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Plasma-assisted material processing

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Introduction

THE highly visible search for controlled thermonuclear fusion in the laboratory—the plasma physicist's holy grail—has often relegated the practical applications of plasmas to the background. While the potential benefit to the society through the fusion route to energy production is enormous, plasmas have already contributed to the nucleation and growth of a new industrial technology—plasma processing—albeit without significant assistance from the plasma physicists. The purpose of this article is to discuss the science and technology of plasma processing, assess its international status and project its potential impact on the Indian industrial scene.

Materials and materials processing remain both internationally and in the Indian context a major industrial and technological concern. The various facets of this issue relate to production, transformation and conservation of materials. The thrust of this article is to highlight the promise offered by integrating the technology of plasmas to the material and manufacturing engineering technologies, assess its present status in the country and comment on the possibility of its growth into a major component of the Indian industrial scene.

Plasma state and plasma processing

Plasma is the ionized state of matter, obtained by dissociating atoms into positive ions and electrons. The electrons can be removed from the bound state by a variety of means, all of which involve imparting energy to the bound electron to enable it to become free of the attractive force of the nucleus. The minimum energy required by the electrons to do this is the ionization potential of the atom. The process of ionization can be achieved thermally, by heating the gas to very high temperature; by photons as happens in the ionosphere, chemically as in flames or through energetic electrons. The electron impact ionization has a peak value of $10^{-16}\,cm^2$ at about 100 volts for most atoms. This energy can be given to electrons in an electric field. Hence the most popular and convenient means of *plasma generation is through electric discharges where* primary electrons are energized in an ambient electric field and made to collide with atoms producing ionized species.

The plasma state is uniquely different from the ordinary states of matter in a number of ways. First of all, plasma contains free electrons and ions, which being electrically charged, can respond to external electromagnetic energy fields and transport electromagnetic energy. The fluid properties are enhanced by the particles setting up internal self-consistent electric and magnetic fields, resulting in the generation of collective effects like flows, waves, instabilities and self-organization. It is, in general, a multispecies fluid, with electrons, ions and neutral particles having independent thermal distributions, which need not be in equilibrium. The internal energy is composed of thermal, electric, magnetic and radiation fields, whose relative magnitudes allow the plasma state to exist in a large parameter space as represented in Figure 1.

Depending on the means of producing the primary electrons, energizing them and how they partition their energy to the plasma particles, we can classify industrially relevant electrically generated plasmas in the following way:

(i) Metal vapour arc plasmas: At very low pressure, one can maintain a plasma by melting and evaporating one of the electrodes. These plasmas are industrially used for ion plating and thin metallic film coatings. A specific example is the deposition of titanium nitride coatings, when the arc is run in a low pressure nitrogen environment.

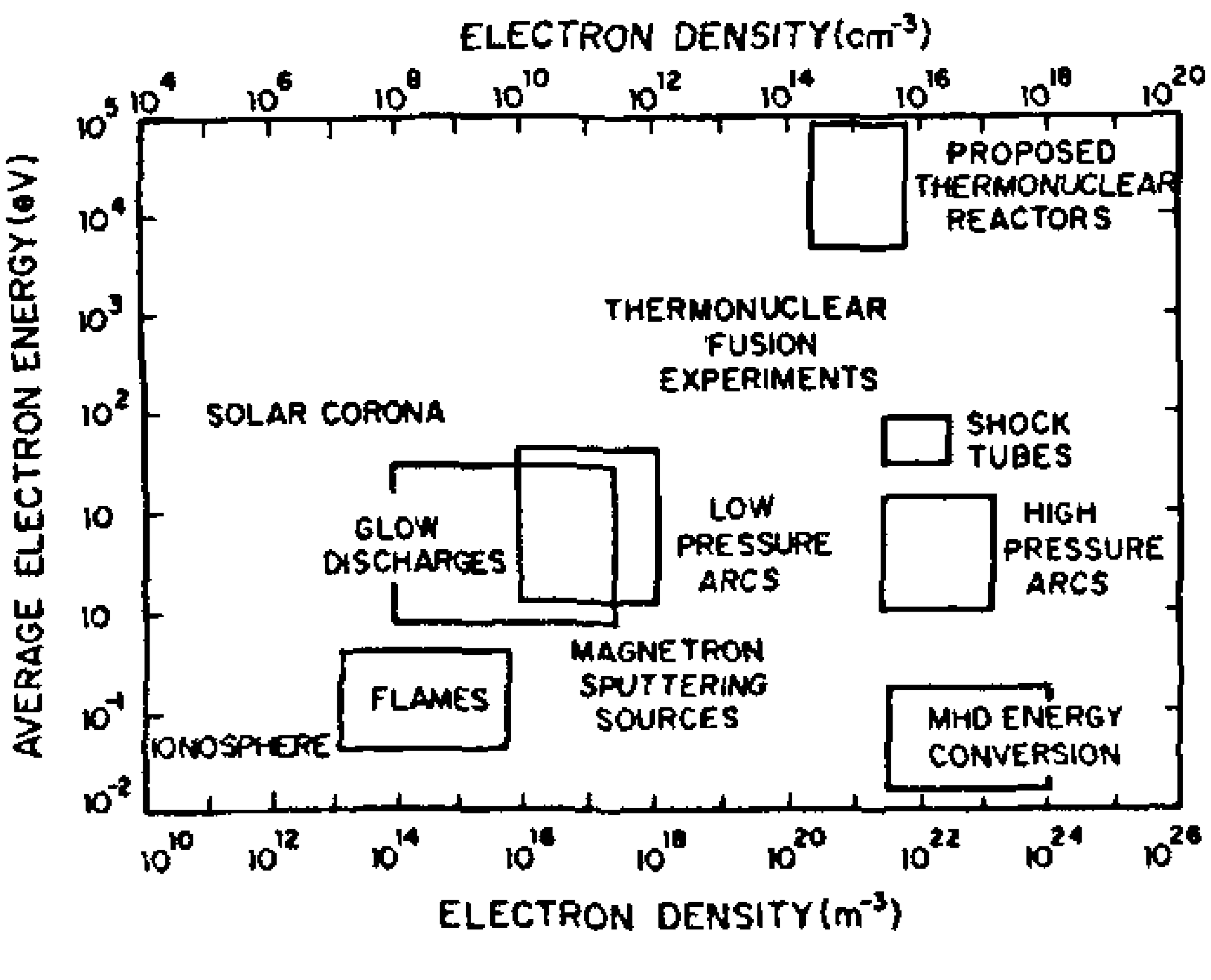

Figure 1. Plasma parameter space.

(ii) Glow discharge plasmas: At medium pressures in the range of millitorrs to torrs, high voltages maintained between non-consumable electrodes will break down the gas. The equilibrium discharge is maintained by electrons emitted from the cathode by secondary electron emission by ion impact. All gases, both reactive and nonreactive can produce glow discharge plasmas. The electric field energy can also be supplied by radiofrequency or microwave power. The non-equilibrium plasmas are industrially used for ion implantation like in ion nitriding, plasma chemistry, plasma polymerization, etc.

(iii) Arc plasmas: When the pressure is very high, that is, near atmospheric pressure, the glow discharge makes a transition to the arc discharge, where the electron emission from the cathode is by the thermionic process and the plasma particles are all at the same temperature due to efficient collisional energy equipartition. The gas and plasma temperatures can reach tens of thousands of degrees in arc plasmas and hence they are high energy density thermal sources. These plasmas are the workhorse of metallurgical and engineering plasma processing.

The potential of plasma technology as an industrial tool arises from the properties of the plasma state. Plasma physicists have enunciated many fanciful ideas—remember Alfven[1], who speculated that the mass segregation which gave rise to the proto-solar system was due to the critical velocity phenomenon which operated on the neutral gas cloud gravitationally falling towards the sun in the presence of the solar plasma and the solar magnetic field—on the possibilities of using plasmas in material processing. However industrial revolutions hinge around simple but workable ideas, of which plasma processing has plenty.

Certain properties of a plasma can be optimized, enhanced or highlighted leading to a focus in the application. Thus we have fusion plasmas where particle temperatures are enhanced, impurity content minimized, and confinement enhanced or MHD plasmas where flow velocities and conductivity enhanced. In the same spirit we will call those plasma processing plasmas where the parameters relevant to plasma processes are enhanced or optimized. The process plasma, thus defined, differs from other plasmas in a number of ways. First of all, there is no confinement required and in fact one prefers deconfinement since the throughput of processing depends upon fluxes of ions and electrons depositing their energy on the process substrate. Hence, there is very little equilibration between species. This means that the characteristics of plasma formation and loss will imprint certain properties on the plasma. Secondly, we will see that the species which are used to form the plasma determine some of the properties due to the specific atomic physics and chemistry; in the process plasma context, an oxygen plasma and a nitrogen plasma could have distinctly different properties.

The very process of ionization in an electrical discharge increases the energy content of the plasma through ohmic heating of the conducting plasma. If the gas pressure is very high, say, an atmosphere, these electrons collide very frequently with the background neutrals and ions, sharing a part of their energy and making them equally hot. Even in this case the average fluid temperature will be quite high, in the range of thousands of degrees and we call this the thermal equilibrium plasma. Such plasmas are essentially very high temperature fluids and hence the most important applications are where materials have to be heated to melting or vaporization temperatures. The major distinction of the plasma flame from other chemical flames is that the temperature is independent of the oxygen potential and indeed it is this freedom to attain arbitrarily high temperatures without the presence of oxygen that renders the plasma a very unique, clean and non-oxidizing flame, which has immense application in high temperature technology.

As the pressure is decreased, the equilibrium between the electron, ion and neutral fluids is lost, with the result that the electron temperature increases, with the ion and neutral species remaining cold. Such plasmas are called non-equilibrium plasmas. The thermal energy content of these plasmas is quite low. It is not unusual for a simple laboratory plasma device to have electron temperatures of the order of 50,000 degrees. A consequence of the high mobility of the electrons is that they escape to the walls in short times. However, the loss of electrons at this large rate results in the rest of the plasma getting a net positive charge, pulling the electrons back. This ultimately results in an equilibrium where the electrons and ions will be lost at the same rate, by the establishment of an electric field within the plasma, called the ambipolar field. This is a process by which the nonequilibrium plasma creates electrostatic energy from the kinetic energy of the electrons.

The ambipolar potential or the plasma potential is thus the potential attained by the plasma with respect to the wall which receives equal fluxes of electrons or ions or in other words, zero current. Alternatively, if we leave a surface exposed to plasma, and leave it floating electrically by collecting no net current to it, it will attain a potential negative with respect to the plasma. Hence the ions, although they may have low temperature and kinetic energy within the plasma, will be accelerated to high kinetic energies when they fall on these surfaces. This collective acceleration process is an interesting plasma phenomenon which has many applications in surface texturing, plasma polymerization etc.

Both equilibrium and non-equilibrium plasmas have a tendency to maintain overall charge neutrality which manifests in the so-called Debye shielding effect. An external electrode introduced into the plasma and biased to a positive (negative) polarity will repel ions (electrons) from it and accelerate electrons (ions) to it. The region where the charge separation takes place is the Debye sheath[2]. Thus ions can be accelerated to large kinetic energies by this formation of the sheath around a biased electrode. One of the earliest applications of this is the sputtering effect and more recent applications include ion implantation on surfaces[3].

So far we have not said anything about the presence of the cold background neutral gas from which the plasma was produced. However, the presence of energetic electrons and electrostatically accelerated ions will not leave the cold background gas unaffected. Excitation of gas species by electron collisions[4] is a very important plasma effect which results in the production of active neutral species. This depends upon the excitation cross-sections and the electron energy distribution function. The production rate is balanced by the loss rate which can be by photon emission and by diffusion to the walls. The net effect of the presence of excited and ionized species and their interaction with each other and with surfaces is that new types of chemistry—plasma chemistry—becomes possible[5].

Plasmas are excellent sources of radiation which can be of atomic (recombination, line) or collective (cyclotron, electromagnetic). Arc plasma sources can radiate up to 50% of its energy[6] which has been efficiently used in film melting applications. Collective radiation is important in plasmas, and has been exploited in coherent microwave generators. A very recent example where plasmas have been used as efficient radiation sources is the so-called E-bulb where a radiofrequency source is used to excite a glow discharge plasma which then emits recombination radiation.

To sum up, the plasma effects that dominate the plasma environment are: (i) Energetic electrons with Maxwellian or non-Maxwellian distribution functions; (ii) Conversion of electron kinetic energy into thermal energy in equilibrium plasmas and into space charge fields in non-equilibrium plasmas which can give directed energy to the cold ions. (iii) Tendency of the plasma to shield and localize externally applied electric potentials creating intense electric field regions called sheaths or double layers. (iv) Creation of excited neutrals by collision with energetic electrons and ions, which have high chemical reactivity. (v) The background of energetic radiation in a plasma produced either by atomic processes or by interaction with electromagnetic fields.

In reality and quite often, many of these processes operate simultaneously in a specific plasma-material interaction process. While this results in a wealth of effects, it also leads to an obscuring of the cause–effect relationship inhibiting the growth of plasma processing into a precise science. This situation is happily giving way as more scientific investigations into the specifics of the processes using modern diagnostics and computer modelling are being conducted.

Plasma as an industrial tool: The right niche

The competitiveness of plasma technology in the field of material processing arises because of certain unique features of plasmas in their interaction with matter. In thermal plasma technology, where plasma is used primarily as a heat source, these features are:

(i) High temperature: Combustion flames give a maximum temperature of about 4000 degrees whereas there is no theoretical limit to the temperature that can be obtained in a plasma flame. Typical atmospheric pressure plasmas have a temperature of 10,000 degree.

(ii) High energy flux: High energy flux as a result of high temperatures, high gas flow velocities and high thermal conductivities of plasmas permit high reaction volume intensities. In addition, additional energy flux from the electron heat transfer at the anode arc root attachment area improves the efficiency of processes like melting, smelting etc.

(iii) Gas environment control: Energy supplied to the system is independent of the oxygen potential and any environment, oxidizing, reducing or inert can be chosen. This makes the plasma flame more versatile than a combustion flame. Reduction of oxides like chromium, magnesium, manganese, silicon, titanium, and aluminium, which are endothermic or require strongly reducing conditions are apropriate for plasma furnaces.

(iv) Independent energy source: The feed rate and power can be controlled independently. The electrical conductivity of materials does not limit the input power. This allows greater freedom of choice with regard to charge composition, without having to consider the electrical characteristics of the charge.

(v) Rapid response: The time constants of the arc plasma are very short resulting in faster response in control and protective functions.

(vi) Fine particle feed capacity: The direct use of fine materials is possible, without the need for costly agglomeration. Plasma systems can operate with a wide range of gas flow rates allowing fine particles to be introduced in a flowing stream reactor.

The uniqueness of the plasma treatment in allowing exclusive niches is even more explicit in the case of non-equilibrium plasmas. A few examples will substantiate this statement:

(a) Nanoscale machining: Extremely high precision and control possible at the micrometer and nanometer dimensions have rendered processes like plasma chemical etching, film deposition etc the mainstay of large-scale semiconductor device technology.

(b) Exotic chemistries: Novel chemistry is made possible with the intervention of high energy electrons in the tail of the electron energy distribution function and the strong microscopic electric field present in non-equilibrium plasmas.

(c) Cold processes: The thermal energy density of the non-equilibrium plasma can be made extremely low with the result that the substrates or workpieces used for film deposition, polymerization etc can be kept at low temperatures. This enables treatment of samples which can be thermally degraded or where dimensional changes cannot be allowed.

(d) Rapid quenching: Non-equilibrium state of the plasma implies very large temperature differentials between the plasma and the wall within sheath dimensions of mms. Thus quenching rates of a few million degrees per cm is commonplace in plasma reactors.

Plasma processing: international status

Metallurgical plasma processing is a very old field. The first practical application of thermal arc plasma technology was introduced in 1878 by Siemens with the development of the direct current arc furnace for the bulk heating of materials.

A quantum jump in the technology of the plasma arc source took place in the 1960's with the advances in missile technology. Atmospheric re-entry of the missiles created a shock-ionized plasma in the air and it was required to simulate this in the laboratory for the development of materials capable of withstanding the searing heat of the plasma. Simulation arc systems were primarily designed to generate the re-entry conditions using clean, high enthalpy gases at high stagnation pressures. Many of the present-day arc plasma sources are derivatives of the plasma jet sources built for this application.

The impact of the plasma technology in the field of melting and remelting furnaces has been prompted by the ability to operate in both inert and reactive environments, thus providing complete control of the atmosphere; provide steady state operation for long times because of the absence of consumable electrodes, and give rise to compact systems that can process materials in a variety of forms at high throughput rates and with relatively high electrical and thermal efficiency[7]. Freital in Germany and Voest-Alpine in Austria have developed 15 to 35 tonne plasma furnaces for manufacturing high quality steels. Daido Steel in Japan has been operating a progressive casting furnace for melting and casting as a competitive process for vacuum arc melting, electro-slag refining and electron beam melting.

The impact of plasma processes in extractive metallurgy has been in their ability to process ores in the fine powder form. Mintek[8] in South Africa have been pioneers in adapting plasma furnace technology for the enrichment of low-grade ores. Recent plasma furnace work at Mintek involved high intensity smelting, high temperature reactions at the arc-attachment zone and the application of large scale plasma systems up to 3.2 MVA capacity. Furnaces for the direct reduction of ores to produce ferrovanadium and ferrochrome have been set up in Mintek in South Africa.

Plasma spraying or deposition is considered to be the most versatile coating technique. The desired material, in powder form, is introduced into a plasma stream. The injected particles get melted, highly accelerated onto the substrate forming the desired lamellar structured coating. Recent developments in this include vacuum arc spraying[9] or low pressure plasma deposition which give rise to higher particulate velocities producing greater than 98% dense coatings, broad spray patterns which produce large deposit areas, with high deposition rates up to 50 kg/hour.

Thermal plasma synthesis of ultrafine and ultrapure metal, alloy and ceramic powders has become an important international technology. This may proceed from solid, liquid or gaseous precursors. The international market for fine ceramic powders is estimated at $ 5 billion per year, with a projected annual growth of 28%.

Plasma consolidation includes the processes of spheroidization, densification and sintering. Sintering of high tech ceramics in thermal plasmas has the potential for drastically reducing the time required for this process. In addition restrained grain growth and tailoring of heat transfer during the sintering process are possible.

A recently emerging application of thermal plasma technology is in waste processing using plasmas. Commercial plasma energy systems are being developed for processing chemically active and hazardous wastes. Using a plasma arc torch at very high operating temperatures in a furnace smaller than that required for fossil fuel incinerators, studies show a lowering of both the volume and weight of waste significantly. The process produces only two by-products, gas and a glassy residue. They meet the statutory regulations on air quality and leakability. Analysis shows that the process is quite competitive in comparison with standard methods.

The foremost application of non-equilibrium plasma has been in the field of semiconductor device fabrication which utilizes the capacity of the plasma to etch materials from insulating surfaces exposed to the plasma using physical or reactive etching. The semiconductor processing industry is estimated to have a market of $ 26 billion annually.

Another important application of nonequilibrium plasma processing is in thin film deposition. The energetic ions from a plasma are used to sputter materials which get deposited onto substrate in submicrometer thickness. A related process is the plasma-assisted chemical vapour deposition. The market for fabrication of thin film electronic and optical component is a huge $ 40 billion. Thicker coatings such as titanium nitride and titanium carbide coatings can also be made by using the same technique and are important in the tool industry to increase the tool hardness and hence life.

A very recent and exciting development in this field has been the discovery of various techniques for depositing diamond-like carbon films[10]. DLC film preparation using plasmas can be classified broadly into ion beam-assisted and plasma-assisted chemical vapour deposition techniques. The plasma cvd technique involves decomposition/dissociation of a hydrocarbon gas in a plasma and was originally developed by Whitemell and Williams[11]. DLC technology is in its early stages. The limitations of the current techniques are[12]: (i) inability to coat large areas uniformly, (ii) inability to produce large deposition rates with the desired properties, (iii) high substrate temperature requirement of the order of 900° C and (iv) difficulty in nucleating diamond films on substrates other than silicon. These are issues which are currently being addressed in research.

The high energies of electrons in the glow discharge plasma of molecular species result in electron impact dissociation of the gas molecules. The by-products of dissociation include highly reactive molecular fragments and atoms that readily combine on substrates to form thin solid films at very high deposition rates of the order of a few micrometers a minute. Polymer deposition can be accomplished with molecular gas plasmas whose parent molecules contain polymerizable structures. Both organic and inorganic films can be formed by this process. Amorphous silicon films for photovoltaic generation, oxides and nitrides of silicon for dielectrics in microelectronic components, polymer membranes for gas separation, water purification and biomedical applications etc. are a few examples. Radicals can also react with the substrate resulting in the alteration of the surface such as molecular rearrangement, surface cleaning, surface hardening, etching and nonvolatile compound formation. Plasma polymerization for growing polymers on surfaces can have applications in corrosion protection which has an annual market of $ 50 billion. Organosilicone and other glass-like deposition to impart hardness to soft plastic surfaces is another major area of industrial interest.

The recent international recognition of the importance of plasma processing as an industrial technology is clearly evident in the US attempt to formalize institutional bases for interaction between scientists and the industry[13]. On the basis of a report and recommendations by the National Materials Advisory Board, the National Science Foundation has established the Engineering Research Centre Program. The program is designed to link academic engineering research and education to engineering practice. The Plasma-Aided Manufacturing Engineering Research Centre at the universities of Wisconsin, Minnesotta and Drexel have the specific mission to adopt the substantial body of knowledge already existing in the apropriate engineering and scientific disciplines to plasma-aided manufacturing, to achieve long-and short-term improvement in the usefulness of this field in industry. The goals of the Engineering Research Centres are: (i) To develop new processes to ensure that plasma-aided manufacturing will satisfy the present and future requirements of the industry. (ii) To develop new diagnostics, sensors, modelling, statistical and control strategies for plasma-aided manufacturing. (iii) To conduct the necessary engineering support studies needed to fulfil these missions. (iv) To provide a unified, cross-disciplinary experience for the large number of students interested in entering this exciting and demanding field of high technology and to expose a large segment of the graduating engineers to new concepts of design and system integration in this area and (v) To foster and maintain strong relationships between universities, industry and government for information exchange and technology transfer.

Plasma processing industry

Induction and assimilation of sophisticated technologies in the industry is a very complex process. In technologically advanced countries the interplay of market forces and technological vectors demand continuous upgradation of technologies and this scenario has not yet appeared in India. Nor is there an effective procedure for anticipating and upgrading technologies through government intervention.

The four components crucial to the development of an indigenous plasma processing industry are: R&D expertise and infrastructure, active system for information dissemination and technical advice, agents for technology absorption and commercialization, and market. Technology development and transfer, to become viable and healthy, must be a consequence of the strong interaction and linkages between the scientist, entrepreneur and the market. In the following, I shall make an assessment of the present status of these elements and discuss the specific steps needed to develop the plasma processing industry in India. Wherever possible I shall also highlight what IPR has already started or accomplished to make the discussion within the realm of possibility.

R&D expertise

The institutionalized research and development expertise in the field of thermal and non-equilibrium plasma science and technology is quite impressive.

The collective expertise in IPR in producing, manipulating and diagnosing non-equilibrium plasmas goes back to the last two decades, with individual experience even predating this. The interest in IPR on plasma-surface interactions from the perspective of fusion devices, as well as the development of spectroscopic and laser-based diagnostics provide powerful new inputs into the overall expertise. The technique of computer modelling of fusion plasmas can be appropriately modified to simulate collisional plasmas and can be a powerful tool in optimizing process development.

The major technological achievement of the institute is in setting up the first indigenously conceived and engineered high temperature magnetic confinement fusion device named ADITYA. This device produces a 5 million degree temperature hydrogen plasma for fraction of a second. The plasma is used for exploring the basic physics of magnetically confined hot plasmas.

In addition a variety of non-equilibrium plasma systems using dc, radiofrequency and microwave power have been built for both basic studies and applications. A 100 kW transferred arc plasma device has also been recently set up at the institute.

The core technologies that have gone into building ADITYA have been substantially developed within the country, often with close collaboration with the Indian industry. A few examples of direct relevance to plasma processing will prove this point: (i) Clean ultrahigh vacuum of the order of 10 (-9) torr in large volume vessels obtained with modern high speed pumps like tubomolecular and cryopumps and operated under computer-automated systems. (ii) Thyristor converter-based power systems with peak current capacities up to 50 kiloamperes and peak power capacities up to 60 MVA with capability of generating complex pulse shapes. (iii) Air-core high field magnetic systems. (iv) Computer-based data acquisition, monitoring and control.

Designing, building and operating ADITYA, as well as other plasma systems gives one the confidence that it is possible to design and build complex plasma systems from first principles using entirely indigenous expertise. Experimental plasma research at the Physical Research Laboratory during the period 1972-82 and later at the Institute for Plasma Research has generated an expertise of over two decades in handling a variety of plasma systems, where the technologies associated with plasma production, parameter manipulation and diagnostics have been developed indigenously.

The R&D activity has to cover the entire range from validation experiments to prototype system development, which will be ultimately transferred to the industry. With this realization, the Institute has set up a Plasma Processing Group which has the primary function of developing close collaboration with the Indian industry in the identification, development and transfer of plasma processing technologies. The ongoing activities include:

(i) A plasma nitriding technique to increase the surface hardness and corrosion resistance of steel has been developed at the institute. The sample is exposed to an abnormal glow discharge plasma in a mixture of hydrogen and nitrogen. The ion current collected by the negatively-biased sample keeps it at an elevated temperature and helps in the dissociation of NH molecules. The nitrogen atoms diffuse into the sample and change the crystal structure and improve the surface properties. The plasma nitriding technology is being transferred to Indian Plasma Systems who will commercialize it shortly.

(ii) The work at IPR on the development of diffusion and film coating and ion implantation techniques for surface engineering is being integrated into the DST programme for establishing Satellite Centres for Surface Engineering.

(iii) A 100 kW plasma furnace has been set up for synthesis, smelting and other metallurgical applications. The furnace is at present being used for the synthesis of AlN, a high performance ceramic by evaporating aluminum wire in a nitrogen plasma. This project is being developed for transfer to a local industry.

(iv) Work on depositing organosilicone polymers on perspex substrate to improve the scratch resistance of the material has been initiated. A distributed magnetic field ECRH plasma will be used for the process. The source will also be used for etching semipermeable membrane to alter the osmotic selectivity. This project has been taken up in collaboration with Gujarat State Fertilizer Corporation, which will commercialize the process.

(v) IPR is also participating in the programmes being initiated by the Titanium Development Advisory Committee of TIFAC to induct plasma technologies for processing titanium slag, scrap remelting and titanium dioxide manufacturing. The institute has participated in collaboration with BARC, MIDHANI, NFC and DMRL in the conceptual design of a 600 kW titanium scrap remelting furnace which will be manufactured by MIDHANI in association with other engineering and industrial groups.

An extensive base in thermal plasma technology exists at BARC from the seventies. The motivation has primarily been for development of applications relevant to nuclear power systems. Plasma cutting and spraying systems have been developed for this purpose. The knowhow in high power torch design is now being applied to metallurgical applications.

Smaller groups with specialized expertise in specific fields of plasma applications exist in IIT, New Delhi, IIT, Madras, Regional Research Laboratory, Bhubaneswar etc.

Information dissemination system

A reliable and efficient system of information dissemination is essential to attract the potential entrepreneur or user of plasma process technology. Institution–industry meetings, newsletters, etc are essential in this. IPR has made a beginning by bringing out a newsletter on plasma processing to inform the industry about developments in this field and stimulate their interest. On the basis of a readership survey, a number of new features have been added in the recent issue. The long-term plan is to let this newsletter grow into an effective forum of communication between R&D organizations, plasma processing industries and user industries. An illustrated brochure describing the basic principles and techniques of plasma processing, including details of commercialized plasma process technologies was also brought out and circulated among industries.

Information dissemination can take an active form in catalysing new applications of existing thermal plasma technologies. We have called this technology facilitation. The existing thermal plasma industry covers a narrow range of applications like plasma cutting, welding etc. Many user industries are interested in applications which are slightly non-conventional. We decided to exploit this opportunity by acting as catalytic agent by bringing together the thermal plasma industry and engineering industries. Specific examples of this interaction are; (i) the use of hard coatings like carbide coating on the rollers of steel rolling mills which wear out repeatedly, (ii) use of multiple torch plasma welding to increase the production of seam-welded steel pipes and (iii) use of microplasma cutting to replace expensive laser cutting for shaping piezoelectric yarn tension sensors. Our present role in this is rather passive, whereas we should take a more active role in identifying problems and expediting solutions and in general set a faster pace for the adaptation of the thermal plasma technology to newer areas of application.

Plasma process industry

A nascent plasma processing industry exists in the country in the form of small and medium scale manufacturers of thermal plasma torches numbering about 15 located in Ahmedabad, Baroda and Bombay. Their technological base is rather primitive, but self-learnt. The annual turnover is about Rs 10 crores with the products mainly confined to plasma cutting and welding. The product base is now being extended to more sophisticated applications like thermal plasma spraying and cladding. They have established good contacts with the engineering fabrication industry and understand what the market needs. They are very receptive to accepting and commercializing advanced plasma-assisted technologies.

The second group of industries who could be the potential agents for the technology induction are the vacuum industries, some of whom are already marketing equipment for thin film coating and plasma vapour deposition. We have strong association with this industry.

Another sector of industries who could be interested in the commercial manufacture of plasma process equipment is the heat treatment industry. Manufacturers of arc furnaces may find it attractive to go into plasma furnaces used for metallurgical applications. A substantial base of heat treatment equipment based on induction hardening already exists in the country and may be persuaded to adapt modern plasma-assisted heat treatment systems.

The fourth group consists of new and established entrepreneurs with good technological background. The latter with background in engineering industry have access to financial institutions and are looking for diversification into high technology areas. The category of new entrepreneurs may be specially encouraged by some form of entrepreneur fellowship scheme, which can be used to support their stay at research institutions for a period of, say, one year, during which time they can identify and develop, with apropriate inputs from the institutions, relatively simple plasma process technologies and set up a small industry.

Market

Large scale exploitation of plasma processing has not yet gone into the Indian industrial stream. This reluctance may primarily be due to the fact that the technology is perceived as exotic and entirely import-based. Thermal plasma equipment like plasma cutting, welding and gouging equipments have been manufactured for the past ten years by small entrepreneurs located around Ahmedabad, Baroda and Bombay. The total annual turnover of the entire industry is a minuscule Rs. 10 crores. An interesting and welcome fact is that the growth of this base industry has been occurring at a fast pace, at approximately 300%. Some of these manufacturers have ventured into production of plasma spray coating equipment. However this industry is sustained entirely using imported equipment and has set up job work facilities in Bombay and Madras. Imported thermal plasma equipment have been used in metallurgical applications like recovery of zinc from industrial dross on a small scale.

Non-equilibrium plasma technology has also not yet got a foothold in India. PVD process of titanium nitriding is done using an imported plant at Pune by the Multi-Arc Corporation. Thin film deposition is also done at labscale plants. Electronic device fabrication facilities at Semiconductor Devices Limited, Chandigarh, as well as at smaller facilities at ITI, Bangalore and CEERI, Pilani are entirely based on completely imported plants.

Technoeconomic surveys made on a few technologies look extremely attractive. The TIFAC survey on surface engineering technologies put the total market at Rs 280 crores of which 60% is for diffusion coating process, 24% for thermal spray coating processes and 15% for the PVD process. The main diffusion process practised currently are gas carburizing and nitriding and their plasma equivalent have not yet reached the industry. The estimated demand for TiN-coated articles like cutting tools, watch cases and straps, spectacle frames, imitation jewellery etc is 40 lakh pieces with an estimated growth rate of 20%. Assuming a charge of Rs. 70 per piece, this works out to a market of Rs 28 crores. A comprehensive market survey on all plasma-assisted surface engineering technologies has recently been commissioned by IPR and it is expected that it would bring out the real scope of the market and attract new entrepreneurs into this area.

The potential market is both the industrial and strategic sectors. In the industrial sector, the likely customers are steel, power, chemicals, plastics, tool and dies, extractive metallurgy, engineering goods, and electronic and optical components. Defence and nuclear sectors will form the major beneficiaries in the strategic sectors.

Conclusion

Integration of plasma technology with engineering and manufacturing technologies lead to the new technology of plasma-assisted processing, which has already made a significant impact in the international manufacturing scene. The research and development base for adaption and generation of plasma process technology exists in the country. An active collaboration between the Indian industry and research institutions can be very fruitful in developing this new technology in the country.

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MEETINGS/SYMPOSIA/SEMINARS

VII International Congress and Exhibition — ITV-2000

Date: 24–25 November 1993
Place: New Delhi, India
Theme: Communication, Informatics and Economic Development
Contact: Prof. P. K. Gupta
Congress Convener, ITV-2000
'Shanti Chambers'
11/6B, Pusa Road
New Delhi 110 005, India
Phone: (11) 5731446, 5736212, 5738104
Telex: 031–77375 CST; Fax: 91 11–5755000

Asian Region Seminar on Crystallography in Molecular Biology

Date: 9–14 December 1993
Place: Madras, India
Topics: Macromolecular structure determination; Principles of macromolecular organization; Macromolecular structures, conformations, interactions and applications.

Contact: Prof. S. Parthasarathy
Convener, ARSCMB
Department of Crystallography and Biophysics
University of Madras, Guindy Campus
Madras 600 025, India
Phone: (44) 2351367; Telex 41 6376 UNOM IN
Fax: 91 44 415856

Tenth International Conference of Organic Synthesis

Date: 11–16 December 1994
Place: Bangalore, India
Topics: Synthesis of natural and non-natural products; Design of new reactions, reagents and techniques for organic synthesis; Asymmetric synthesis; Organometallic chemistry; Design of new materials; Molecular recognition.
Contact: Prof. G. S. R. Subba Rao
Secretary, ICOS-10
Department of Organic Chemistry
Indian Institute of Science
Bangalore 560 012, India
Phone: (80) 344411 extn 2524 (Off.), 346482 (Res.)
Telex: 845–8349 BG IISC IN
Fax: 91 80 341683

National Symposium on Recent Trends of Research in Organic Chemistry

Date: 1–5 November 1993
Place: Bhagalpur
Contact: Dr Rana Pratap Singh
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Marwari College, Bhagalpur University
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