

Plasma metallurgy: current state, problems and prospects*

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Abstract: Current state, problems and prospects of plasma metallurgy are discussed. Investigations of the author and other scientists worked mainly in the former Soviet Union in the field of plasma processes theory and practice are the base for the paper. A number of examples are given of successful practical application ensuring increase of productivity and improvement of ecological condition, saving of resources and energy and formation of products with specific properties. Special attention is given to the problem of energy and metallurgical complexes development on the basis of plasma technology.

Plasma metallurgy as a scientific and technical trend is based on the fundamental investigations of the interaction of high concentrated sources of energy with a substance [1,2].

The modern metallurgy including the most mass steelmaking (Fig. 1) has a lot of essential disadvantages caused by its structure, raw and power sources, imperfection of existing metallurgical units. Disadvantages of the metallurgy are determined by its power sources using solid organic fuels including a deficit coke. Metallurgy is also in a great conflict with the environment. The ferrous metallurgy causes 23.3% of atmospheric air contamination. The coke formation industry is a serious cause of the environmental pollution by such health-dangerous products as benzopyren, etc. The greatest detriment comes from sintering (dust, SO_x). In the whole the ecological detriment by traditional production of steel (blast furnace-converter) is about 25% of its manufacturing cost. The general trend to exclude these processing methods by developing various processes and systems of direct reduction (coke-free metallurgy) is not accidental. In Russia this direction was reflected in the construction of the largest electrometallurgical plant in the town of Oskol where the main apparatus and technological sections are catalytic reforming of natural gas with the production of synthesis-gas used as a reducing agent of iron ore pellets in shaft furnaces followed by remelting of metallized iron sponge in powerful electric furnaces. Use of thermal plasma in the processes of the coke-free metallurgy providing the advantages peculiar to the direct reduction allows enlarge essentially the scope of their application lifting the restrictions caused by the orientation only on the natural gas and its catalytic reforming. Here we have the possibility to use low quality organic fuel and bio-mass as the initial energy source by their plasma-thermal gasification with obtaining high quality synthesis-gas which may be used as a reducing agent in the plasma apparatus and a gas fuel in turbines of a thermal and electric power station. In such a way there is a ground for creation of the energy metallurgical complex. The plasma technique multipurpose application is very important for the metallurgy: the opportunity for treatment of substances in various aggregate states (gaseous, liquid, solid, as a compact and powder) with obtaining of target products in the required state and shape up to production of machine components and mechanisms. To disclose potential resources of the plasma technology it is necessary to provide:

- 1 Development of the fundamental physical and chemical and power technological basis.
- 2 Development of the principles for the production of equipment and apparatus for the plasma processes.

*Lecture presented at the 14th International Symposium on Plasma Chemistry, Prague, Czech Republic, 2–6 August 1999, pp. 1809–1918.

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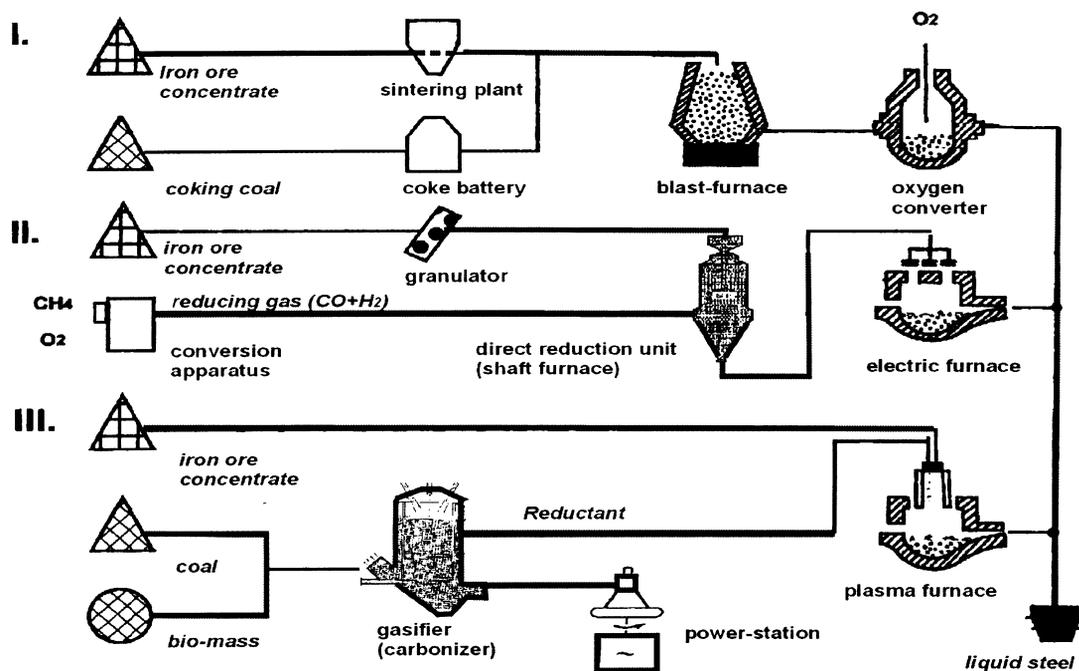


Fig. 1 Comparison of the traditional process (I), gas direct reduction with subsequent electric melting (II) and plasma (III) method of steel making.

- Choice of the most promising fields of the plasma technique and technology application and their realization in practice.
- Development of the efficient ways to include the technique and technology in the advanced structure of the commercial production and power engineering.

For the theoretical analysis of the plasma chemical processes [2,3] first of all it is necessary to diagnose the system and to determine its belonging to non-equilibrium or quasi-equilibrium systems. As the thermal plasma is usually used in the metallurgy we have no necessity to consider the plasma chemistry of non-equilibrium processes. From the procedure viewpoint the problem of thermodynamic calculations of the system with a plasma heat carrier is reduced to determining the equilibrium parameters of multicomponent system. The degree of depth utilization is determined by the presence of appropriate algorithms and program. The main part of calculations of the high-temperature systems which are of interest for the metallurgy has been carried out using a procedure based on the law of acting masses. As a result of these calculations we have the information about the equilibrium composition, the product output, specific energy consumption.

In analyzing special features of high-temperature kinetics, it is convenient to examine gradually the homogeneous or gas-phase process and processes in which condensed phases take part.

As the kinetics of gas-phase homogeneous reactions is related to rather developed parts of the physical chemistry the problem includes estimation of the possibility of its extension to high temperature processes.

Here for the boundary of possible applicability of the classic kinetics we take the condition of essential violation of the equilibrium distribution $E = 5RT$. As it is seen for the processes with the activation energy of 25 kJ/mole that is typical for the high temperatures of the dissociation processes this temperature boundary may lay in the region of 10 000 K.

The condensed phase as the material being treated or the target product is very typical for the metallurgical processes in the whole. Comparison of the activation energy for the reduction homogeneous processes with the experimental data for the heterogeneous reactions of reduction shows that the activation energy is essentially lower for the heterogeneous processes due to catalytic effect of the surface. Comparison of temperature dependence for the rate constants for the homogeneous reactions and

heterogeneous processes testifies that in the low temperature region the heterogeneous process has the kinetic advantages. With the temperature increase the rate difference becomes lower and above some temperature the advantage is going to the homogeneous reaction. Considering possibilities for the reduction processes intensification at the temperature increasing it should be noted that for the processes solid-gas they are essentially limited due to both the low activation energy and possible reduction of the surface absorption catalytic properties leading in some cases to failure of the acceleration process. The heterogeneous processes may be essentially inhibited by formation of the dense layer of the solid blocking the surface and leading to the impedance of the reduction process.

Thus, with the temperature increase the process heterogeneity instead of the fact facilitating the interaction becomes the obstacle for the process intensification. It is quite natural that further essential acceleration of the process may be achieved by reagent transfer to the gas phase. Really for the processes of tungsten trioxide reduction by hydrogen and carbon the correlation was marked between the oxide reduction degree and the degree of the transfer to the gas phase of less volatile component.

The above mentioned gave us the opportunity to generalize the position about rate-controlling step of the jet-plasma reduction by the degree of the components transfer to the gas phase.

The model-mathematical simulation was considered as a means of forecast and as an instrument of investigation and as the base for process optimization and management. So, for plasma conversion of dispersed raw materials a unified model was developed by us in which the process is considered with taking into account real diversity of equipment-technological schemes of carrying out and in mutual interconnection of output parameters of the process with characteristics of plasma jet, conditions of input and moving of raw materials, dynamics of heating, volatilization of raw materials particles, chemical transformation of the initial vapour in condensing, nuclear formation of a new phase, condensation growth of its particles and their coagulation [1,4]. According to our unified model there was investigated the formation of the condensed metal powder while plasma jet reduction of the tungsten trioxide. Later we perfected and concretized this model to the problems of controlling management of plasma jet processes and particularly for producing particles with maximally fine size [5,6].

The processes in which the melt takes place represent one of the most promising directions of plasma metallurgy. They are mainly governed by the relationships of diffusion and convection in the bath volume in combination with absorption processes at the interface [7].

As it was mentioned above we are to find the optimal solution of ecological and technological problems of the metallurgy by the development of the energy technological complex on the base of the plasma technique [1,2,8–12]. The basic scheme of such a complex is presented on Fig. 2. As it is seen under various raw and energy initial materials it consists of the following assemblies using the module principle: the system for obtaining of the gas-reductant and gaseous fuel by gasification, the energy assembly and the metallurgical assembly combined by the energy and mass flows.

Now we consider the modern level of the main versions of plasma metallurgical modules. According to our proposed classification they are: a plasma shaft furnace, a plasma ore-thermal or melting furnace, a jet-plasma reactor. As a rule jet-plasma processes used to obtain materials in the dispersed form. They are the base of the plasma powder metallurgy. The scheme presented on Fig. 3 illustrates wide possibilities of this very promising branch of the plasma metallurgy [12]. Thus, while treatment various powders in plasma by the inert concerning the substance gases we may spray, melt and evaporate any substance with obtaining spheroidized, composite and ultra-fine powders. Plasma including chemically active reagents opens extremely wide possibilities. It allows to conduct the reduction and synthesis with obtaining of wide range of powder materials. Composite or clad powders are very interesting products of the plasma treatment along with the well-known spheroidized powders. Their production is made by melting of the ceramic material base with subsequent metal deposit onto it by evaporation and controlled condensation. The obtained composite combines positive properties of the components, for example, low specific weight and heat resistance of the aluminium oxide and nickel electric conductivity.

Examples of chemically active plasma jet processes may be the developments carried out on various scales including the former USSR on producing ultrafine powders of metals, carbides, nitrides, carbonitrides, borides, silicides, and other compounds in reduction of oxides, chlorides and fluorides in contact with hydrogen, natural gas, ammonia, nitrogen using arc and high frequency plasma generators

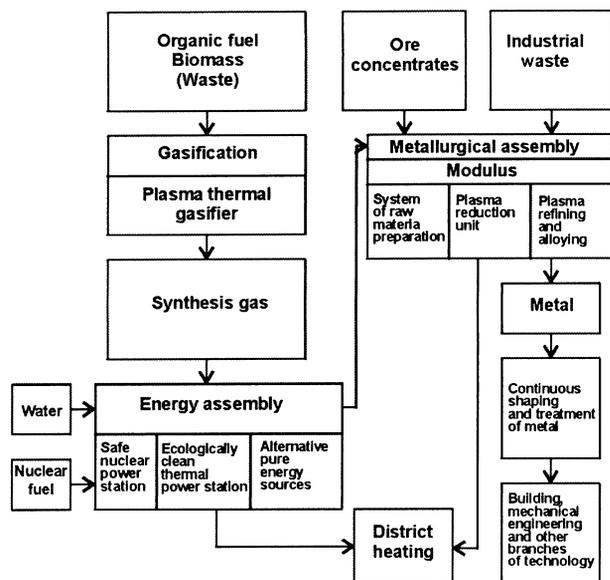


Fig. 2 Basic scheme of the energy metallurgical complex.

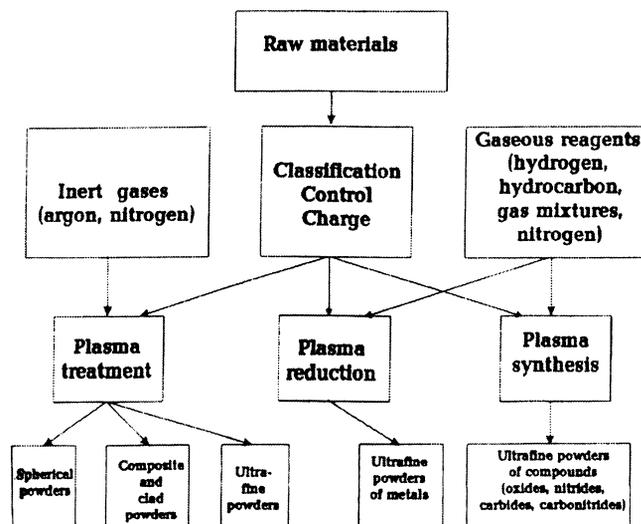


Fig. 3 Scheme of powder plasma production.

[1,2,13]. We shall examine in more detail the plasma hydrogen reduction as in this direction the most essential results have been received. In metallurgy hydrogen is a chemical reagent ensuring production of high pure metals. The plasma hydrogen processes [2,14] are ecologically clean. As any process of hydrogen reduction these processes can be carried out using a closed cycle in reduction of both oxides and sulfides. The advantages of hydrogen as a medium and a reagent are based on high chemical activity in the ionized state, generation of a large amount of heat in recombination of hydrogen atoms and the efficiency of heat and mass exchange. Plasma-hydrogen processes of reduction and synthesis may be regarded as a source of producing ultrafine powders having unique properties.

The optimum area of the plasma-hydrogen reduction application is the industry of refractory metals based on using hydrogen as a reducing agent and a medium for sintering and treatment processes.

A considerable achievement of Soviet science and technology is the development of the ecologically clean highly efficient process of plasma hydrogen reduction. Baikov Institute of Metallurgy together with a number of organization (ChF VNIITS, Tsentroenergotsvetmet and VNIETO) have applied this process to the reduction of tungsten oxides to produce ultrafine powders at plant UzKTZhM (Chirchik) [1,2].

Figure 4 presents the scheme of the commercial unit (PUV-300) for the plasma hydrogen reduction of the refractory metal oxides. This assembly became a reproduction specimen of a series of the commercial plasma units designed for the re-equipment of the production of the tungsten and molybdenum powders at UzKTZhM. One of the similar units was installed at 'Pobedit' plant in Vladikavkaz.

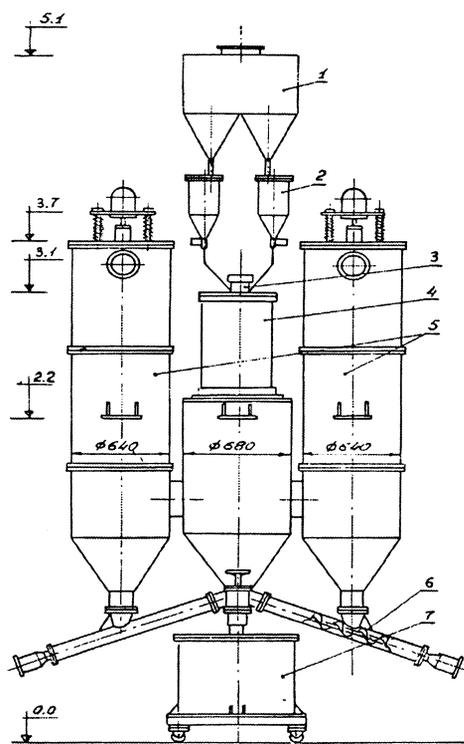


Fig. 4 Scheme of the plasma commercial units for plasma hydrogen reduction. 1: hopper for raw materials; 2: raw materials feeders; 3: plasma generator; 4: reactor; 5: sleeve filters; 6: screw conveyers for the product output; 7: receiving hopper.

Table 1 illustrates technical and economical indexes of the commercial operation in comparison with the standard technology: the hydrogen consumption is lower by 1.5 times, the electric energy consumption is lower by 1.8 times with a large increase of productivity. This demonstrates convincingly the efficiency of energy and resources supply facilities with the optimum combination of plasma technology in the metallurgical processes. It should be mentioned that this relationship has also been reflected in a number of other proposals of Baikov Institute applied on the industrial or enlarged scale as it is seen from the comparison of the technological parameters of a number of plasma and traditional processes given in Table 2. The results of special investigations point to the improvement of the environment and labour conditions.

Unique properties of the ultrafine powder facilitate compacting (decrease of sintering temperature, reduction of the number of rejects caused by insufficient melting) and improvement of the service properties of components produced from it, including the wear resistance of hard alloys. The alloy on the base of the plasma powder has more uniform and fine-grained structure that has predetermined the improvement of mechanical and service properties of the hard alloy and the cut instrument made from it. Along with the plasma powder application for obtaining hard alloys with high service properties it may be also used for the production of the compact metal at reduced sintering temperature (about 1500 °C).

Another practical way of plasma powder efficient use as the sintering activator is its addition to the standard powder. Thus, addition of 25% of the ultra fine powder allows to obtain tungsten density near the theoretical one while sintering.

What concerns the shaft furnace processes with the plasma heating the well known impressive results were advertised by the Swedish Company 'SKF-Steel' (the processes 'Plasmared', 'Plasmasmelt',

Table 1 Parameters of tungsten powders plasma production

Parameter	Tubular electric furnace	Plasma method	
		Reduction	Annealing
Power(kW)	70	300	70
Capacity (kg/h)	6	80	36
Duration of operation (24 h)	300	250	300
Production volume (tonnes/year)	43.2		480
Metal extraction (%)	92		94.87
Occupied place (m ²)	40	80	40
Service personnel (person/shift)	0.35	1	0.35
Consumption			
hydrogen (nm ³ /h)	21	35	8
water (m ³ /h)	3	25	1.2
electric energy (kW/h)	35	210	21

Table 2 Comparison of technological parameters of plasma and traditional production

Product	Specific consumption			
	Electric energy (KWh/kg)	H ₂ , (nm ³ /kg)	N ₂ , (nm ³ /kg)	water, (m ³ /kg)
Powder				
—tungsten	<u>3.21</u> 5.83	<u>2.6</u> 3.5	<u>0.002</u> 0.002	<u>0.35</u> 0.5
—molybdenum	<u>8.0</u> 10.8	<u>1.13</u> 4.62	<u>0.003</u> 0.003	<u>0.87</u> 1.23
—cobalt	<u>4.5</u> 9.17	<u>0.58</u> 5.0	<u>0.003</u> 0.003	<u>0.42</u> 0.25
—titanium carbide	<u>10.8</u> 36.7	<u>0.8</u> 1.33	<u>0.006</u> 0.006	<u>1.0</u> 0.37
—melting cobalt	<u>2.2</u> 2.95		<u>0.05</u> 0.0	

Note: numerator = plasma processes, denominator = traditional production.

‘Plasmachrom’, ‘Plasma dust’, ‘Plasmazink’) [15]. However, at the present time the advertisement of the firm quiets down. In the USSR, in 70 years proposals have been made to equip the blast furnaces of low capacity at old Ural plants with the plasma generators. After successful large-scale tests at Chelyabinsk electric metallurgical plant there was developed a pilot plasma shaft furnace for ferro-alloys production. In the Ukraine at Petrovsky metallurgical plant in Dnepropetrovsk the unit of 10 tonnes per day capacity for the continuous steel production from the iron ore concentrate was successfully operated by the plasma heating [16]. This assembly combined the reduction in the shaft with the finite reduction in the liquid barbotage bath.

One of the simplest processes used in plasma metallurgy is plasma re-melting. In contrast to conventional arc and vacuum-arc melting, this process is characterized by considerably high stability of the energy parameters, the possibility of using various gas media (neutral, reduction, oxidation) and enables production of a highly clean metal with the purity comparable with that obtained in electron beam and electron slag re-melting. The losses of alloying components of the alloys are minimized. The plasma-arc furnaces have a number of labour hygiene and ecological advantages: there is no emission of smoke

into the atmosphere, the noise level is lower, and the effect on the operation of the energy system is reduced.

On the whole, development of industrial technology equipment for plasma remelting in furnaces with a ceramic crucible should be attributed to Russian plasma metallurgy (Bardin Institute of Ferrous Metallurgy, VNIIEO, Baikov Institute of Metallurgy). The results of these investigations were used to develop a plasma section at Chelyabinsk metallurgical plant equipped with furnaces with melting plasma generators with a tungsten cathode and a hollow graphite cathode with a unit power of 10 MW. Approximately 150 grades of steels and alloys are melted.

Plasma furnaces were constructed and developed in the former USSR. These furnaces have been successfully introduced and operate at the plant producing high-grade steel in Freital (the former German Democratic Republic), including a 30 tonne plasma furnace producing corrosion resisting and alloyed steel (around 40 grades). Consequently, the experimental and East German licence were used to construct the most powerful plasma steel melting furnace (45 tonnes) by the Austrian Company Voest Alpine [17].

In the group of plasma melting processes a special position is occupied by reduction smelting in which the oxide material is subjected to plasma heating in the presence of the reducing agent. Up to the present time the most successful development of this process was marked in the South African Republic [2].

The plasma furnace with the hollow graphite cathode is a promising plasma unit. It is commercially used for the technology (developed by Baikov Institute of Metallurgy, Tsentronegotsvetmet) of the plasma reduction melting of oxide raw materials (using nickel and cobalt). The photography in Fig. 5 testifies practical commercial use of the plasma furnace with the hollow graphite cathode in the cobalt section of Yuzhuralnickel plant in the town of Orsk. The similar furnaces are also delivered to Severonickel plant (Monchegorsk) and to the copper-nickel plant (Ufaley). In comparison with the previously used technology and equipment, the rate of the reduction increases, the losses of expensive and difficult available metal with dust emission and slags are reduced, the consumption of graphite material in the reducing agent is lower, the number of processing cycles is also lower and the working conditions are improved [1,2].

The promising way to use the plasma technique is the plasma heating of the ladle in the continuous casting machine [2]. Here besides the thermal plasma effect which provides the controlled constant high

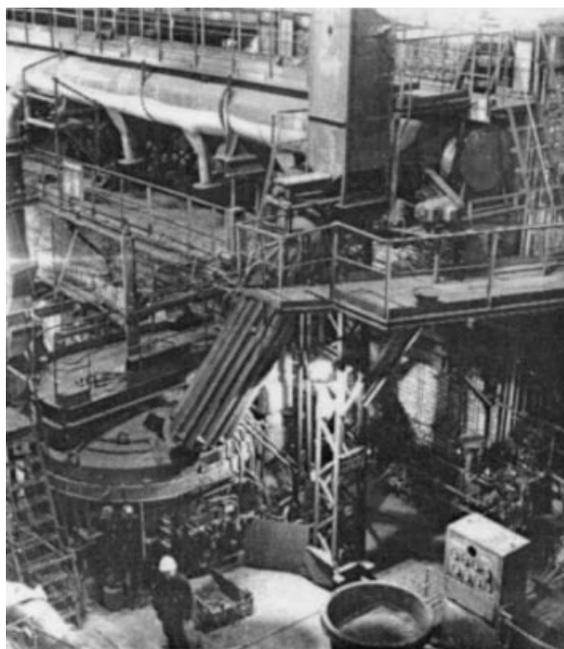


Fig. 5 Commercial plasma furnace for the reduction smelting of oxides.

temperature in the melt the additional refining and alloying is possible. Company Tetronix essentially succeeds in the business realization of the process 'Plasma Tundish Heating for Continuous Casting Plants' predominantly at Japan metallurgical plants.

Recently the problem to use the plasma technique for wastes treatment becomes extremely actual. The Company 'Tetronix' claims about its essential progress in the treatment of wastes with the application of its known developments—plasma arc furnaces with precessed cathode [18].

The important problem for the ferrous and nonferrous metallurgy is the necessity for processing of iron zinc containing dusts and slimes of the steel making process. Treatment of the zinc containing wastes of the ferrous metallurgy was successfully conducted at the pilot plant of the Swedish Company 'SKF-Steel' (Landskrona) for the blast furnace variant and by the Company 'Tetronix' with the application of furnaces of its own design. We tried to treat slimes of a number of the Russian plants. We used furnaces with the liquid bath and plasma heating, and plasma furnaces with the hollow graphite cathode at the pilot plant in Ryasan. We succeeded in complete elimination of zinc while iron reduction providing such technological indexes which are advertised by the Company 'SKF-Steel' and 'Tetronix'. On the base of our experiments we developed the technical proposal for one of the Russian zinc plant.

The proposal to use for treatment of industrial and domestic wastes of the metallurgical assemblies being out of service is rather total. Here the plasma heating may essentially intensify the process and provide multipurpose treatment of the wastes [19]. We suppose that investigations on oxidation of organic compounds in water under injection of thermal plasma jet are of definite interest to find optimal ways for treatment of liquid wastes containing organic compounds [20].

Returning to the problem of the plasma energy metallurgical complex development we should like to note that the base element of its power assembly is an ecologically pure heat and electric power station [2,21]. The most important unit of the station is a plasma thermal reactor where gasification of the organic fuel occurs. Use of low quality organic fuel of the biogenetic origin (wood chip, wood sawdust, low quality wood, peat, nut shell, etc.) is foreseen in one of the variants of the energy technological complex. The technological scheme of this complex includes the modified iron-vapour method of the inexpensive hydrogen production and the technology for the production of methanol from the pure synthesis-gas. The thermal plasma is used both at the gasification stage in chemical and metallurgical processes.

Using the methodology of the system analysis of the energy and material structure of high temperature metallurgical processes we consider energy properties of the heat sources used in the metallurgy. The energy intensity of the plasma furnaces with the water cooling crucible is by two or three orders of magnitude greater the corresponding indexes for the fuel units and the arc furnace with the ceramic crucible.

Structure energy analysis of the modern metallurgical production testifies that the high energy consumption of the steel production is caused by numerous processing stages, low energy indexes of the main units, high output of secondary energy resources with their low utilization. Energy technological indexes may be essentially improved by reduction of the technological stages and combining material and energy flows in the production of energy and metal products. A set of energy balance equations was derived for the energy and metallurgical units of the complex. Here it was shown when the electric power consumed by the metallurgical module is lower than 27 GJ/tonne (it occurs when we use the plasma furnace with the ceramic crucible) the complex power intensity is lower than the power intensity of the blast furnace-converter production of about 1.5. The solution of the set of the energy balance equations allows to compare the coefficient of the efficient use of the organic fuel energy which is equal to 0.78–0.84 for the energy metallurgical complex. This value essentially exceeds the similar one for the blast furnace process.

Comparison of energy costs also showed the advantage of the complex solution of the energy technological problems of the steel production: when the electric energy consumed by the metallurgical module is changed from 10 to 50 GJ/tonnes the energy cost is 15.85–28.45 USD/tonne. That is more than twice lower in comparison with the traditional technology (about 47.5 USD/tonne) [10].

Figure 6 presents easy-to-interpret the structure of a future plasma energy-metallurgical complex. The possibility to follow material and energy flows in the metallurgical unit of the complex is of special

attention. It consists of the continuous operation plasma assembly—the plasma furnace with the melt flowing layer. Iron ore concentrate is subjected to the solid phase reduction in the plasma generator with the hollow cathode, finish reduction in the liquid bath with the subsequent refining, alloying and shaping up to the output of the final rolled products.

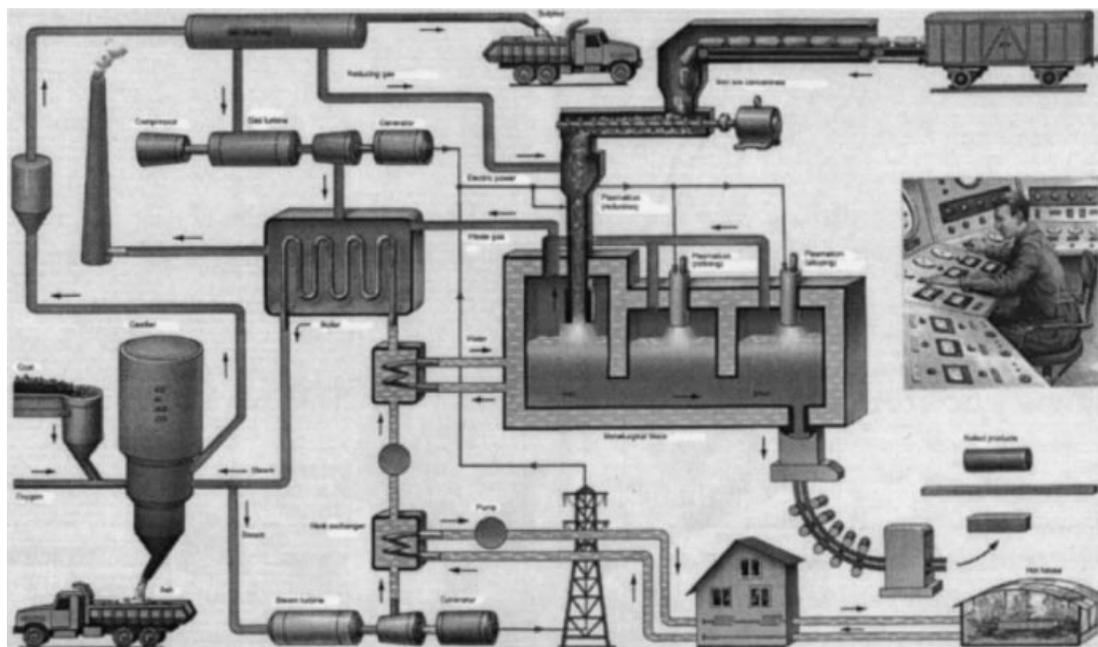


Fig. 6 Plasma energy metallurgical complex of the future.

CONCLUSIONS

At present there are grounds for commercial development of the plasma metallurgy manifested in high level of theoretical developments with realization of numerous research studies revealing the main types of the plasma metallurgical processes; there was confirmed the efficiency and advisability of the plasma technique application, there were determined the most promising fields of plasma treatment.

The efficient solution of the technological problems of the modern power engineering and metallurgy is to be provided by combination of the electric energy production with chemical and metallurgical productions within the scope of the energy technological complex with the plasma technique use.

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