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Industrial Applications of Thermal Plasmas-Review

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Abstract

The major technological advancements and applications of thermal plasmas are examined here. Industrial applications of thermal plasmas can be bifurcated into welding, low power cutting, environment, spraying, metallurgical and steelmaking. The implementation of thermal plasmas in environmental domain has garnered significant attention as the regulations residue disposal has been tightened. More development and research are essential especially for decreasing the electrode erosion of plasma torches and to enhance the fundamental understanding of heat transfer, high temperature chemistry and electric arcs for expanding the thermal plasma applications.

1. INTRODUCTION

Plasma has been seen by mankind in nature ever since a long time. It is also known be the 4th state of matter. Most of the universe consist of the plasma instead of gas/liquid/solid. Astrophysicists have also found that galaxies are predominantly comprises of plasma. This was first noticed by William Crooks in 1879, and this state of matter was officially subsequently identified as ‘Plasma’ by Irving Langmuir in 1928. The plasma sheath theory was established by Langmuir, known to be the boundary layer developed between the ionized plasma and solid particles. Langmuir also found that in certain regions of the plasma discharge there is periodic variations of electron density, known as Langmuir waves. This was the start of plasma physics era. Plasma primarily comprises of heavy charged particles and negative ions. Hence, plasma can be described as partially ionized gas typically generated by an electrical discharge at near surrounding temperature. The implementation of plasma in various areas of engineering and technology has garnered significant attention in recent years due to its extensive properties both physical and chemical. Numerous researchers attempted to model this plasma and formulate equations to define it. These were the equations that apply to several proposed controlled thermo-nuclear reactors. Various issues regarding plasma developed, for example, there was localization of plasma anisotropic heating. To resolve such issues, models were already established. These include models that provide useful information about associated processes of emission of radiation, impact of frequencies and absorption of radiation[1-3]. Plasma as such is implemented across various domains of science and engineering. The effective use and implementation of plasma for synthetic fabrication make it much prominent in several industrial products. In the field of artificial products, plasma also serves as a base for enhanced research in the field of organic materials control and integration. Highly ionized as well as moderate ionized plasma can provide temperature resistive effects for inorganic materials like alloys and ceramics.

Plasma is also utilized in medical application during the process of biological and chemical distillation, sterilization and the blood coagulation process, plasma therapy. The effectiveness of plasma technology for the subsequent development of interdisciplinary sciences can usefully provide essential data for the equipment’s designing needed for monitoring of diseases level and diagnoses. Numerous researchers have developed plasma-based devices generating cold atmospheric pressure plasma jets (CAPPJ) implemented for biomedical applications

[4]. Many CAPPJ devices have been designed which include, double ring electrode design, floating helix electrode design and pin electrode design [5-10].

Moreover, several other applications of plasma in the medical field will be discussed later.

In the future, a crucial challenge to be confronted will be a shortage of energy resource for power generation. Researchers and scientists believe the use of alternative energy is the only solution to this problem, also they propose that most practical method is implementation of plasma in the field of power generation. Electrical scientists can further examine the implication of plasma and its dynamic attributes for integrating into the electrical system. One of the best examples is the plasma torch [11].

2. Thermal Plasma Characteristics

The main attributes of thermal plasmas are examined here, subsequently the description of the devices that are normally utilized to produce the thermal plasmas, i.e., the plasma torches are also mentioned.

2.1 Thermal Plasmas

Thermal plasmas are employed in industrial processes for: a. high energy densities of the plasmas, b. high temperatures reached in the plasma jets and c. probability of utilizing numerous plasma gases depending on desired application. Predominantly thermal plasmas are produced by either of these 3 different ways: an electric arc /high frequency discharge/ using a laser. The electric arc method of generating thermal plasma have significant importance and will be considered here.

The plasmas are produced by collision processes between the molecules of the working gas and electrons form the electric arc. The electric field (E) accelerates the electrons (in-between the electrodes) which gain kinetic energy which will be partially transferred to gas particles during the collision process. Thermal plasmas are usually produced at atmospheric pressure/ close to atmospheric pressure, consequently resulting low values of E/p (p is the absolute pressure of the gas), usually in the range of 10-3 V/cm Pa [12].

It is convenient to consider thermal plasma in a state called LTE, i.e., a Local Thermodynamic Equilibrium. In the LTE, the plasma is considered to be in state wherein, the local gradients of the plasma properties (heat conductivity, density and temperature etc.) are adequately small so that given particle has enough time to equilibrate [13] whilst diffusing form one location to another and collision processes govern the reactions and transitions in the plasma. Majority of researchers are known to consider thermal plasmas in LTE for modelling work [13-14].

The electric arc and plasma surrounding it are generally distributed in three regions: anode, column and cathode. The principal part indicating the arc is the column. Typical current densities of 100 A/cm2 are observed in this region. In the arc column quasineutrality exists; thermodynamics properties and temperature distribution adjust themselves in such a way that the electric field strength necessary for driving a certain current becomes a minimum [15].

Most of the valuable attributes of thermal plasmas (heat transfer ,chemical reactions, luminosity) are due to the plasma/arc column. It will be shown later how the arc column is employed in an industrial process. [16]

The electrode region, i.e., the anode and cathode regions, comprise of the electrode surface, transition zone until the arc column and the sheath region (net space charge) directly in front of the electrodes.

The electrode regions are characterized by much higher field strengths (up to 106 V/cm), temperature gradients (around 104 °K and current densities (up to 108 A/cm2) than in the arc column. In the electrode regions one cannot typically consider the plasma to be in LTE. The electrode regions are responsible for generation and elimination of the charged particles. [16- 18]

2.2 Plasma Torches

Thermal plasmas produced by electric arcs are typically generated in devices called plasma torches. These devices combine electric arc and fluid flow to transfer heat to a condensed or gaseous phase.

Plasma torches are generally divided in two major categories: non-transferred and transferred.

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2.2.1 Non-transferred plasma torches

In non-transferred plasma torches the electric arc strikes between two electrodes inside the torch. The electrodes can be made of different geometries and metals (or even metal oxides) and if the cathode material is chosen as thoriated tungsten, an inserted button or tip of this material is made and an external copper cylindrical anode completes the torch, and copper electrodes are usually employed to be used as concentric cylinders. The schematic representation of both types of torches are shown in Fig.1. [19-20]

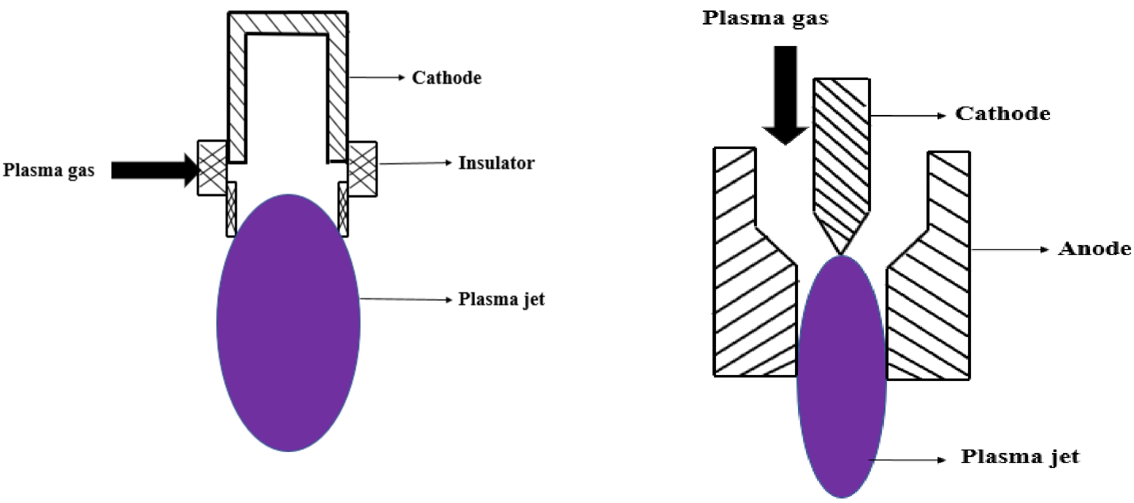

Fig.1.(a) Non-transferred copper electrodes Fig.1.(b) Non-transferred torch tungsten electrode

Then the gas flows inside the torch it is heated by the electric arc, thus forming the plasma jet at the outlet of the torch. This plasma torch type is generally applied for liquid residue treatment and powder spraying applications. The torch power can range between 1 kW- 6 MW. Major issue with torch type is electrode erosion [19-20].

2.2.2 Transferred Plasma Torches

In this type of plasma torches the electric arc strikes between an electrode of the torch and a metal (or other material) bath (at the beginning of operation the metal is normally solid, melting during olmation) located inside the vessel as can be seen in Fig.2. The electrode is made of metals such as graphite rod (which contains central hole for passage of gas) or thoriated tungsten. The gas injected in the plasma torch is heated by electric arc formed between the metal pool and inside electrode. These plasma torches have a high-power level (greater than 10 MW) and also gas level has to be kept minimum if necessary [21-22]. Fig.3 shows Ion arc process. These devices are generally implemented for treatment of solid residue or in metallurgical processes. The transferred plasma torches has greater energy efficiency as compared to non-transferred type as majority of the heat is transferred to the material to be treated directly.

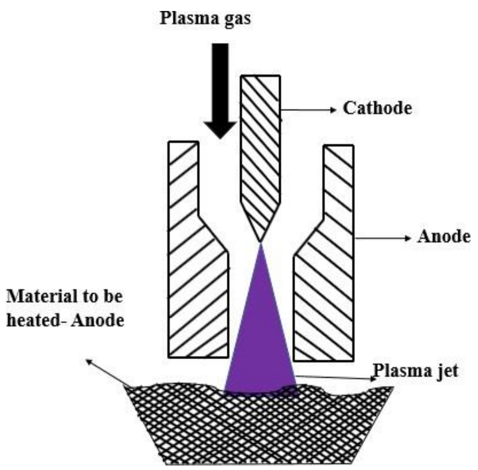

Fig.2. Transferred torch

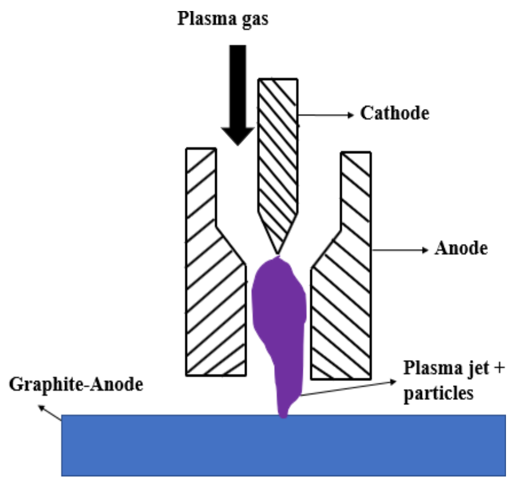

Fig.3. Ionarc process

3. Industrial Applications of Thermal Plasmas

Thermal plasmas are implemented in broad range of engineering applications. The major areas of industrial applications can be divided into; a) metallurgical/ steel making, b) environment, c) materials, d) low power-plasma cutting and welding, powder spraying. The low power applications (welding and cutting, powder spraying) of thermal plasmas is an established industry. However, the other three areas of high-power applications have garnered significant attention globally and specifically in the domain of environment.

3.1 Low power applications – powder spraying, welding and cutting

Plasma torches operating from 1 to 100 kW are employed in welding, cutting and powder spraying. The geometries of these torches vary according to the application, but in general they all have a thoriated tungsten cathode and a cylindrical copper anode. In the case of welding and cutting the torches operate in a transferred mode (the copper anode of the plasma torch in this case is used to help the stabilization of the arc but does not carry current; the anode for the arc is the piece been cut); for powder spraying usually the plasma torches are non-transferred type.

Plasma torches operating from 1 to 100 kW are implemented in powder spraying, cutting and welding. Based on the application type the geometry of the torch varies, but basically, they all comprise of a cylindrical anode (copper) and cathode (thoriated tungsten). In case of cutting and welding the torches operate in the transferred mode (the stabilization of the arc is done by the copper anode which does not carry the current; the piece been cut is the anode for the arc); For power spraying the generally the non-transferred type plasma torch is used.There are various manufacturers of low power plasma torches, include

AVCO, Metco, Plasma Technik Metco, Metco, and etc. [23]

Earlier in the 60’s thermal plasmas were predominantly used for cutting metal pieces. The various working gases used for cutting include argon-hydrogen, air, nitrogen, oxygen, argon and water (injected into the plasma column to reduce the diameter), depending on the plate thickness and material type to be cut. Plasma torches can also used when the metal piece is kept within the water pool for avoiding any plate deformation. Amongst the three main techniques of cutting, ie, hydrocarbon-oxygen, laser and plasma, plasma offers the higher cutting speed (upto 20 m/rain for 1 mm steel plate), however for precise cutting CO2 laser is generally preferred (precision of laser is tenth of a millimeter whereas for plasma its order of millimeter). The final decision on which method to be employed depends on several factors such as characteristics of the piece to be cut, time required for operation, investment costs (laser is the most expensive),followed by plasma and hydrogen-oxygen. The torches employed for welding are similar than for cutting, i.e., transferred arc plasma torches, though lower power levels are utilized (2-10 kW). The plasma gases used are usually argon or argon, hydrogen, to guarantee the integrity of the welding (avoiding the formation of oxides on the metal plate). Particularly interesting is the welding of thin sheets or pieces, where the classical TIG (tungsten inert gas) presents an erratic behavior of the electric arc due to the low currents used;

The working gas used to generate plasma are generally argon hydrogen or argon, to ensure the reliability of welding (avoid oxide formation on the metal plate). Particularly noteworthy is the welding of the thin pieces or sheets, wherein tungsten inert gas (TIG) presents an inconsistent behaviour of the electric arc due to the low currents employed. For these conditions plasma torches have a substantial advantage (the torch geometry and the usage of the gas stabilizes the arc column) [22-24].

Plasma torches have been utilized in industries for more than 5 decades now to weld copper, Inconel, stainless steel, titanium and other metals (except aluminium and its alloys). The utility of plasma torches for spraying powder dates back more than 5 decades, demonstrating today a standard tool for such applications. The operating principle is the particulate material injection (such as ceramics or metals) into the plasma jet (at the outlet of the non-transferred plasma torch) where the particles are softened or melted in the plasma jet and further accelerated where the particles impact, consolidating therefore and forming a deposit or coating.

Plasma spraying can operate at low and atmospheric pressure, depending on the application desired. Materials such as tungsten carbide, zirconia, alumina, chromium oxide, chromium carbide. Plasma spraying can operate at atmospheric pressure as well as low pressure, depending on application requirements. Metals such as zirconia, chromium oxide, chromium carbide, molybdenum, nickel-chromium, etc are usually employed for depositing using plasms torches to form mechanical, chemical or thermal barriers for metal or ceramic substrates. Aircraft engines, pumps, compressors, and others in the aerospace, chemical and automobile industries are few of the general uses of plasma spraying.

Plasma Transferred Arc (PTA) have also been employed for locally melting surfaces whilst depositing new particulate materials [23-24].

3.2 Metallurgical Applications

High power plasma torches have been initially applied in metallurgical applications. The practices in these industries are highly energy demanding. Generally, very high temperature is essential for these processes (1,000 ℃ to 2,500 ℃ promoting the application of thermal plasmas.

3.2.1 Melting of Iron

In 1989, the General Motors installed a cupola which was plasma assisted in their foundry at Ohio to remelt scrap and iron turnings. Six plasma torches of 2 MW (each) non-transferred type were mounted on the tuyere end to superheat the air blast. The energy required for melting is partly supplied by air blast and combustion of coke.

In comparison to the conventional cupola, the merits of plasma system are lower air pollution control cost, enhanced productivity, lower exhaust gas volume, improved alloy yield, usage of low cost raw materials (borings)[23].

3.2.2 Tundish heating

Thermal plasma has been applied for heating of metals in laddie and tundishes of continuous casters in steelmaking process. The molten metal temperatures are kept within 5℃ using plasma torches (non-transferred and transferred) that enhances the steel quality to be fed to the caster whilst maintaining the optimal temperature for casting process.

Companies such as C.F.&I, Chaparral Steel, (USA based), Kobe Steel ,Nippon Steel, NKK Co (Japan based) have implemented plasma system for this application [23-24]. The overview of industrial applications of thermal plasma is shown Fig.4.

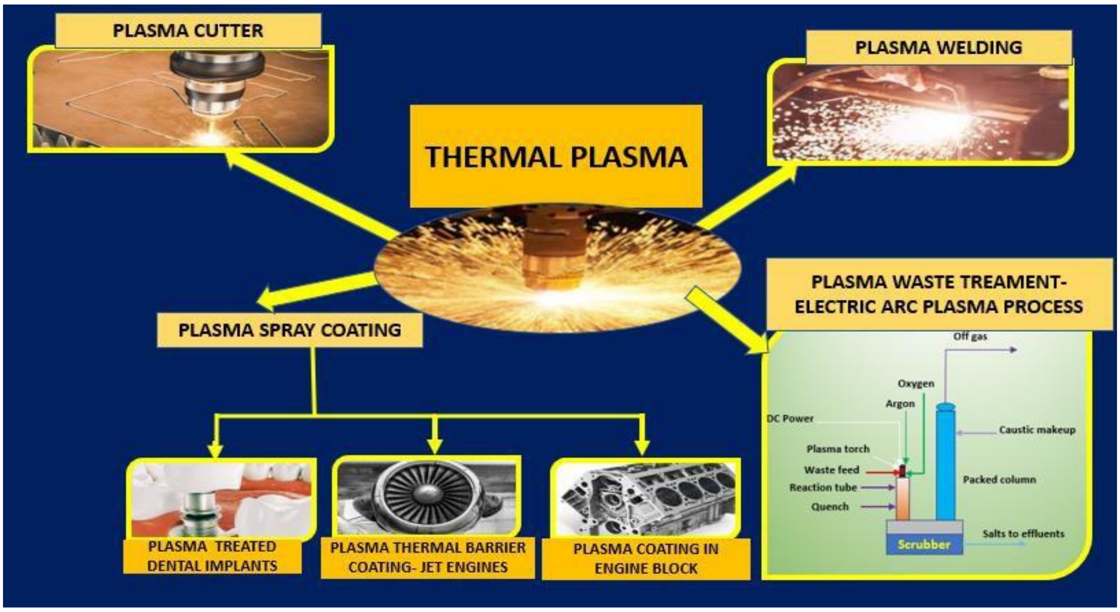

Fig.4. Industrial applications of thermal plasma

3.2.3 Melting or Remelting & Refining

Plasma refining/melting of metals & their alloys have been implemented effectively in industry, precisely with respect to refractory metals and alloys. Some of major benefits of employing plasma furnaces in this area are: inert atmosphere, high melting rates, low noise levels, minimum contamination of the products, and stable power conditions. Typically, transferred plasma arc process is used for refining/melting [25-26].

In this particular furnace design, homogeneity of the metal was obtained via induction coil which was used for stirring molten bath. There are numerous examples of plasma melting furnace which includes hybrid plasma furnace (Induction & DC) that had been developed by Daido steel [27] for refining/melting special alloy types, Fretial [28] in Germany had developed a plasma furnace that used 4-transferred arc plasma torches with a power consumption of 4 MW each which had been successfully applied for melting of nickel and iron alloys and further, Rowan et al.[29] designed arc plasma- DC transferred type for direct steel making and waste dusts.

Plasma based processing technology is being employed for titanium alloys in cold hearth melting [30]. In the aviation industry, the prerequisite for titanium to be employed is that it should be free of impurities ie, high density inclusions (HDI), eg. high interstitial defects (HID) and tungsten carbide. The cold hearth technique of titanium melting prevents the occurrence of impurities. In this technique, feed material might be recycled scrap/ titanium sponge which is fed into hearth made of copper wherein the melting is done by the plasma source. The molten metal goes to refining hearth and finally to the withdrawal crucible.

Generally, Titanium ingot of high quality fulfil the demand of titanium (defect free) for the aircraft industry.

4. Plasma chemical synthesis

One of the most vibrant areas of research in plasma technology is the synthesis of fine (submicron sized) powders of high value materials (such as nitrides, oxides, carbides and borides). The gas phase synthesis generates powder with essential characteristics such as small average size, narrow size distributions & high sphericity as these processes are done in controlled and pure atmosphere. Furthermore, these characteristics are essential for successive fabrication of advanced materials via powder metallurgical processing.

One of the essential requirements for advanced structural material is the generation of fine quality powder. The powder's purity and size of the particle is imperative in defining the final properties of sintered material. The reactivity of these fine particles improves the densification process. As material comprising of fine particles have smaller flaw size which inherently optimizes the mechanical properties such as fracture toughness and strength. The mechanical reliability, fracture toughness & strength in the sintered product necessitates a fully dense ceramic body as possible. Further, as pore size increases there is drastic decline in the fracture toughness, especially near the surface of sintered product. Further when the particle size is less than 1 µm then it leads to similar pore size that could become precursors for failure and crack propagation at even low stress. Numerous processing methods have been established which include chemical vapor deposition and sol-gel technologies to produce fine ceramic powders with oversized particles kept to a minimum[42]. The plasma reactors generate high temperatures which is sufficient to vaporize any material & also improve the kinetics of reaction by several orders of magnitude. It is possible for generation of fine sized particles in these plasma reactors as they provide steep temperature gradient.

There exist several technologies that can produce/ synthesize nanophase materials such as, gas condensation, rapid solidification from liquid state, mechanical alloying, chemical vapor deposition etc. However, plasma arc (thermal plasma) has high concentrated enthalpy which can vaporize any material under one important condition, which is reactant being properly injected into the plasma arc and has sufficient residence time in hot zone. The steep gradients of temperature present in the plasma reactor provide homogenous nucleation resulting in generation of nanosized particle [31-33].

There have been several excellent investigations linked to the development of fine ceramic powders in plasma reactors[31-35]

Plasma based processing has been established for production of fine ceramic powders. Until recently, this processing had been done only on pilot scale or in research labs. Further, various novel plasma reactor systems (RF & DC arc) had been designed for producing fine ceramic powders. Some of the plasma based processes for generation of ceramic powders is listed in the Table-1.

Table-1. Plasma-based process for ceramic powder generation

Reactants	Gas	Product	Type	kW	Size	Ref
SiO_2 + CH_4	Ar	SiC	RF	10	µ size	31
$MeSiCI_3$	Ar + H_2	SiC	RF	10	< 1.0 µ	32
$TiCl_4$ + CH_4	Ar, H_2	TiC	DC	11.4	.01 µ	33
$TiCl_4$ + CH_4	H_2	TiC	DC	30	10-40 nm	34
WCl_6 + CH_4	Ar, H_2	W_2C	DC	11.5	02 µ	33
W + CH_4	Ar, H_2	WC	DC	-	10 nm	35

Further, in industries, there is ever growing demand for nanomaterials effectively to reduce the size of electronic gadgets [36-38]. Zoltan et al.[39] employed RF based thermal plasma systems for generating nano sized ceramic powder.Zoltan et al.[39] used two ceramic materials lanthanum hexaboride & SiO_2 in their experimental study for understanding the effect of synthesis conditions on the nano-particles properties which includes the composition concentration, feed , plasma power, state of matter, phase composition. Their results proved the effectiveness of RF based thermal plasma for synthesizing nano-sized ceramic powders with special characteristics.

Another type of plasma generation method is Radiofrequency (RF) induction plasma produced via inductive coupling mechanism. When the high voltage and alternating current of RF is supplied to a spiral coil, then due to alternating electromagnetic field there is heating of conductor which is placed at the center of the coil. During this process if there is gas flow through this coil then it will ionize the gas and heat it, leading to the formation of plasma, thus facilitating the conversion of electrical to thermal energy. The plasma is referred to as inductively-coupled plasma (ICP). Guo et al.[40] had successfully generated inductively coupled plasma employed for nano powder synthesis as shown in Fig.5.

Fig.5. Photograph of the inductively coupled

plasma [40]

Silicon nanopowder can be derived from silane gas or from vaporized micro-sized silicon powder using induction plasma synthesis process [41] as shown in Fig.5. Fig.6 shows the induction plasma synthesis of nano powder.

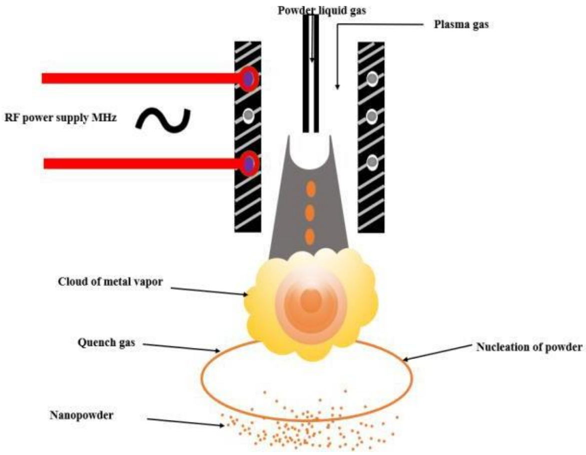

Fig.6.Induction plasma synthesis process of nanopowder

Audrone et al.[42] successfully employed RF plasma synthesis process for generating nanosized amorphous ceramic particle. In this study, an amorphous ternary system of alumina-silicate ceramic powders containing an alkaline earth metal was prepared by the RF thermal plasma processing route. For the preparation of precursors, Al_2O_3 (~10 μm), KOH and two different sized SiO_2 powders with particle size (~6 μm and ~40 μm) were used as starting materials. Their experimental results established that the SiO_2 particles size played a pivotal role in the development of the alumo-silicate nanoparticles. Fig.7. shows the SEM images of SiO_2 powder after injection into thermal plasma (RF-coupled) and collection of particles after cooling.

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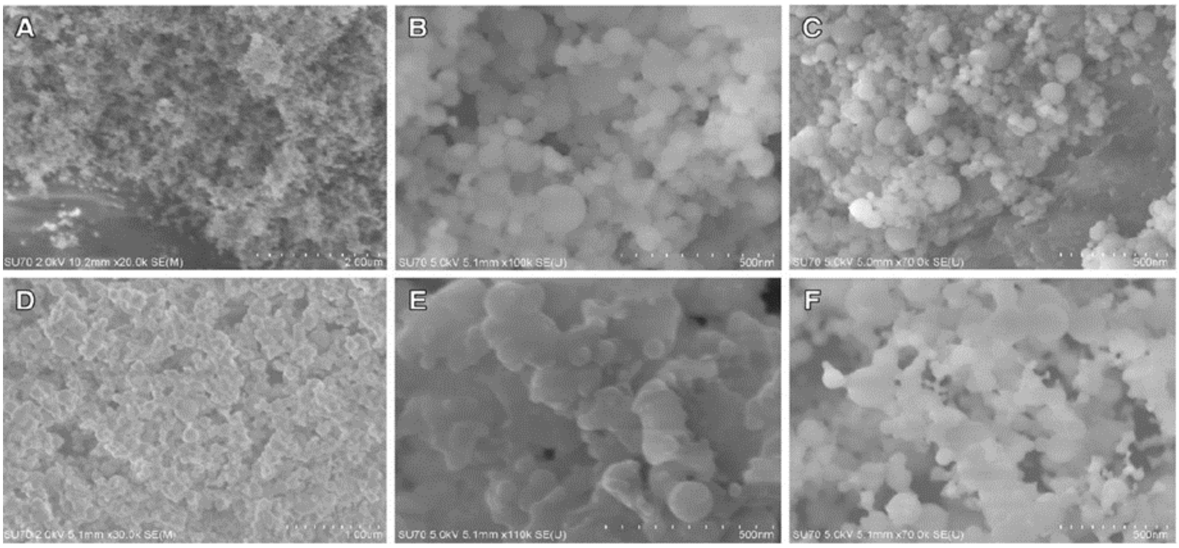

Fig.7. SEM images of the SiO_2 powders with particle size 40 µm (after injection into thermal plasma and cooling) at magnifications 20,000× (A), 100,000× (B), 70,000× (C) and of the KAS40 powder at magnifications 30,000× (D), 110,000× (E) and 70,000× (F) [42].

The results [42] indicated that with increasing particle size of SiO_2 powders from 6 to 40 µm, smaller grains and spherical shape of the synthesis products were achieved using RF coupled plasma. Furthermore, representative TEM images of the SiO_2 (particle size 6 µm) and SiO_2 (particle size 40 µm) samples as seen Fig.8. show that fine spherical particles are

highly agglomerated, and almost no individual particles can be observed.

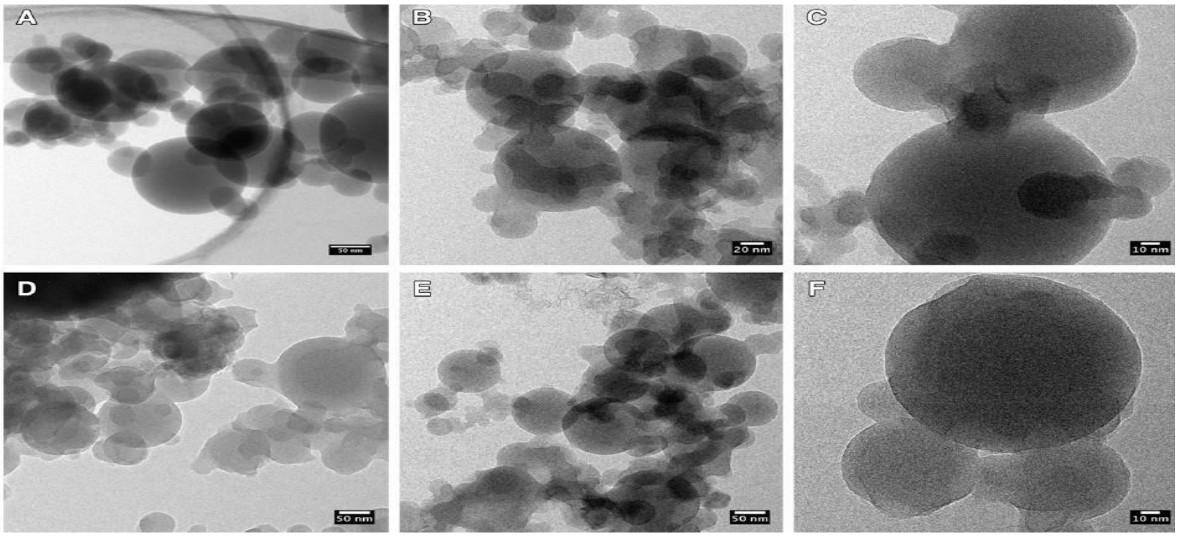

Fig.8. TEM images of the SiO_2 powders with particle size 40 µm (A, B, C) and the SiO_2 powders with particle size 6 µm (D, E, F) particles taken at different magnifications [42].

In this field of thermal plasma, Uda [43] produced nanosize metallic powders with DC plasma arc furnace. Kikukawa et al. [44] employed a RF plasma reactor successfully producing nanosize Ni particles with a 12 nm diameter. Girshick et al. [45] produced iron powder (20-70 nm size) using RF plasma reactor at atmospheric pressure.

One pivotal factor for the application of plasma reactors for the manufacture of nanosized materials is the significance of producing significant quantities of different material types in clean atmosphere. Moreover, as plasma arc contains high enthalpy it can vaporize any refractory material, enabling the possibility of creating nanophase structures of refractory materials.

5. Plasma Based Spray Coatings

Plasma sprayed coatings on various types of substrate material have been used for the last 5 decades for applications such as corrosion and wear resistance, thermal barrier etc. These coatings can be of metals, ceramics, alloys, composites [46-51].

5.1 Plasma Spray Techniques for Deposition of Functionally Graded Coatings

5.1.1. Atmospheric Pressure Plasma Spraying (APPS)

There are various methods of coatings manufacturing in the field of thermal plasma. Among them, plasma spraying technique is one of the most widely employed, due to its reasonable cost and broader range of applications [52]. First patents, connected to the introduction of this method in the industry, were done during 1960s [53-54].

The schematic representation of atmospheric pressure-based plasma spraying techniques are shown in Fig.9 (a,b)

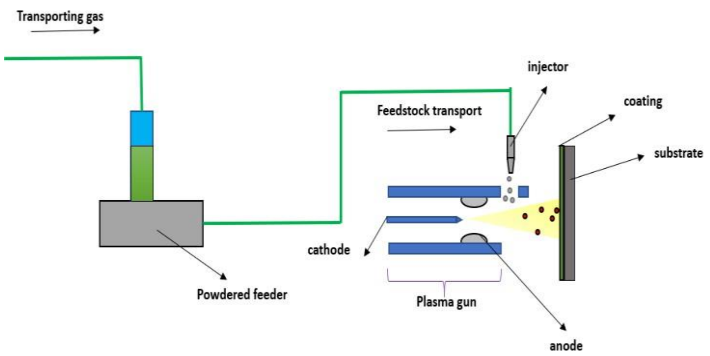

Fig.9.a

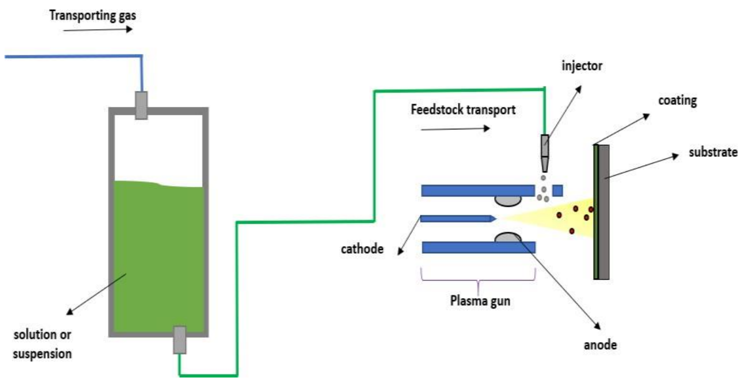

Fig.9.b

Fig.9.a. Schematic representation of plasma based spraying coating using atmospheric plasma spraying

Fig.9.b. Schematic representation of plasma based spraying coating using suspension plasma spraying

The electrical arc is ignited between thoriated tungsten cathode & copper anode. Plasma gases are heated ,ionized, which expands further leading to the formation of the plasma jet. Carrier gas is employed for transport of the powder particles ,which are then forced into hot stream of plasma jet, this leads to heating and acceleration due to drag force. These particles which acquire higher kinetic energy from the plasma collide with the substrate material thereby develop splats. These splats would solidify and form the coating [55].

The main mechanism involves the composition of the working gas. There are two groups of gases employed; (i) primary; and (ii) secondary. The role of the primary gas is to stabilize the arc inside the torch's nozzle, eg. Argon

(Ar). Whereas, the secondary gas only enhances the thermal conductivity of the plasma [56].

The other factors governing the APPS system include the following.

1. Flow rate of plasma gases
2. The size distribution (particle size:20-90 micron) and feed rate of the used powder.
3. Power supply
4. The velocity of plasma torch with reference to the substrate.

Fig.10 shows the schematic view of process parameters considered during APPS.

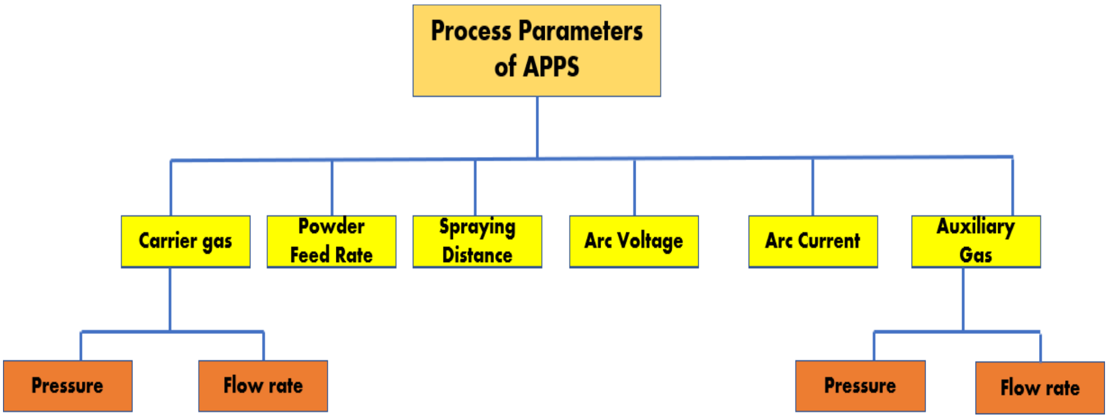

Fig.10. Schematic view of process parameters considered during APPS

Nevertheless, there are many other parameters, which influence also the coatings structure and properties. Therefore, their optimization is very important. Other than the these there are numerous parameters that impact the properties and structure of coatings. Therefore, optimizing these parameters is very essential [57-58].

Generally, the powder is injected radially with injection angle between 75-120° with regard to the axis of torch. The injectors are mainly outside the plasma torch. The flow rate of the plasma gases vary from 40 (low power torch)-450 slpm (high power torch) (standard liter per minute) [59].

The powders sprayed by APPS technique are most commonly oxide ceramics, such as, ZrO_2, TiO_2, Al_2O_3, Cr_2O_3 which includes both mixture and their alloys [58,60]. It is imperative to mention that some of the non-oxide coatings can also be done using APPS such as nitrides, carbides, and borides [61-62]. In similar fashion, cermet coatings can also be deposited using APPS [63-65]. The Fig.11 shows manufactured coating by APPS technique.

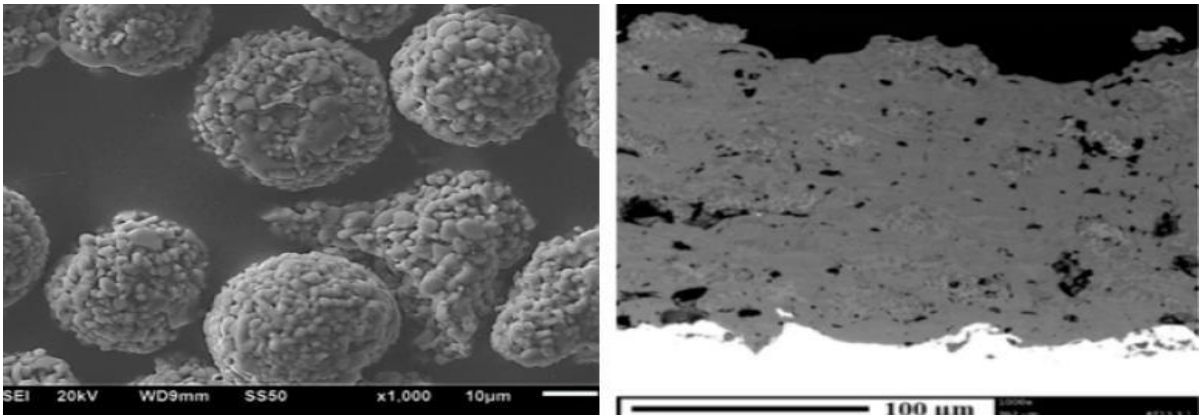

Fig.11. SEM image of Al_2O_3 + 13 wt.% TiO_2 powder (left) and APPS coating sprayed therewith (right) [66].

In case of air based APPS, the adhesion strength usually varies between 15- 30 MPa. Whereas for bond coat employing materials such as Ni-Cr/Ni-Al have higher adhesion of about 70 MPa. The physical attributes of APPS coatings may highly porous (greater than 20 %) or low depending on the process parameters. The coating thickness of APPS technique is typically few hundred µm [65].

6. Plasma based Suspension Spraying (PBSS)

One of the major drawbacks of powder based conventional thermal spray techniques is the fine powder processing. Smaller particle size of low-density materials cannot be injected easily into high-energy flame or jet [66-67].

This fact clearly illustrates that nano sized/sub micro grained coatings cannot be obtained using conventional power based thermal coatings. For solving this issue, the novel idea of implementing suspensions instead of dry powder had been patented by Gitzhofer et al. [68].

The most significant advantages of PBSS [69] is that -

1. The force of compressed gas is used for used pushing the liquid which in turn transports the feedstock from feeder to torch.
2. The microstructure of any coating can be implemented by using either continuous or atomized liquid stream.
3. Fine powders in the form droplets can be introduced into the plasma jet without much effort.
4. Solvent may act as some form of barrier between the fine particles and high temperature plasma jet

The application of PBSS technique is beneficial in the deposition of functionally graded coatings. This PBSS process creates the opportunity to design the microstructure. Macwan et al.[70] had deposited yttria-stabilized zirconia electrolytes (YSZ) coatings on stainless steel substrates using PBSS. There results proved that the porosity in as-deposited YSZ coatings reduced with higher torch power. Marr and Kesler [71] implemented PBSS technique for coating YSZ electrolyte on stainless steel substrate and found that shorter stand-off distances generate better adhered and denser coatings. They observed that at high torch powers will effectively evaporate the suspension liquid and lead to melting of feedstock particles, and further the implementation of stand-off distances diminishes particle fraction that re-solidify prior to impact. Latka et al.[72] had used PBSS for spraying ZrO_2 + 8 wt.% Y_2O_3 (8YSZ) on stainless steel substrate and proved that larger spray distance decreases Martens hardness. The implementation of PBSS process involves accumulation of numerous parameters that is depicted in Fig.12.

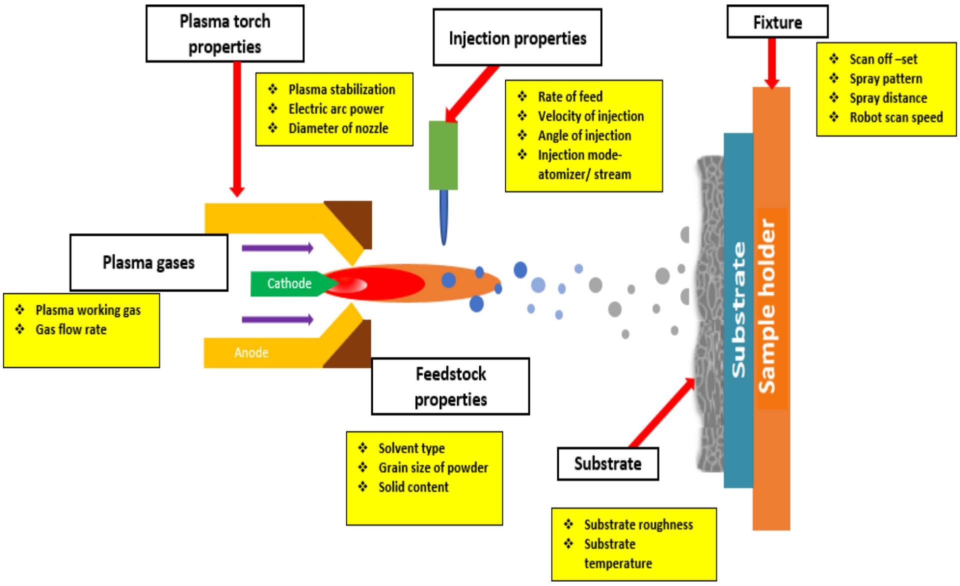

Fig.12 Process parameters in PBSS technique

It is also imperative to understand the interaction between the plasma jet and suspension which is essential for optimizing the PBSS process. The interaction between the liquid phase of suspension on the hot gas is vigorous. During the injection process of suspension, the liquid suspension is influenced by inertia, surface tension and viscosity. These interactions can be quantified using Weber number (We) and Reynolds number (Re). Generally high values of We & Re promote finer and rapid atomization [73]. Initially after the injection of suspension an aerodynamic breakup takes place. This breakup is predominantly due to the aerodynamic forces. Further, the solvent (liquid) evaporates in short duration due to the high energy of plasma jet. Then, sintering process of fine particles is initialized. This could pose an issue due to the nature of collection of fine particles into coarse ones. The sintering time purely depends on the plasma jet temperature. Immediately just after the sintering the melting of fine solids takes place and they start to buildup. Furthermore, the partial liquid begins to vaporize and finally (partial/full) molten particles impact the substrate. As shown in the Fig.13 there are limited particle types to impact on the substrate.

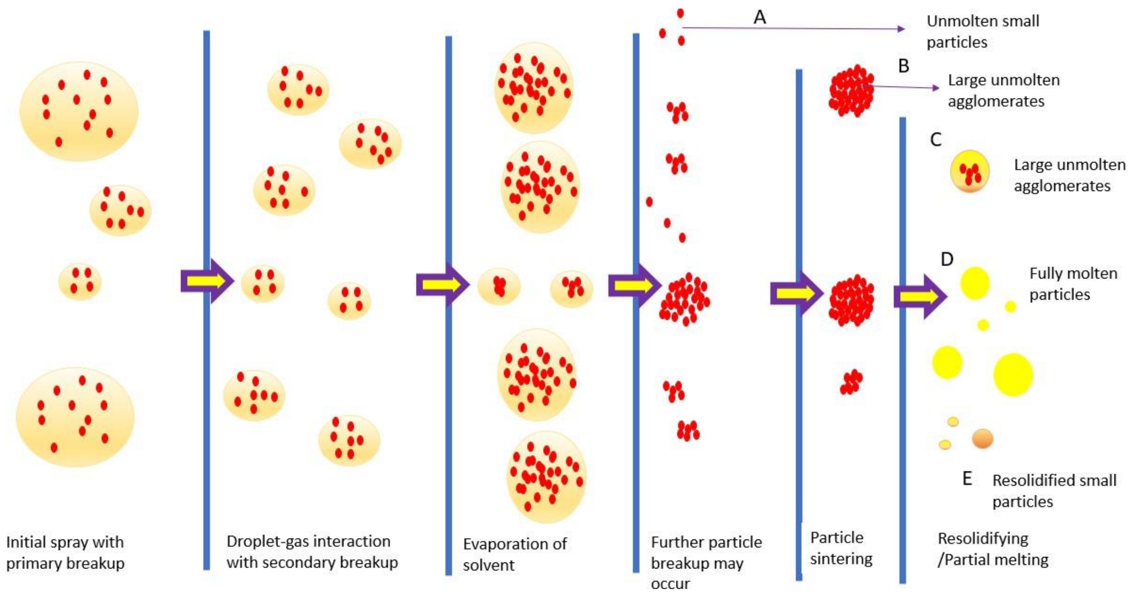

Fig.13 Droplet formation process in PBSS technique

7. Challenges of Thermal Plasma Production

Processing of materials by application of thermal plasma involves: material melting, providing momentum to material and requirement of chemical reactions. One of major technological challenge is to obtain best possible interaction between the processing material and plasma generated. In plasma spraying technology the particles have to be melted and provided required momentum by the plasma jet. In spite of the decades of plasma spray technology development the thermal efficiency of melting and heating plasma remains still low at 5%.

When a liquid material is to be processed, then the liquid needs to be atomised and injected into the plasma along with a carrier gas. There is an issue of non-uniform entry of the atomised liquid into the plasma. Gaseous material injection into the plasma seems simple in comparison to injecting atomised liquid or solid particles. The electrothermal instability of an arc column shows problems when an engineer tries to load material in the current-carrying region. As a cool material is injected into an arc column, the temperature in that region reduces. As the electrical conductivity is a dependent on temperature, the electrical conductivity falls in the part where the material is loaded and hence the current in that region reduces. That is, the arc column moves away from the cooler material when the rate of material loading increases above a certain limit. There are several methods to solve these issues occurring in thermal plasma employed in industries, the methodology to enhance the efficiency of material interaction with plasma is to inject the processing material in the axial direction of a plasma. The electrode polarity implemented in an arc system is important for the success of the plasma applications. The other methodology for enhanced generation of plasma in the downstream region of the arc column is to enable radial entry of gas into the arc column in the downstream regions. This technique has been applied in transpiration-cooled arcs.

Conclusion

The development and the present status of research of thermal plasma application is discussed. The obstacles that restricts thermal plasma from being applied in commercial ways. The various thermal plasma generation methods and its significant merits in materials processing areas have been analysed. The industrial requirements for technology development are to enhance the plasma utilization properties and to deliver a greater process control. Future progresses of plasma technology requirement to consider issues related to the plasma-electrode interactions ,plasma-material and generation of plasma and control in the context of industrial necessities. Thermal plasma is the potential future of material processing.

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