facility consists of a plasma torch energized by a dc power source. A high-frequency unit will provide initial starting up of the discharge. The auxiliary services include plasma gases and cooling water for torch-cooling and associated cabling. The feed, torch and job-handling systems will help in the proper functioning of the facility. Figure 3 shows a typical plasma-spray facility. Table 3 gives some of the well-known torches with salient technical features and their applications<sup>8</sup>. There are basically two types of high power, industrial plasma torches; hollow-electrode type and solid-electrode type. The mode of operation of the torches can be in transferred or in non-transferred mode and in straight polarity (when the work-piece is positive) or in reverse polarity (when the work-piece is negative).

The basic requirements of the dc power source is that it should provide a suitable electrical output for the plasma arc, with a provision that the positive or negative terminal can be grounded and different power packs can be connected serially or in parallel. In addition, the output should be controllable to meet the specific application (voltage, current, static and dynamic characteristics) and should withstand momentary short-circuit. The curve showing the variation between the voltage and current is known as the Volt-Ampere (V-I) characteristics. The arc V-I characteristic is said to possess a negative dynamic resistance, that is, with increasing current the arc voltage decreases. It can be shown that for electrical stability, the power source should have a drooping or a constant-current characteristic. While initiating the arc, the cathode and anode are virtually shorted, resulting in a current surge. Thus, the power supply should have a saturation current, beyond which the current should not rise even under short-circuit. For easy ignition, the open-circuit voltage should be higher than load voltage. The arcs cannot be operated in parallel without individual stabilizing resistors.

### Application of plasmas torches

Plasma technology has given a new direction and impetus to many industrial operations by opening up a new range

**Table 3.** High power industrial torches

Torch make	Power (MW)	Voltage/current (V/A)	Gas flow (Nm <sup>3</sup> /hr)	Electrode type	Electrode material	Application
Metco	0.1	40/2000	5 (Ar)	Rod	Tungsten-copper	Plasma spraying
Ionarc	0.35	300/1200	Ar	Rod	Tungsten-copper	Zirconia production
Linde-Retech	0.7	250/3000	60	Hollow	Copper	Plasma melting
Daido	1.0	250/5000	—	Rod	Tungsten-copper	Scrap remelting
Westinghouse	2.0	1000/2000	250	Hollow	Copper	Scrap melting
PEC	4.5	900/5000	175	Hollow	Copper	Ladle heating
Tioxide	5.0	1700/3500	2000	Hollow	Copper segment	Titanium dioxide
Aero-Spatiale	5.0	2630/1900	1850	Hollow	Copper	Ferro-manganese
SKF	7.0	3500/2200	1500	Hollow	Copper	Recovery from dust
Voest-Alpine	7.5	830/12000	— (Ar)	Rod	Tungsten-copper	Steel remelting
Huls	8.5	7000/1200	4000	Hollow	Steel/copper	Chemical synthesis

of mechanical, chemical and metallurgical processing techniques. As an illustration, the various applications are mapped onto a Volt-Ampere diagram of plasma torch (Figure 4). The torch impedance and power levels are also indicated. The transferred arc torches are used for plasma-cutting, welding, melting, evaporation, refining and surface treatment. The non-transferred arc torches are used for spraying, gas-heating, plasma synthesis, dissociation, sintering, fine-powder preparation, plasma-assisted CVD and plasma waste-treatment.

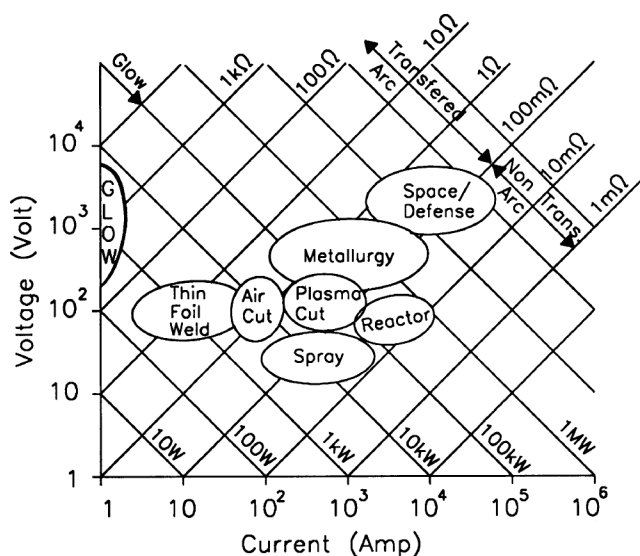
### Plasma-cutting and welding

Plasma-cutting and welding torches have been in operation as specialized machines in the industrial environment. These torches are currently being exploited in handling stainless steels, nonferrous materials, high temperature alloys, etc. The major advantages of the plasma-cutting equipment are burr-free cut-edges, minimum kerf width and heat-affected zone. Due to the absence of

oxygen in the cutting mechanism, slag and scale formation on the cut surface is low. The plasma jet is operated in a transferred arc mode and the arc is electrically transferred to the work-piece. Some of the typical operating data generated at BARC using an indigenously designed 100 kW torch system are shown in Table 4. For comparison, data for underwater operations are also given. The cutting efficiency normally increases with higher cutting speeds and thickness. The underwater cutting efficiency is lower by 10–20%. The heat-affected zone in air operation is about 300 microns and is substantially reduced in underwater operations.

The air-plasma torch uses compressed air as plasma gas. The cathode is made not from tungsten but from hafnium, niobium, copper or zirconium alloys. The use of air instead of bottled gas makes the process economic, but the life of electrodes is comparatively short and the plasmas arc less stable than with conventional torches, especially during arc initiation. The exact cost of plasma-cutting depends on several factors, including the total volume of work carried out<sup>9</sup>. A comparison gives the cost of cutting 12.5 mm-thick carbon steel by conventional oxy-acetylene cutting at Rs 4.50 per metre compared to Rs 5.40 per metre by argon-gas plasma-cutting and about Rs 1.50 per metre by air-plasma cutting.

Plasma arc welding (PAW) is a more updated version of tungsten inert gas (TIG) welding process. TIG welding has a free-burning arc, which is unstable and tends to wander in the low current range. With increase in current, the arc power increases and the arc diameter also increases. This leads to a lack of concentrated power in the work-piece, which results in larger seam and a larger heat-affected zone. Unlike TIG-welding torches, PAW employs two separate flows, which give rise to a concentrated plasma arc having a narrow columnar shape. The plasma column is now stabilized along the axis of the electrode and is more intense than the TIG-welding arc. The column temperature is 10,000–20,000 K compared to 8000–15,000 K in case of TIG-welding arc<sup>10</sup>. A comparison of plasma welding with TIG welding and electron-beam (EB) welding is given in Table 5. Performance-



**Figure 4.** DC plasma torches: Voltage-current diagram. Power rating and device impedance are also shown.

**Table 4.** Selected plasma cutting experimental results

Operating medium	Operation in air			Underwater		
	ms	ss	ss	ss	Al	U
Thickness (mm)	55	50	125	20	19	21
Plasma gas	N <sub>2</sub>	N <sub>2</sub>	N <sub>2</sub> + H <sub>2</sub>	Ar	N <sub>2</sub>	Ar
Gas flow rate (LPM)	50	50	50 + 5	40	40	35
Voltage (V)	150	140	210	150	128	180
Current (A)	500	550	550	250	320	200
Input power (kW)	75	77	115	38	41	36
Cutting speed (mm/min)	200	300	100	360	320	280
Kerf width (mm)	14	15	18	7	12	10
Cutting efficiency (%)	34	37	25	17	6	7

LPM, Litres per minute; ms, mild steel; ss, stainless steel.

wise, plasma welding does not perform as well as EB welding. However, for the cost, it gives superior weld capability<sup>11</sup>.

### Plasma spraying

Plasma-spray technology is one of the most widely used surface-engineering techniques to prepare structural parts with improved surface properties and increased life span. Plasma-spray process was developed by Union Carbide in 1957 as a general technique using a plasma gun. In the plasma-spray process, the high enthalpy present in a thermally-ionized plasma is utilized to melt and propel finely-divided particles onto a substrate where they adhere and solidify to produce coatings. The powder to be sprayed is introduced with plasma stream near the nozzle and is retained in the plasma stream just sufficiently long to attain melting and high velocities, and not lead to evaporation. Plasma deposition is a continuous process and can be used to spray-coat ceramics, metals, alloys and compounds. The twin-wire, arc-spray technique useful for spraying metallic wires is an analogous technique. The main advantages of plasma spraying are

- (i) Any powder which melts without sublimation can be coated and the coating thickness can go from microns to a few mm.
- (ii) The substrate temperature can be as low as 50°C.
- (iii) There is no restriction on the size and shape of the job and the coating process is comparatively fast.
- (iv) Mechanical and sometimes metallurgical bonding is obtained.

Plasma-spray process uses a non-transferred plasma torch. Figure 3 shows the schematic of plasma-spray system. In plasma spraying the quality of coating is affected by many variables, which are inter-related. The parameters are related to the plasma (power input, type of plasma gas, plasma gas flow-rate, type of arc, plasma-torch geometry), powder (composition, physical properties, method of manufacture, particle size), substrate (composition, surface preparation, surface roughness, temperature) powder feed (type of feed system, rate of feed, type and flow of carrier gas, angle and port of entry) and spray procedure (torch to base distance, traverse rate, angle of spray, shield gas and spray atmosphere). A

careful optimization of the spray parameters is required to obtain good-quality, reproducible coatings on substrates for any specific application<sup>12</sup>.

Wear-resistant coatings covering a range of oxide, carbide, and nitride coatings can be used for protecting bearings, surfaces wetted with molten metals and hot gases, cutting edges, hard facing for dies, etc. Thermal-barrier coatings are primarily used for reducing the rate of heat flow from a hot environment to a metal surface. These consist of oxide on alloy (MCrAlY), and zirconate coatings in gas turbine applications, internal combustion engines, rocket nozzles, etc. They should possess low thermal conductivity, high oxidation resistance and improved thermal shock behaviour. Abrasive coatings are specially designed to produce surfaces which wear away an intruding material or which are sacrificial to the intrusion of a mating member. Tungsten carbide, alumina, alumina-titania are excellent abrasion-resistant materials whereas an organic-metal coating forms an abradable material. In addition, there are special purpose coatings to cover the range of products to meet specific requirements. These include among others, bioceramic coatings, electromagnetic shield coatings and superconducting coatings.

Plasma-spray technology has been exclusively done in air with shield gases. This is known as the atmospheric or air-plasma spraying (APS). Plasma-spraying in normal ambient conditions is suitable for oxides. However, one of the major problems with the plasma-spraying of metals, alloys and intermetallics is plasma effluent-powder mixture coming into contact with the atmospheric oxygen<sup>13</sup>. This results in coating contamination and new developments are taking place to minimize this contamination. These include the controlled environment (CEPS) or inert-plasma spraying (IPS) and vacuum-plasma spraying (VPS). The spraying is performed in a low-pressure chamber or in chambers filled with inert gas. During VPS the chamber is evacuated to pressures in micron level and then is back-filled by the plasma gas to torr level during spraying. Plasma-spraying in the absence of oxygen allows the coating/substrate system to be maintained at a very high temperature during processing, resulting in interfacial diffusion, producing a true metallurgical bond. A comparison of APS and VPS along with twin-wire arc-spray is given in Table 6 (ref. 14).

### Plasma chemical processing

Plasma chemical processing has several distinct advantages over the conventional methods, which involve the use of electrically heated or gas-fired furnaces. The maximum temperature attainable in the conventional heat sources is just about 3000 K, whereas plasma torches offer temperatures as high as 20,000 K. A unique feature of the plasma devices is the highly concentrated nature of the thermal power. This enables the system to be made

**Table 5.** Comparison of welding processes

Parameter	GTAW*	Plasma	EB
Penetration thickness (mm)	0.5–5	0.1–10	0.5–200
Maximum power (kW)	4–6	15	100
Power density (W/m <sup>3</sup> )	10 <sup>8</sup>	10 <sup>8</sup> –10 <sup>10</sup>	10 <sup>13</sup>
Equipment size	Small	Medium	Very large
Cost comparison	1	1.2–2	5–10
Welding speed	Slow	Medium	Fast
Distortion	High	Moderate	Very low

\*Gas tungsten arc welding.

compact and to approach chemical and metallurgical processes by new reaction paths inconceivable in the conventional sense. The high quench rate makes it technologically more attractive. Many high-temperature reactions of importance in extractive metallurgy (e.g. carbothermic reductions of metal oxides), which cannot be realized in conventional furnaces due to thermodynamic and kinetic limitations, can be successfully carried out in plasma reactors. The presence of excited atoms and ions is another distinct feature of reactions occurring in the plasma medium. These active species in the plasma considerably enhance the reaction probabilities. Most of the plasma processes are single-step processes and are not very sensitive to impurities in the raw materials. Process conditions in the plasma reactor can be accurately controlled over wide ranges of composition, temperature and pressure.

Thermal-plasma chemical reactors are normally non-transferred arc devices in which heating of the gas phase or the dispersed particulate phase is achieved. The main components of the plasma chemical reactor system are the input feeding system, the plasma generator with the associated power supplies, a mixer-reactor unit and a quenching system. The mixing can also be achieved by premixing the reactants in the input feed system to the generator, especially with gases. However, it is not a preferred choice, since the electrodes are subjected to corrosion. The role of the quenching system is to freeze the products at the high-temperature equilibrium level. It can be achieved by cold gas injection, cold-wall quenching, fluidized bed, adiabatic expansion or by impinging into a liquid spray/bath.

The production of acetylene from coal in a hydrogen plasma is one of the early applications of the plasma route for preparing coal-based chemicals. The primary motivation for this approach is that acetylene-like ethylene is a starting material for the manufacture of many compounds. The major developmental works were carried out at Chemische Werke Huls AG. The individual units are rated at 8–10 MW with capacity over 100,000 tons per year. The energy input into the system is about 8 kWh/kg of coal<sup>15</sup>.

The vapour phase syntheses of carbides, nitrides, borides and oxides are of significance. The use of thermal-plasmas in the chemical synthesis of these ceramic materials is extremely interesting due to the high temperatures involved, the flexibility in the choice of reactants and the rapid cooling which is possible<sup>16</sup>. The plasma process is usually a single-step process which can help in the preparation of pure, ultra-fine particles and in spherodization. The starting material is introduced in the form of a gas, solid or liquid or in combination<sup>17</sup>. The process proceeds in several steps: vaporization, vapour-phase reaction, nucleation and condensation. Submicron aluminium oxide and other metal oxide powders have been produced at the nuclear aerosol generator set-up at BARC. It has been seen that with coarse powders the particles melt, react and partially evaporate leading to smaller size particles (spherodization). On the other hand, injection of fine powders results in total evaporation and recondensation, leading to very fine particles (nano-particles). Thus, with a mix of powder sizes, a bimodal distribution results (Figure 5).

Nickel aluminide and its derivatives have excellent high-temperature mechanical properties and oxidation resistance, which makes them useful as a bond coat material in thermal-spray applications. Nickel aluminide was synthesized at BARC in a plasma torch operating in a non-transferred arc mode using premixed powders with excess aluminum as precursor material, argon as carrier gas and argon and nitrogen as plasma gas. X-ray diffraction patterns of the coated substrates showed a single homogeneous phase of Ni<sub>3</sub>Al (reference). Since the residence times of particles in a plasma torch are small, of the order of few milliseconds, intimate mixing of reactant powders is essential. The formation of Ni<sub>3</sub>Al is highly exothermic and once the reaction is initiated, it goes to completion. The thermal-plasma technique is simple and cost-effective compared to conventional techniques of producing such materials.

One of the emerging areas of active development is plasma waste-treatment. It is one of the most effective

**Table 6.** Comparison of different coating techniques

Parameter	Twin-wire arc	Air plasma spray	Vacuum plasma spray
Gas flow (m <sup>3</sup> /h)	70	4	2–8
Plasma exit temp. (K)	6000	6000	8000
Ambient gas	N <sub>2</sub> , O <sub>2</sub>	A, N <sub>2</sub> , O <sub>2</sub> , H <sub>2</sub>	A, He
Particle velocity (m/s)	250	250	250–600
Adhesive strength (1-low)	6	6	9*
Cohesive strength	High	High	Very high
Oxide content (%)	0.5–3.0	0.5–1.0	ppm
Process cost (1-low)	1	5	10
Max. spray rate (kg/h)	15	5	10
Power (kW)	4–6	30–80	50–100
Energy to melt (kW/kg)	0.2–0.4	12–20	10–20
Material	Metal	All	All

\*On a scale of 1–10.

methods for treating organic and inorganic wastes, including chlorinated compounds. The wastes treated in a plasma reactor decompose and form simple substances like  $\text{CO}_2$ ,  $\text{H}_2\text{O}$ ,  $\text{HCl}$  and  $\text{N}_2$ . After treatment, the gas can be exhausted into the atmosphere. Currently, plasma treatment of hospital waste has been attracting attention and a pilot unit is being developed at the Facilitation Centre for Industrial Plasma Technologies<sup>18</sup>.

### Plasma metallurgy

The introduction of plasma furnaces in the metallurgical industry has revolutionized the concept of making superior-quality products at costs comparable to conventional techniques. These furnaces have a high melting efficiency, and are capable of producing alloys with low carbon, low hydrogen and low oxygen content. The transferred arc-plasma devices used in metallurgical industry are characterized by high energy concentration, high thermal efficiency, excellent heat and mass transfer conditions, and adequate residence time. In these plasma furnaces, the arc is transferred to the molten pool in the crucible or in the form of a falling film.

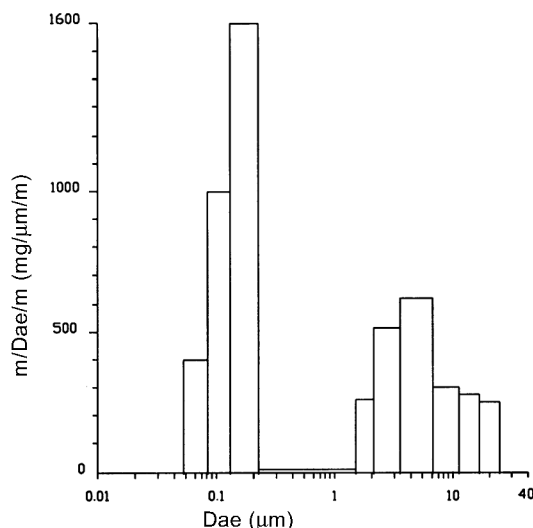
Plasma-arc remelting (PAR) has demonstrated that it can compete with other comparable techniques like vacuum-arc remelting (VAR) and electron-beam melting (EBM) in terms of quality and cost. The increasing

demand for cleanliness has led to the development of the cold hearth furnaces. The cold hearth is an intensely cooled copper hearth where the charge is melted, refined and resolidified. A plasma torch melts the charge and the molten metal flows along the hearth forming a skull in the copper hearth. The previously melted metal forming the skull prevents the molten metal from directly coming in contact with the copper surface. VAR, electron-beam cold-hearth melting (EBCHM) and plasma-arc cold-hearth melting (PACHM) are all skull-melting techniques. The EBCHM has been carried out since the sixties, whereas PACHM is less than a decade old. A comparison of the two techniques for titanium melting is shown in Table 7. (ref. 19).

Plasma decomposition offers itself as an excellent technique for decomposing minerals or raw materials. Plasma decomposition can be employed for even thermally stable oxides. At elevated temperatures, these oxides dissociate when the dissociation pressure exceeds the partial pressure of oxygen in the surrounding medium. Since plasma gases are free from oxygen, a number of stable compounds like silica, alumina and magnesia can decompose. The decomposition of zirconium silicate (zircon sand) into zirconium dioxide and silica is of technological importance. An extensive parametric study has been carried out by Ananthapadmanabhan *et al.*<sup>13</sup> using a 50 kW dc plasma reactor. Some of the other metallurgical operations include 'plasmasmelt' process of SKF for the direct smelting reduction of iron, carbo-thermic reduction of chromite ores, production of a variety of ferroalloys: ferrochrome, ferromanganese, ferro-silicon, ferromolybdenum, ferrovanadium, etc.<sup>20</sup>. The application of plasma technology implies two options, either preparing a new flowsheet based entirely on plasma technology or to retrofit a plasma system to an existing conventional unit.

### Summary and conclusions

In summary, thermal-plasmas are equilibrium plasmas characterized by a single temperature for the different species and processes. They are generally produced by high intensity arcs, rf discharges or by thermal ionization. The desirable technical features of an ideal plasma source have been established<sup>21</sup>. The technological worth of these plasmas is on the rise mainly due to the ease with which they can be produced and sustained through devices called plasma torches which convert electrical energy to



**Figure 5.** Bimodal distribution of aerosols generated from aluminium powder with compressed air dilution.

**Table 7.** Comparison of electron-beam melting and plasma cold hearth melting of titanium

	Electron beam	Plasma beam
Separation of W, Cr	Nearly 100% efficient due to small pool stirring	100% efficiency due to enhanced pool stirring
Chemical composition	Volatile components to be compensated	No essential losses during the process
Reduction of $\text{O}_2$ content	By adding titanium sponge	By adding titanium sponge/other methods
Operating experience	Already established technology	To be applied for production

Table 8. SWOT analysis

Strength	Weakness
<p>Temperatures, enthalpies and heat fluxes obtained in the plasma jet are far higher than any other known technique.</p> <p>Plasma jet produces an effluent over a wide range of composition and operating conditions, which can be closely controlled.</p> <p>Presence of charged particles and radicals gives access to non-equilibrium operating regimes.</p> <p>Can be used at atmospheric and sub-atmospheric pressures.</p>	<p>Highly power-intensive and high operational cost.</p> <p>Generation of intense ultra-violet radiation and noise during operation.</p> <p>In general, the physics of the process is reasonably understood and the process works well. Yet there are grey areas of understanding.</p>
Opportunity	Threat
<p>Plasma torch can be used for cutting, welding, spray-coating of ceramic/metal powders, powder-processing and as a heat source in furnaces.</p> <p>Widespread application in areas of material testing (thermal shock, thermal resistance, ablation, dynamic oxidation).</p> <p>Space vehicle reentry simulation and rocket exhaust duplication.</p> <p>Plasma chemical treatment of toxic waste.</p>	<p>Plasma, electron and laser-based machines are competing technologies.</p> <p>Electron-beam machines, of necessity operate under high vacuum conditions and this ensures production of high-purity and highly reactive materials.</p> <p>High control and focusing capability of laser machines enable good spatial and time resolutions.</p>

a concentrated flux of thermal energy. In order to have critical review of the technology, a SWOT analysis has been carried out (Table 8). It is desirable to address the following issues:

- Has plasma technology reached a state of technological maturity commensurate with the demands of the manufacturing and processing sectors?
- What are the competing technologies having intersecting domains of applications and how do they compare in terms of performance with laser and electron-beam technologies?
- Are there established design, inspection, operation and maintenance procedures for plasma equipment?
- Do the subsystems like power supplies, work-handling units, etc. possess a robust engineering base built into them and have high reliability and safety?

The major user interest in thermal-plasmas today is focused on the high energy density of the medium. This means high operating temperatures for the reaction gases and high energy fluxes. Last two decades have witnessed rapid progress in the successful implementation of thermal-plasma technology for industrial applications. Yet the true potential of these devices has not yet been fully exploited. This is primarily due to the fact that there is still a lack of basic understanding regarding the processes which occur in the plasma region, the electrode regions and the interaction of the plasma with external flows, electric fields and magnetic fields. E. Pfender, one of the pioneers in this field, attributes this to the uncoordinated industrial efforts based on empiricism and not backed by basic studies at universities.

Plasma technology is of the twenty-first century and at present we do not have the full insight into the potentialities of using high reactivities of the species, quasi-equilibrium conditions, and the high heat and quench rates available for the creation and modification of new materials. The need of the hour is the creation of the basic database, improvements in instrumentation, formu-

lation of a control strategy, process modelling, system analysis and optimization.

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