THERMAL PLASMA APPLICATION IN METALLURGY
(REVIEW)

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ABSTRACT

A classification of the most perspective plasma technologies and equipment are presented including the initial working raw materials, and the type of resulting materials. The main pilot plasma technologies and such with industrial application are indicated.

The important factors predetermining plasma technology development in metallurgy are evaluated.

The basic works of Plasma Metallurgy Research Laboratory “PLASMALAB” for thermal plasma application in metallurgy are shown, based on actual results, experience, raw materials state, technological, economical and ecological conditions.

Keywords: plasma technology, plasma torch, plasma furnace, metallurgy.

INTRODUCTION

The actual state concerning raw materials, energy, technology and ecology worldwide predetermines the development of new metallurgical technologies and equipment based on thermal plasma application as a concentrated heat source and for chemically active components of the processes.

Contemporary unfavourable state of resources for metallurgy, serious energy and ecology problems and incessant increase of metals and alloys demand lead to a new strategic concept concerning the world metallurgy.

According to a present prognosis on the development of 21st century metallurgy we find that the following main principals would be valid:

- Widespread use of alternative electroenergy sources.
- Tendency for an expanding application of hydrogen as reducing agent obtained from water dissociation and a gradual replacement of traditional fossil reductants.
- Gradual decrease of the absolute volume of metallurgical production in favor of improved quality of produced metals and alloys.
- Gradual replacement of presently used classical alloys by new advanced metal-based materials with better properties.
- Development of new nonwaste, clean metallurgical technologies and equipment, providing a maximum utilization of the valuable components in natural and waste raw materials.

All of these principals can be observed in the case of plasma metallurgy technologies. Its perspectives
are confirmed by numerous theoretical and practical researches carried out in the field of thermal plasma metallurgy application during the last 20 years in technically advanced countries.

The application of thermal plasma in metallurgy at present is developing in two directions - improvement of classical metallurgical technologies and development of principally new plasma metallurgical technologies. According to the scope of their application, plasma technologies are classified generally as smelting and reducing (extracting) processes upon which existing classifications are based.

The growing limitation of quality raw materials for the metallurgical industry, and the serious ecological problems imposed on them require to keep in mind as a classification characteristics not only the existing plasma processes, but also both the type of initial raw materials source and the type of the final material (Fig.1). The basic plasma metallurgical processes used in industry as well as the most perspective plasma pilot units and technologies are included in this scheme.

The main idea of the Swedish PLASMABLAST [1] technology for improvement of the blast furnace process is overheating of the blow air, which aims mainly cutting down of coke consumption. Besides, plasma overheating of the blast makes possible a more flexible control of the furnace heating process.

The developed process PIROGAS (Plasma Injection of Reducing Overheated Gas System) provides also low quality pulverized coal to be blown into the furnace through the plasma torches. The experimental data show that this technology can reduce coke consumption to the necessary minimum for reduction processes in the blast furnace, i.e. from 470 kg/t pig iron to 385 kg/t [3].

Calculations show that the development of new advanced technologies corresponding with raw materials, energy and ecology requirements in many cases are sounder from an economical point of view compared to reconstruction of the classical technologies. This prompted the development of alternative reduction plasma metallurgical technologies.

These technologies are intended for processing of raw low quality polymetal ores, as well as of waste materials (slags, slimes, chemical industry waste materials, etc.). Gaseous (hydrogen, methane, carbon oxide) as well as solid (fine coke, coal powder and others) reducing agents are used.

The characteristic feature of these technologies is that the materials are processed to a finely powdered condition and in most cases are subjected to prior partial reduction (Fig.1). The aim in all the different plasma units is to provide through various technologies a short melting time of the raw material and a good contact (maximum area) between the reducing gas and the melted oxide material.

In general plasma reduction technologies are classified according to the heat-exchange type between the plasma arc and the processed material and according to the conditions under which the reduction processes run.

Industrial production of metals and alloys through reduction - from natural and waste raw materials is done in plasma furnaces, similar to the plasma-arc ones, working in “open bath” 3 (Fig.1). The industrial furnaces TETRONICS-FOSTER WHEELER (EPP-Expanded Precessive Plasma, Fig. 2) [5, 6] are well known, in which the plasma torch rotates with a velocity of 50-1500 min⁻¹ around the furnace vertical axis at 5-15° angle and of arc length 500-750 mm while the powdered material is introduced around the heating surface of the resulting plasma cone. The latest data, obtained from processing of powder slimes and slags in a 2 MW plasma furnace are: specific energy consumption 1300 kWh/t powder; reducing agent consumption 90-300 kg depending on the type of processed material [7].

Some plasma units [8,9] use an extended arc 4 (Fig.1) in combination with a vertically located tube reactor (EAFR-Extended Arc Flash Reactor, Fig.3) in whose upper section the powdered charge is introduced. The plasma arc is generated between three hollow graphite electrodes (three-phase-power supply).

The basic ELRED concept [10] is the reduction of fine (size below 0,1mm) iron ore concentrate (more than 65 % Fe) in two stages: an initial stage for pre-reduction in solid state in the presence of an excess of carbon to a partially metallized product containing carbon and a final reduction stage for smelting of this product using electrical energy.

The pre-reduction takes place under pressure and temperature 970-990°C in a circulating fluidized bed in a reactor vessel with internal refractory lining.
Using shaft furnace 5 (Fig. 1) ASEA SKF founded the basic plasma process PLASMASMELT [12] (Fig.4) for pig iron production, which was further developed in the PLASMADUST [13] modification - for non-ferrous metals dusts processing and PLASMACHROME [14] - for FeCr production. The shaft furnace is filled with coke, while in its stove zone are installed three plasma torches of 6 MW each. The powdered initial raw material is subjected to two-grade pre-reduction in two furnaces of “fluidized bath” type, using reducing agent, the gas (carbon oxide), obtained in the shaft of the furnace. This gas acts both as transporting medium (to deliver the pre-reduced material and the low quality powder coals into the plasma torch zone) and as a plasma gas.

Bethlehem Steel developed a FFP (Falling Film Plasma) reactor 6 (Fig.1), which actually gives the best of technological technical and economical results [17]. The essence of this method is concluded in the reduction of a thin layer (film) of melted oxides (Fig.5). The fine raw material with powdered solid reducing agent is tangentially introduced by reducing plasma gas in a vertical water-cooled cylinder camera, acting as a plasma torch anode section. The intensively whirled gas dispersed flow forms a melt film on the wall of the reactor-anode. This film falls down to the bottom part of the reactor getting reduced on the way. Thanks to the high temperature and speed of the plasma reducing gas the surface processes in the liquid film take place comparatively quickly and the time of the stay of the material in the reactor is long enough for a nearly full reduction of the raw materials. The 1 MW FFP pilot unit was constructed after this scheme. Hematite from the Carol Lake source was processed in it, resulting in a metal of chemical composition: 0.005 % S; 0.001 % P; 0.006 % C; 0.06 % Si; 0.07 % Cu under electrical energy consumption of 3.9 kWh/kg Fe. A mixture of hydrogen and natural gas with ratio of 2:1 was used as a reducing and transport agent. In spite of the promising results of this original idea on plasma reactor for reduced production of metals and alloys from fine raw materials it did not find industrial application. The main reasons for this are the lack of arc plasma torch of high power with sufficient working life and the high working voltage (over 1000 V) needed for obtaining a stable maximum long arc.

Plasma furnace technology was first applied in South Africa in the mid-to late 1970s, when it was realized that advantages could be obtained in the pro-
cessing of fines for the production of ferro-alloys. A number of processes have been investigated, and a 40 MVA DC transferred-arc ferrochromium furnace has been implemented on an industrial scale at Palmiet Ferrochrome, Krugersdorp. South Africa has well-developed plasma-furnace research facilities, which include the 3.2 MVA DC transferred-arc plasma furnace at Mintek, Randburg [18-20].

All described reducing processes have some technological and design advantages and disadvantages. After critical estimation of them Plasma Metallurgy Research Laboratory “PLASMALAB” proposed a new conception on design of plasma furnace and of technology for scrap remelting (Fig. 6) and production of metals and alloys from different materials by reduction (Fig. 7).

According to the general conception [21] our first PLASMALAB FFP-reactor improved design offers a combination between a hollow graphite cathode and a copper water cooled nozzle, Fig. 8 [22]. A special feature of this construction is that the plasma gas is introduced from both sides (interior and exterior) of the tube graphite cathode, i.e. the gas is bilaterally blown, and
the relation in the capacity, respectively the velocity of the two gas streams (V₁ and V₂) is regulated in such a way that the plasma arc reaches a tube-like configuration. Such organization of the plasma arc enables the introduction of the powder feed into a volume surrounded with highly heated plasma. The adopted type of charge introduction ensures its maximal convection and radiation heat exchange with the plasma arc on its way between the cathode and the anode. The anode spot, according to the general concept offered, is in a continuous motion with a controlled velocity and trajectory.

The motion of the anode spot follows a complicated rotary and at the same time reciprocating trajectory i.e. the anode spot would move as a spiral upwards downwards along the interior wall of the reactor-anode.

The organization of the motion of the plasma arc is realized with simultaneously working electro-, electromagnetic and gas dynamic devices, computer controlled and synchronized.

In our first experiments [22] the motion of the anode spot along the reactor height is provided by synchronized increase of the gas flow rates V₁ and V₂ and the plasma arc current. The arc’s rotation in the upper reactor zone is provided mainly by tangentially blowing plasma gas V₂ and in the lower zone - through DC magnetic field.

Several undesirable effects were registered in these experiments:
- Obtaining a stable burning plasma arc with length up to 280 mm requires high consumption of the tangentially blowing plasma gas (16 m³/h) [22].
- Tangentially blowing gas V₂ is inadequately effective for cathode spot rotation.
- Gas stream V₁ blows some powder raw materials out of the reactor.

To avoid above-mentioned disadvantages the Plasma Torch - FFP-Reactor system construction has been modified [23].

The plasma gas is unilaterally introduced into the space between the graphite cathode (Fig.9) and the nozzle, situated at the top of the plasma reactor. The plasma gas is tangentially introduced under a gradient of 40°C to the vertical axis of the reactor through an insulation flange. The charge is introduced into the space between the cathode and special flange through three feeding screw systems. The powder material is swiped
Fig. 7. Conception for plasma installation for reduction processing of disperse natural and waste raw materials and production a continuous caste metal ingot [21 39].

along from the plasma gas and is blown through the nozzle on the reactor wall.

The centrifugal force caused by the plasma gas blown out tangentially orients the particles on the reactor wall.

The rotating motion of the cathode and the anode spot is realized with a circular magnetic field, obtained from a monophase AC power supply stator, situated coaxially to the tube reactor-anode. Besides, the stator moves under controlled velocity upwards-downwards the reactor height with the help of hydrocylinders.

The next step is synchronization of the gas flow rate change, the plasma torch current and the stator position along the reactor height. For this purpose a special gas valve (Fig.9) is constructed to regulate the plasma gas flow rate, combined with the inductive transducer for the arc current control.

The main target is to study the energetic parameters of the DC transfer plasma arc and the possibility for its effective rotating under the influence electromagnetic action. An experimental stand has been made (Fig.10).

It includes DC plasma torch with hollow graphite cathode and graphite tubular reactor-anode, with which the processes of electromagnetic and gas dynamic control of the plasma arc are simulated.

A major requirement to this system (“plasma torch–plasma reactor”) is to provide a possibility for a conveniently observation and photographing of the plasma arc in the volume of the tube reactor-anode, as well as measuring of its main electric, gas dynamic and geometrical parameters.

One of the original solutions in the present work is the series inductor connection in the anode electrical chain of the system “plasma torch cathode-reactor-anode” (Fig.10). Thus, the “PLASMALAB” system for Auto-Electro-Magnetic Rotation (AEMR) of DC transferred plasma arc generates in the inductor from plasma arc current, i.e. an additional DC source is not necessary for arc electromagnetic control.
Fig. 11 shows the behaviour of the arc and heating of graphite reactor–anode without axial magnetic field (the anode chain is connected directly to the graphite reactor). It is seen that the arc burns calmly between the clearly outlined static/immobile anode and cathode spots.

At series connection of the inductor, in the anode chain (Figs.10, 12) the arc unscrews under the influence of the created by the inductor, axial magnetic field (under the action of Laurence force). The graphite reactor–anode is heated evenly (Fig.12a), because of the high rotational speed of the anode spot, which is the main target of the electromagnetic control of the arc in FFP-plasma reactor “PLASMALAB”. The cathode spot also rotates, but its speed is lower. An evidence for this is the observed spiral trajectory of the arc column (Fig.12b), i.e. the cathode spot drops behind in its rotational speed compared to the anode one.

The rotational speed of the arc depends on flowing current which is the same that creates the magnetic field in the inductor–as the arc current grows, the magnetic induction of the electromagnetic field grows too.

In accordance to the conception developed in “PLASMALAB”, for plasma installation and technology for reduction production of metals and alloys, the processed disperse charge is blown through a hollow graphite cathode on a gravitational principle and gets in FFP-reactor, in the zone of DC plasma arc. It is proved that the arc has transport phenomena [24].

The main idea is that the charge particles are sucked by the rotating arc at the exit of the hollow cathode and are transferred to the wall of the concentrically situated tube reactor–anode. It is supposed that in the volume of the arc column, the particles will be heated and melted while getting on the reactor–anode wall. The melted metal-slag suspension runs down the reactor anode wall and reduction processes run. The obtained metal-slag melt drops in the reactor bath.

Fig. 13 shows the behaviour of the arc at different current values. At minimal current-20 A (Fig.13h), due to a substantial difference in the rotational speed of the cathode and anode spots, the arc column is seen as a part of the helical line.

With the increase of the current up to 80 A, the arc column gradually becomes fade (it is not noticeable on the pictures due to its high rotational speed). At
Fig. 10. Scheme of the experimental “PLASMALAB” stand for investigation of system “plasma torch-FFP-plasma reactor” [40]. 1-argon cylinder; 2-throttle valve; 3-gas collector; 4-flow meter; 5-plasma torch; 6-refractory insulator; A7-graphite tube-anode; K-cathode; 8-water-cooling copper inductor; 9-contact clamp; 10-protective screen; 11-video-camera; 12-transferred plasma arc; E-DC power supply; Sh-shunt.

Fig. 11. a) Heating of the tube graphite anode; b) DC transferred plasma arc in the system “hollow graphite cathode-tube graphite anode”, without axial magnetic field [40].

Current 80A, three cathode spots appear on the cathode (three sources of intensive thermionic emission), and their number grows with the current increase. Simultaneously, the cathode spots start rotating faster on the adjacent edge of the cathode. Under these circumstances of increased current, the anode spot rotates at speed extremely higher than the one of the cathode. At current 250 A the rotational speed of the cathode spot is so high that the whole adjacent edge is heated evenly. In the whole investigated current range, the motion speed of the anode spot is much higher than the one of the cathode.

The arc column crosses the cathode axis with frequency equal to the revolutions of the anode spot, i.e. the particles falling through the hollow cathode are taken by the arc column and transferred to the tube graphite anode wall. A demonstration of this is the pic-
tured trajectory of graphite particles that are moving away from the cathode (Fig. 14). The trajectory of the moving away particles follows the trajectory of the arc column, which is clearly shown on Fig. 14.

The results from the experiments give us confidence that the idea about charge feed through a hollow graphite cathode in “PLASMALAB” FFP-reactor is perspective.

The dimensions of the model graphite tube reactor are used for design of a working laboratory FFP-reactor “PLASMALAB”, shown on Fig.15. Its technological potentialities lie ahead.

The smelting plasma technologies (positions 8 to 12 in Fig.1) find wider application at present.

Plasma-arc melting (Fig. 1, position 8) is developed as an alternative of the classical electric arc melting. Three types of plasma furnaces are working in the world today differing in the way of power supply (DC and AC) and in the way of plasma torch location. The first plasma melting furnaces Linde type [25] (Fig.16), working still in Russia, are actually reconstructed classical electric arc furnaces, where the graphite electrodes are substituted by plasma torches (cathodes) with an independent DC electrical power supply and a water cooled bottom electrode (anode). The next step in the plasma-arc melting development is the Freital - Voest Alpine system, where four DC plasma torches are located at the furnace jacket walls under a certain
angle towards the metal bath (Fig.17) [25]. A 45-t Vost Alpine plasma furnace went to operation in November 1983. The main disadvantage of this furnace is situation of the plasma torches. At the beginning of the melting, plasma arcs melt a horizontal craters in the scrap. Due to plasma arc length limit the torches body enter in the furnace space under the unmelted scrap. Often the scrap falls on the plasma torches and breaks them. As a result this plasma furnace construction did not find further industrial application but it remains a significant step in plasma metallurgy development.

KRUPP [26] developed AC melting plasma furnaces, where the bottom electrode was avoided (Fig.18). A starter DC plasma torch works as an electrode in main powerfull AC plasma torch (Fig.19). The possibility for regulation of the plasma torches inclination towards the vertical furnace axis improves the furnace heating work and decreases the refractory lining consumption.

The plasma-arc melting compared with classical electrical arc melting leads to an improved quality of the produced metal, decrease of the specific electric energy consumption under increased output, enables the production of low carbon alloys, increases the alloy elements assimilation grade and the output in general, improves the production ecology (decreases the noise degree and the quantity of the harmful emissions due to the relat-

Fig. 14. The graphite particles moving away from the cathode to the anode follow the plasma column trajectory [39,40].

Fig. 15 “PLASMALAB” FFP-plasma reactor with charge feeding system [39, 40].

tively silent work of the plasma torches and the high airtightness of the furnace working space). The main problem of the high capacity power steelmaking (AC and DC) plasma furnaces is the short working life of the plasma torch electrodes (cathodes) under high current density.

Plasma-induction melting (Fig. 1, position 9) takes place in the classical induction furnace which has a plasma torch installed over its crucible and works after the transferred arc scheme with bottom water cooled electrode-anode (Fig. 20) [27].

The use of two principally different methods for heating - plasma and induction - leads to a decrease of the smelting time (respectively an increase of the furnace output) by 20-50 % in comparison with the classical induction furnace. In addition this heating combination decreases the specific electrical energy consump-
tion by 10-18%. The highly active slag (heated from the plasma torch) resulting from the process and the effective stirring makes possible the production of a metal of low sulphur, gases and non metallic inclusion contents. The use of argon as plasma gas leads to a substantial decrease of the burn-off alloy elements.

Experiments on melting of copper, brass, bronze and high-speed steel turnings were made in a plasma induction furnace [28] at the plasma research laboratory PLASMALAB during the last few years.

The good pilot results obtained in the 60 kg plasma-induction furnace led to the design and reconstruction of an industrial 2.5 tons induction furnace operated in the metallurgical complex Kremikovtsy Ltd. to a plasma-induction one [29]. This furnace consists of two independent devices – an 1 MVA classical main frequency Russian induction furnace and transferred arc metallurgical plasma torch (PLASMALAB-3000) fitted into its cover over the crucible (Fig. 21). The plasma torch works with the plasma gas argon or nitrogen or their mixture at maximum currents of 3000 A. The power supply is realized by two DC units of 300 kVA each working parallel.

The possibility for effectively melting industrial bronze turnings in this furnace and for producing high quality bronze castings has been proven. The plasma torch current during the melting was kept constant at 1500 A and the voltage varied from 120 to 230 V depending on the arc length. Depending on bronze turnings bulk density and preliminary processing the yield was 90-93%; the specific power consumption for melting was 420-464 kWh/t; the specific melting time was 1.2-1.55 h/t; the aluminium oxidation was 0.7-0.9% [30].
The replacing of DC (W-cathode) plasma torch in pilot PLASMALAB 60 kg plasma induction furnace with hollow graphite electrode reduces the running cost for copper and copper alloys production (Fig. 23) [31]. This system has turned out to be simple, very reliable and easy to maintain. On the other hand the productivity and the yield are practically the same. As a result of the pilot experiments the DC transferred arc plasma torch in 2.5 tons plasma induction furnace was replaced with 100 mm graphite electrode with 16 mm hole for plasma gas blowing.

In the case of graphite electrode operation and argon blowing through the electrode hole, the arc length and the voltage are decreased compared to the length and voltage of the plasma torch arc under otherwise equal conditions due to the lack of the cooling and isolating effect of the plasma gas. This is the reason for substantial arc deviation to the crucible wall. The cathode spot moves on the edge of the hole, the anode spot has no clear contour. The V-A characteristics of graphite electrode arc have been measured in the current range 500-2300 A, constant arc length 300 mm and gas consumption 3800 l/h (Fig. 24).

The graphite electrode curve is of a rising type similar to the V-A characteristics of the plasma torch arc, but voltage is 30 to 50 V lower. In the case of simultaneous operation of plasma and induction heating the plasma arc expands due to interaction between the magnetic field of the induction furnace and the plasma arc. The expansion of the arc in this case strongly depends on the current frequency of the induction fur-
nace (max expansion at 50-60 Hz). While in the case of using a plasma torch this effect is undesirable – as it leads to the appearance of non-controllable secondary arcs and higher erosion of nozzle and plasma torch body, in the case of graphite electrode the expanded arc leads an increase of the working arc voltage (Fig. 24), respectively to an increase of arc power at constant current. Compared with the classical plasma torch, the hollow graphite electrode (both working at nominal current 500 A) decreases the average furnace productivity with 5-8 %. On the other hand, when the two systems - arc and induction heating work simultaneously the furnace productivity increases with 9-11%, the melted crater in the scrap is wider and the local overheating of the metal decreases.

**Plasma arc remelting** (Fig.1, position 10 ) is a plasma technology, which has found widest industrial application at present. Patented in the institute Paton (Ukraine) (Fig. 25) [33] and developed by some leading world companies as Daido, Retech and others, this technology is recognized as a basic refining process, successfully competing with electro-slag remelting and vacuum-arc remelting. The technology essence consists in melting of a metal ingot with plasma heating in a copper water cooled crystallizer, and obtaining of a refined ingot of desired structure and with a decreased gas and non-metallic inclusions content. The main advantage of plasma-arc remelting to vacuum-arc remelting is that the process takes place under atmosphere pressure or under increased pressure and enables an effective gas alloying of the metal.

The effective nitrogen alloying during melting of high speed steel turnings is carried out by PLASMALAB at present in two variations: plasma-induction melting and plasma-arc melting in a copper water cooled mould under increased nitrogen pressure. Plasma gas (argon-nitrogen - 3:1) flow rate is 1200 l/h. The melt in the plasma-induction furnace is blown with nitrogen during the total melting process through the bottom water-cooled electrode-anode with a constant gas consumption of 180 l/h. The final nitrogen content in solid metal varies in the range 0,092-0,098 % [34].

The rapid development of ladle metallurgy (Fig.1, position 12) and of continuous metal casting, opened a wide field for plasma heat application. The replacement of the ladle furnace graphite electrodes by plasma torches, assures all the advantages, described for plasma arc furnaces and in addition leads to a faster liquid metal heating, due to the high specific heat plasma capacity. The plasma ladle reheater is used at U.S. STEEL, Lorain, OH, to save aborts or to homogenize the temperature of the molten steel in the ladle [36].

The quantity of steel produced by continuous casting has reached over 90 % of total world-wide production. The conventional characteristics of the continuous casting processes are: high heat losses from the melt in the tundish at the start of the casting of the comparatively high degree of average superheating DT during the further casting processes and the continuously changing casting parameters. As a result it is impossible to guarantee constant quality of the cast product. The plasma heating systems offer an optimal solution of the mentioned problems in the conventional continuous casting process [37].

Heating of the tundishes in continuous metal casting machines enables the decrease of the metal tapping furnace temperature by approximately 20°C, which leads to the refractory consumption decrease and increases the melting furnace productivity. The intensive metal heating in the tundish, makes possible its argon blowing, and in result - an optimal constant temperature and chemical composition homogeneity of the cast metal.

In addition, this technology facilitates the organization of the processes in the melting plants (provides a simple synchronization between the melting furnace and the continuous casting machine).

The Tetrions Limited has installed 20 Tundish Heating systems worldwide, including 13 for major Japanese steel companies, most of which are today heating millions of tonnes of steel per year. Until 1993 Tetrions’
tundish plasma heating system used a single polarity torch with an arc running from the torch to the steel, with a counter electrode immersed in the steel providing the return path for the DC current. Installation of the counter electrode requires tundish and/or tundish car modifications and the refractory lining becomes complicated with expensive additions. Tetronics has now successfully introduced an improved avoiding any modifications to the tundish to incorporate the counter electrode [38].

Presently over 35 plasma tundish heating systems are operating in steelwork world-wide, mainly in Japan, China, Europe and USA. Main parameters of these systems are tundish size 5-80-t, heating power 0.3-4.3 MW, torch current 1.6-12 kA, current mode 90 % DC, 10 % AC, plasma gas argon (nitrogen).

During the last decade the thermal plasma processes based on electrical arc or induction plasma generation has been successfully applied in metallurgical industry (tundish heating for continuous casting, ladle heating for temperature control, plasma heated cupola for metal recovery), also in materials elaboration (powder synthesis, coatings, spheroidization) and in materials processing (cutting, welding, surface treatment, etc.). The impressive increase of production of plasma manufacturing equipment worldwide clearly indicates that the thermal plasma technologies become extensively employed by industrial users. Therefore, scaling-up of plasma processes is extremely important for the further development of plasma manufacturing technologies.

CONCLUSIONS

Based on the review made on the existing pilot and industrial metallurgical plasma technologies, sources and energy state and perspectives for world wide metallurgical development the following conclusions can be made:

- The plasma reduction technologies are still under development and their industrial application is limited due to the following main reasons:
  - insufficient single power and operating reliability of existing non-transferred arc plasma torches;
  - complicated exploitation scheme for maximum heat and reduction potential utilization of off-gases from plasma units;
  - dynamic change of relation between electric energy and coke prices and last but not least the conservative thinking and insufficient financing of big metallurgical companies.

- The lack of qualitative ores on one side and the significant quantities of stored waste from metallurgical and chemical industries on the other are a favorable perspective for future application of plasma technologies in metallurgy.

- Plasma melting technologies development is limited mainly by designing and manufacturing of powerful metallurgical plasma torches with enough single power (required currents: 100-130 kA) and reliability.
  - The cathode and the nozzle are the main element.

- The most perspective and easily applicable technologies in the near future are plasma induction melting, plasma remelting, plasma heating in the tundish technologies, which are already working in the developed countries and have proved economical effectiveness.

- In the case of a stable financial support for intensive design, scientific research and introduction work in the field of application of plasma in metallurgy, we can expect actually working plasma technologies for processing of raw polymetal materials and waste from the metallurgical and chemical industries in the beginning of the 21st century. This would facilitate the solving of the complicated raw materials, energy and enviromental problems in industry.
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