ТЕХНИЧЕСКИЕ НАУКИ И ТЕХНОЛОГИИ

МЕТАЛЛУРГИЯ
МЕТАЛЛУРГИЯ
METALLURGY

DOI 10.51885/1561-4212_2022_1_70
МРНТИ 44.29.01

A.T. Mukhitov[1], S.A. Abdulina[2], Małgorzata Rutkowska-Gorczyca[3]
[1]D. Serikbayev East Kazakhstan technical university, Ust-kamenogorsk, Kazakhstan
[2]Wroclaw University of Technology, Wroclaw, Poland
*E-mail: mukhitovadilet@gmail.com**
E-mail: abdulina.saule@mail.ru
E-mail: malgorzata.rutkowska-gorczyca@pwr.edu.pl

USING NEURAL NETWORKS In THE PROCESS OF OBTAINING SPONGE TITANIUM

КЕУЕКТІ ТИТАНДЫ АЛУ ПРОЦЕСІНДЕ НЕЙРОНДЫҚ ЖҮЙЕЛЕРДІ ҚОЛДАНУ

ПРИМЕНЕНИЕ НЕЙРОННЫХ СЕТЕЙ ПРОЦЕССА ПОЛУЧЕНИЯ ГУБЧАТОГО ТИТАНА

Abstract. *This article is devoted to the planned development of a software module based on deep learning of neural networks in the workshops of the JSC "Ust-Kamenogorsk Titanium and Magnesium Plant" (JSC "UKTMP"). Now, the production of sponge titanium in UKTMP JSC is accompanied by a manual mode of work of specialists, which does not exclude human error of specialists in production. One of the ways out of this situation is the developing of full automation of the process of obtaining sponge titanium based on deep learning of neural networks, as well as the implementation of a MES system. The article indicates the method of deploying neural networks for analyzing the accumulated data of the technological process for obtaining sponge titanium.*

Keywords: *titanium; spongy titanium; neural networks; supervisory control of production.*

Аңдатпа. *Бұл мақала «Өскемен титан-магний комбинаты» акционерлік қоғамының («ӨКТМК» АҚ) цехтарында нейрондық желілерді терең меңгеруге негізделген бағдарламалық модульді әзірлеуге арналған. Қазіргі уақытта «ӨКТМК» АҚ кеуекті титан өндірісі мамандардың қолмен жұмыс істеу режимімен жүреді, сондықтан өндірісте мамандардың адами фактор салдарынан қателіктері болуы мүмкін. Бұл мәселені шешудің бір жолы – нейрондық желілерді терең меңгеру негізінде кеуекті титан алу процесін толық автоматтандыруды, сонымен қатар нейрондық жүйесін енгізу. Мақалада кеуекті титан алудың технологиялық процесін зерттеу үшін нейрондық желілерді қолдану мүмкіндігі көрсетілген.*

Түйін сөздер: *титан; кеуекті титан, нейрондық желілер; өндірісті диспетчерлік басқару.*

Аннотация. *Данная статья посвящена планируемому к разработке программному модулю на основе глубокого обученя нейронных сетей в цехах Акционерного Общества «Усть-Каменогорский титано-магниевый комбинат» (АО «УКТМК»). На данный момент производство титана губчатого в АО «УКТМК» сопровождается ручным режимом работы специалистов, что не исключает ошибок человеческого фактора специалистов на производстве. Одним из путей выхода из данной ситуации является внедрение полной автоматизации процесса получения титана губчатого на основе глубокого обучения нейронных сетей, а также внедрением MES-системы. В статье указан способ внедрения нейронных сетей для анализа накопленных данных технологического процесса получения губчатого титана.*

Ключевые слова: *титан; титан губчатый; нейронные сети, диспетчерское управление производством.*

Introduction. The relevance of research on the production of pure sponge titanium is associated with significant technological difficulties due to the high chemical activity of this metal. The reaction of titanium interaction with oxygen, nitrogen, carbon, carbon oxides and water vapor proceed with a large decrease in the Gibbs energy. Therefore, the processes of reduction and melting of the metal are carried out in sealed equipment in an atmosphere of inert gases (argon, helium) or, in a vacuum. One of the most important conditions is the high purity of the starting compound and the used reducing agent. To analyze the technological data accumulated over decades, it is necessary to use neural networks, the data source for which will be the MES system.

The scientific significance of this article is the creation of different models of the chemical composition of sponge titanium using neural networks, using big data analysis based on pattern recognition or object clustering.

Purpose and objectives of the research. The purpose of this article is to explore the possibilities of creating different models of the chemical composition of sponge titanium using neural networks, using big data analysis based on pattern recognition or object clustering.

Artificial intelligence is the most powerful of modern technologies, and it is a mistake to ignore it. Leaders of countries and companies see tremendous opportunities in it and are afraid to be left behind in the race for artificial intelligence [1]. Research in the field of artificial intelligence has its own challenges. Currently benchmarks for comparison are established by brute force and pattern matching, and minor changes in input signals can completely break machine learning models. Perhaps the current campaigns do not have enough structural strength to teach artificial intelligence to cope with the most difficult tasks, such as solving the “common sense” problem or recreating situational models. Researchers would like machines to be able to act on situational contexts and draw general conclusions without having to be pre-trained on huge datasets, but this is not yet possible [2]. The world of artificial intelligence is constantly changing. Its boundaries are constantly expanding. When a particular problem is solved, it leaves the realm of artificial intelligence and gradually moves into the classical set of tools [3]. The best way to learn a new field of knowledge is to start analyzing your data yourself [4]. Collecting data requires a cost – an investment. Its size depends on how much data is needed and how difficult the collection process is [5].

Digital platforms are typical cells of the new digital economy, replacing the multinational companies of the industrial era [6]. Therefore, the use of artificial intelligence and neural networks is essential in the modern world.

Materials and methods of research. Drawing conclusions about the practical applicability of a scientific article, it can be assumed that the obtained material can be used as a guide to modeling the process of obtaining sponge titanium using neural networks.

The research methods were carried out using modern information technologies as a neural network to simulate the results of the chemical composition of sponge titanium.

The mathematical basis of artificial intelligence has been intensively developed in the last decade. Currently, it is being introduced directly into the foundation of industrial automation. In the near future, a significant increase in the use of artificial intelligence systems in the main production processes, including in metallurgy, is predicted. Metallurgical production includes a wide range of distributed processes of a complex nature - from the preparation of raw materials to the production of rolled metal. Each of them is characterized by some degree of inaccuracy.

Currently, with the development of the concept of neural networks and fuzzy logic, it is significantly leading the industry, including the following areas: fuzzy sets; genetic algorithms; evolutionary computing; chaos theory; Artificial Intelligence; modeling systems; probabilistic reasoning; study of the principles of the mechanism; study of intelligent control algorithms; pattern recognition and image understanding; self-organization of complex systems; fuzzy databases; fuzzy information search, etc.

The goal of data science is to improve the decision-making process based on a deeper understanding of the situation through the analysis of large data sets. As a field, data science includes a set of principles, problem-setting methods, algorithms, and processes for discovering hidden useful patterns in large datasets. It is closely related to data mining and neural networks, but has a wider scope [7]. Each of the levels of automation had its own definitions, in connection with this, standardization was required to bring clarity and consistency [8]. Also, the area of use covers almost all areas, this requires a large number of specialists who understand how artificial intelligence and machine learning algorithms work [9].

The listed directions are widely used in metallurgy, both in stand-alone and combined applications. The areas in which they are effectively used are different: assessment and forecast of technological parameters; control and diagnostics of technological processes; optimization and planning of results; process modeling and interactive modeling in dialogue modes. In particular, significant results have been achieved in predicting the change in the silicon content in cast iron during blast-furnace smelting, the hydrogen content in the metal during vacuuming; control of laser welding, quality control of welded seams; detection of hidden defects in rails; hot rolling optimization and billet deformation control during rolling; planning the reduction of tolerances during rolling; modeling the solidification of a continuously cast billet, cold rolling technology; control of changes in the temperature of the strip during hot rolling and the thickness of the metal coating in the galvanization line; metal level control in the tundish during continuous casting, etc.

To research the applicability of neural networks for the analysis of technological parameters, the description of the process for obtaining sponge titanium is given below. Obtaining pure metallic titanium is associated with significant technological difficulties due to the high chemical activity of this metal. The reaction of titanium interaction with oxygen, nitrogen, carbon, carbon oxides and water vapor proceed with a large decrease in the Gibbs energy. Therefore, the processes of reduction and melting of the metal are carried out in sealed equipment in an atmosphere of inert gases (argon, helium) or, in a vacuum. One of the most important conditions is the high purity of the starting compound and the used reducing agent.

UKTMC JSC uses magnesium reduction of titanium tetrachloride. Magnesium-thermal production of titanium is based on the reaction: $TiCl4 + 2 Mg = Ti + 2 MgCl2$.

The first ideas about the mechanism of the reduction process were formed under the influence of the results of laboratory studies by Watman et al. It was found that the initial formation of a sponge begins on the reactor wall at the level of a mirror of molten magnesium. Over time, the sponge grows upwards and towards the center of the reactor. It was suggested that the main interaction occurs on the surface of the sponge between TiCl4 and liquid magnesium, which diffuses in the sponge mass due to capillary forces, reaching its surface. The resulting MgCl2 flows down the surface to the bottom of the apparatus. The decisive role of surface phenomena was substantiated by experiments in which steel rods were placed in a vertical position in the reaction space of the apparatus: some of them were welded to the bottom of the reactor and protruded above the level of liquid magnesium. The other part was welded to the reactor lid so that their ends did not touch the magnesium level. The titanium sponge formed only on those rods that protruded from the magnesium above the melt.

The hardware design and technology of the recovery process is determined by the specific properties of titanium and magnesium, namely: titanium in a heated state actively interacts with oxygen, nitrogen, carbon, and water vapor. In addition, when heated above 1000°C, titanium with iron forms a fusible eutectic; the reduction of titanium tetrachloride with magnesium is accompanied by the release of a large amount of heat, which must be removed from the apparatus; since in the process of reduction the amount of magnesium chloride formed by volume is 10.4 times greater than the amount of titanium formed, magnesium chloride must be removed to ensure maximum utilization of the apparatus capacity; contact of titanium tetrachloride and molten magnesium with air during their introduction into the apparatus is unacceptable both from the point of view of their contamination and for safety reasons. Therefore, it is necessary to provide conditions for their hermetic loading into the apparatus.

Currently, for the production of titanium, sealed vessels made of stainless steel are used, equipped with devices for loading magnesium and titanium tetrachloride, as well as draining magnesium chloride. The apparatus is placed in an oven equipped with an air manifold to cool the reaction zone of the apparatus. The recovery process is carried out in a protective atmosphere of an inert gas - helium or argon.

The following practice and sequence of basic technological operations have been developed. The reductant is simultaneously loaded into the reactor filled with an inert gas in such a way as to ensure the need for the entire reduction cycle. Then, a continuous regulated supply of titanium tetrachloride is carried out on the magnesium surface. The resulting magnesium chloride, which has a greater specific gravity than magnesium, sinks to the bottom of the reactor, thereby raising the level of metallic magnesium. To remove magnesium chloride, it is necessary to maintain the temperature of the resulting reduction products slightly above the melting point of chloride (712ºC). Intensification of a highly exothermic process requires intensive cooling of the reactor. Thus, the problem arises of creating such a design of the furnace and the reactor cooling system that can satisfy the conflicting requirements of the technology: intensification of heat removal from the apparatus while maintaining a sufficiently high temperature on its surface. Difficulties also arise due to the fact that the main heat source, located near the interface between the condensed and vapor-gas phases, changes its location due to the accumulation of reduction products in the reactor and periodic discharges of magnesium chloride.

The titanium sponge is removed from the retorts with pneumatic chisels. Sometimes a thick false bottom is placed in the lower part before restoration, with which the contents of the inverted retort are squeezed out using a hydraulic press rod. After separating the part contaminated with oxides, the sponge is crushed on special gear and disk machines and divided into fractions by size.

The interaction of titanium tetrachloride with magnesium begins at 300 °C, but at this temperature the reaction proceeds at a low rate. Acceptable for industrial conditions is such a speed of the beginning of the process, which develops at temperatures >800°C. At such temperatures, magnesium and the resulting magnesium chloride are in a liquid state throughout the entire process, in which case the separation of these substances and the normal conduct of the process are possible. If magnesium is poured into the reactor at a temperature of <800°C, then heat must be introduced into the reactor before starting the reduction process. During the process, –687 MJ of heat is released per 1 kg of titanium produced. Heat must be removed, otherwise the temperature in the reactor will rise rapidly.

To increase the speed of the process, it is desirable that the temperature in the reaction zone was as high as possible. In the central zones of the reactor, high temperatures can be allowed to develop, but in those places where titanium, magnesium and titanium tetrachloride are in contact with steel, the temperature increase above certain limits is unacceptable. If steel is in contact with magnesium and titanium tetrachloride at >900°C, the resulting titanium is contaminated with iron. The most dangerous is the interaction of steel with titanium at high temperatures. Iron with titanium forms an alloy with a melting point of 1085 °C. Therefore, if the temperature in any place of the steel wall of the reactor rises above 1085 °C, the reactor will melt in this place.

In connection with the above, the process is carried out at a strictly defined temperature of the reactor wall.

The mechanism of formation of a block of reaction mass in an industrial reactor can be represented as follows. In the first period, titanium sponge is formed mainly on the surface of the melt and sinks to the bottom along with magnesium chloride. Formed on the surface, the sponge “absorbs” both magnesium and magnesium chloride, which condenses due to the intensive removal of heat by the sponge into the melt. The heat of condensation is spent on the evaporation of magnesium. Due to the lack of a reducing agent, which can occur starting from a certain period of the process, the sponge also "absorbs" titanium dichloride, which dissolves in magnesium chloride. Titanium dichloride can be formed as a result of the secondary reaction of titanium tetrachloride with titanium already present in the reactor. Getting under the upper layers of the reaction mass, the sponge encounters a flow of magnesium directed to the reaction zone. Magnesium reduces titanium dichloride and displaces magnesium chloride from the small pores of the sponge. This is confirmed by the ratio of the amount of magnesium and magnesium chloride: in the upper zone it is 2:1, in the middle zone 4:1, in the lower zone 10:1. In this way, a finely porous sponge is formed. Despite the presence of small pores, the reaction mass is separated from the middle zone faster than from the upper zone. Small pores in the middle zone are filled mainly with magnesium, and in the upper zone with magnesium chloride.

As the sponge compacts as a result of the secondary reaction, the access of magnesium to the reaction zone becomes more difficult, and the process gradually slows down, passing into the second stage. In addition, the attenuation is also affected by the fact that by the end of the process, almost all of the remaining magnesium is in the pores of the sponge and is retained in them by wetting forces.

The sponge block occupies almost all sections of the reactor (Figure 1). In the center it is a monolithic mass, at the walls it is more loose, layered. This means that the process proceeds not only in the center, but throughout the entire section. The peripheral zones of the block are formed in the same way as the central ones, only less magnesium usually enters here. In these zones are the main channels through which magnesium chloride flows. During some drains, the structure of the block is broken (the sponge settles, the “bridge” is broken in the second stage of the process, etc.). As a result, channels are also formed on the periphery, along which magnesium intensively flows to the surface of the sponge. This situation is confirmed by a sharp increase in temperature in some places of the peripheral zone in the second stage of the process.

The considered process is semi-continuous, more precisely – periodically continuous, cyclic. The following positive factors testify to its viability:

- comparative simplicity of design;
- the possibility of pre-refining magnesium before the start of the process in the same reactor;
- the possibility of separating the main amount of magnesium chloride before the subsequent process – vacuum separation;
- acceptable performance, which can be increased in the future;
- good combination of reduction and vacuum separation processes carried out in one retort;

– high yield of metallic titanium, approaching stoichiometric.

Equipment for the recovery process.

The recovery apparatus (reactor) is the main technological equipment of the redistribution. It is structurally closely related to the subsequent redistribution – vacuum separation, since in the magnesium-thermal process it alternately plays the role of a reactor (in the process of reduction), a muffle and a condenser (in the process of vacuum separation).

Figure 1 schematically shows the structure of the recovery apparatus.

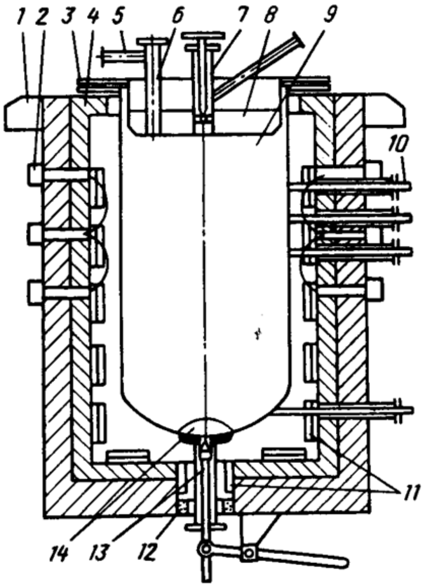


Figure 1. Scheme of the reduction apparatus placed in the furnace [10]

There are 1 – furnace support; 2 – manifolds for supply and exhaust air; 3 – water-cooled flange connection; 4 – furnace lining; 5 – nipple for evacuation and argon supply; 6 – magnesium pouring unit; 7 – TiCl4 supply unit; 8 – reactor cover; 9 – retort; 10 – contact thermometers (thermal probes); 11 – heaters; 12 – sand gate; 13 – the stem of the drain device; 14 – false bottom.

The reactor is a cylindrical steel retort with a flange and a spherical bottom. In this design, the design is stable, manufacturable, easy to use. Alloy steel, from which retorts are usually made, is mainly needed to reduce the oxidation of the outer walls of the reactor, which are in contact with air for a long time at high temperatures. In addition, the risk of titanium contamination with iron is somewhat reduced. The use of chromium-nickel steels ensures the production of high-quality metal and a sufficiently long service life of the reactor.

The material of the reactor must have good weldability, welds must be resistant under the specified conditions.

Cyclic thermal shocks lead to alternating plastic deformations. Such conditions occur during periods of cooling air supply, when the temperature difference across the wall thickness reaches 70°C (outside temperature 850 °C).

The reactor can be made of two independent parts - a retort and a glass, which is inserted into it for the duration of the process and removed together with the products after cooling.

The performance of a reactor largely depends on the ratio of its height to diameter. With a small value of this ratio, the utilization factor of the reactor volume decreases, with a large value, the operation of extracting the titanium sponge block becomes more complicated.

With an increase in the diameter of the reactor and a decrease in its height, the process accelerates, since the central zone of the intense reaction expands and the conditions for transporting magnesium and magnesium chloride inside the reactor improve, the power consumption decreases during the reduction process, because the lower zones and the drain device are heated due to process heat.

The lid serves mainly to seal the reactor. In addition, it acts as a thermal screen when the reactor is heated and as a heat-removing element during the reaction. The sealing of the connection between the lid and the reactor is carried out using a rubber gasket sandwiched between the water-cooled flanges of the lid and the reactor. Mounting and dismantling of the cover on bolted connections is simple. One of the advantages of the concave lid design (Figure 2) is that a significant amount of heat can be removed from the reactor through it, and this can significantly speed up the process.

Magnesium loading unit. Figure 2 shows one of the options for connecting the crucible with liquid magnesium to the reactor during the pouring period. This design reliably protects magnesium from contact with air during loading.

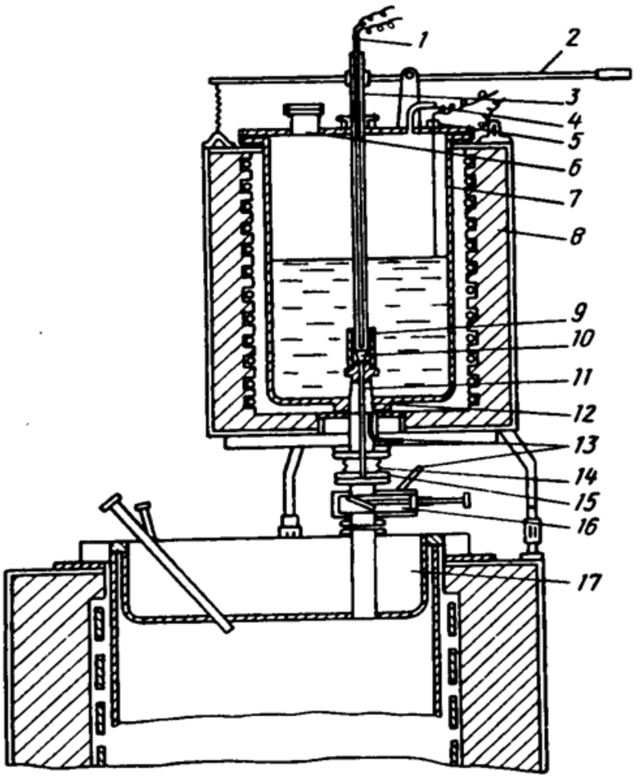


Figure 2. Device for loading molten magnesium into the reactor [10]

There are 1 – thermocouple; 2 – rod control; 3 – stock; 4 and 13 – argon supply fittings; 5 – contact level gauge; 6 – magnesium loading pipe; 7 – crucible; 8 – lining; 9 – glass; 10 – locking needle; 11 – drain pipe; 12 – thermal insulation; 14 – spring compensator; 15 – flange connection; 16 – valve; 17 – reactor cover.

Draining unit for magnesium chloride. The mechanical locking device (Figure 3) consists of a steel rod with a spherical head and a conical socket in the bottom of the retort. To prevent the titanium sponge from getting on the locking contact surfaces, a false bottom is installed above the drain fixture. After installing the reactor in the furnace and filling it with argon, the shut-off rod is connected to the drain control unit, for example, to a pneumatic cylinder. Rodless devices for draining magnesium chloride "with freezing" are also used (Figure 3), but it is difficult to control such a device.

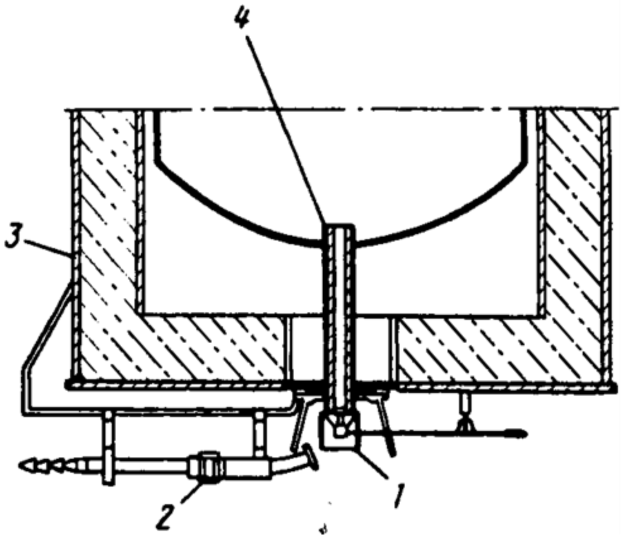


Figure 3. Rodless drain fixture [10]

There are 1 – lever; 2 – burner; 3 – furnace; 4 – drain pipe.

The heat of the reaction products also appears in full in the expense items, since the reaction products are eventually removed from the reactor and this heat is lost. The amount of heat obtained from electricity and the process itself is equal to the amount of heat carried away by artificial and natural cooling (the third expense item).

These data show that the forced cooling of the reactor walls plays an important role in removing the heat of the reaction. Nevertheless, a significant part of the heat is removed through the lid and the reactor flange. A lot of energy is spent on heating the lower zones of the reactor, although for this purpose it would be advisable to use the heat of the exothermic reaction. The theoretical consumption of magnesium per 1 ton of titanium is 1020 kg, titanium tetrachloride - 3960 kg. This produces 3980 kg of magnesium chloride.

The coefficient of magnesium utilization here is assumed to be 65%, the coefficient of magnesium chloride drained during the reduction process is 96%, it can be neglected. Heat transfer inside the capillaries by radiation is also low, since the temperature of the block during this period does not exceed 750°C.

The process of external heat transfer from the surface of the reaction mass to the condenser proceeds as a transfer of radiant energy and the movement of a heated vapor-gas mixture.

The greater the amount of heat supplied, the faster the temperature rises in the layer of the reaction mass and the higher the rate of evaporation. With rapid heating, more volatiles are removed and more heat is spent on evaporation, as the volatiles are removed, the vapor pressure of the components decreases, as a result, the evaporation rate decreases. This again leads to an increase in temperature, and so on. Consequently, self-regulation of the distillation process occurs in the system. Such a process is called autothermal.

By the nature of the change in the temperature of the central point of the block of the reaction mass, one can judge the onset of one or another stage of the process and evaluate the separation efficiency in apparatuses of various geometric dimensions.

Technological methods with the help of which it is possible to intensify the separation process include: drilling a block of the reaction mass in the center after reduction, obtaining a coarsely porous sponge during recovery.

It follows from the foregoing that the features of the technological regime and the design of the vacuum separation process are determined by the structure of spongy titanium and the parameters of the reduction process.

The separation process ends when the entire sponge is heated to the highest possible temperature. Based on this, the end of the process can be judged by reaching this temperature at that point of the reaction mass, which is heated last. This point is usually the middle of the surface of the block of the reaction mass. However, this parameter is not always reliable enough.

The second, more accurate method for determining the end of the process is the method of measuring the pressure of gases in the retort after the vacuum line is turned off. Figure 6 shows the pressure in the retort and the temperature at some points. The separation process was terminated at the moment when the temperatures at all points of the block surface (t1, t2 and t3) were equal. On the pressure curve, the vectors a1, a2, a3 and a4 indicate the pressures that are reached in the retort 3 minutes after the vacuum valve is closed. The last vector a4 is directed downward, at this moment, after the valve was closed, the pressure did not increase, but decreased. Consequently, there was a moment when the pressures in the retort and in the vacuum line were equal and the gases did not move in either direction. This moment is called the turning point of the gas flow. This point c on the pressure curve is located in the region of intersection of the pressure curve by the line connecting the ends of the vectors a3 and a4. The turning point of the gas flow determines the end of the separation process. The gas flow turns due to the fact that the release of gases (mainly hydrogen) from the sponge stops, which occurs during the entire process, and then the sponge begins to absorb gases flowing into the retort through leaks. The pressure in the retort (vector a4) at this moment becomes less than in the vacuum line.

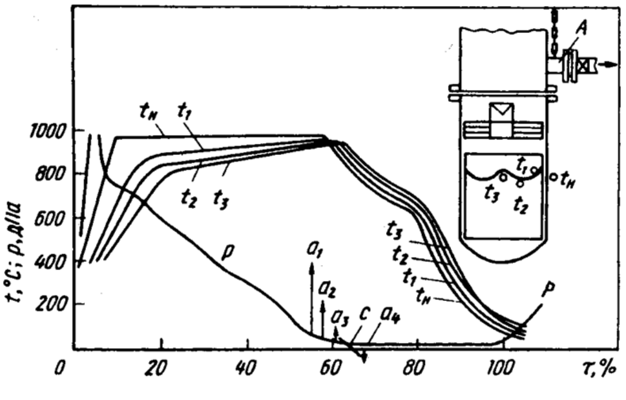


Figure 4. Determining the end of separation by changing the temperature and pressure in the apparatus [10]

There are A is the place of pressure measurement; t - temperature measurement points.

The further course of the pressure curve indicates that the pressure in the retort begins to increase only after the temperature of the sponge becomes <200°C. Then the sponge ceases to absorb the gases flowing into the retort.

Equipment for vacuum separation.

The main elements of the vacuum separation apparatus include a retort with a reaction mass, an oven, a condenser and a heat-insulating screen. The scheme of the separation apparatus is shown in Figure 5.

The retort (or muffle) with the reaction mass is the heated part of the apparatus. The height of the muffle should ensure a uniform temperature distribution over its working part, i.e. in the area where the titanium sponge is located. With a small muffle height, the temperature difference that should be between the muffle and the condenser must be created over a very small height segment. This is possible only with increased heating of the upper part of the muffle near the cold flange, which entails large heat losses. In the absence of enhanced heating of the upper part of the muffle, the heat shield overgrows with condensate.

Bake. For a separation furnace, electric heating is most appropriate: it is more convenient to place the muffle heated by electric current in a vacuum furnace. If a furnace with gas heating is used, then it is impossible to create a countervacuum in it, and it is necessary to make a thick-walled muffle from heat-resistant steel.

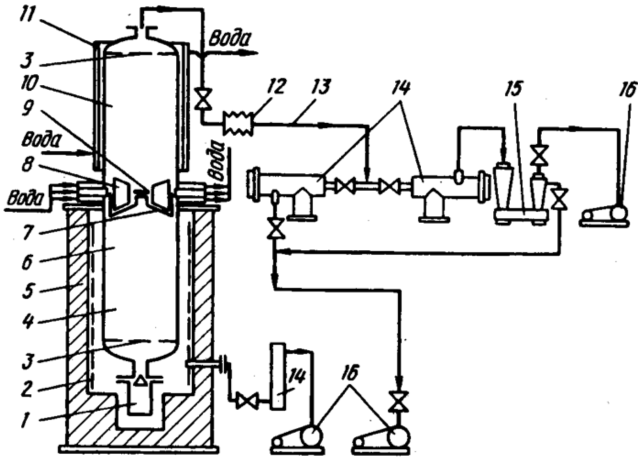


Figure 5. Scheme of the vacuum separation apparatus [10]

There are 1 – vacuum cap; 2 – furnace heaters; 3 – false bottom; 4 – reaction mass; 5 – electric furnace; 6 – reactor; 7 – reactor cover; 8 – heat-insulating screen; 9 – fusible plug; 10 – retort - condenser; 11 – condenser cooler; 12 – pipeline compensator; 13 – vacuum line; 14 – vacuum trap; 15 – booster vacuum pump; 16 – spool vacuum pump.

Figure 6 shows the placement of equipment at the working sites of the metallurgical shop of the JSC UKTMC enterprise. On the left in Figure 6, the recovery site is shown, in the foreground there is an apparatus that is transported by an electric overhead crane, and a number of furnaces with apparatuses installed in them - recovery installations are also visible.

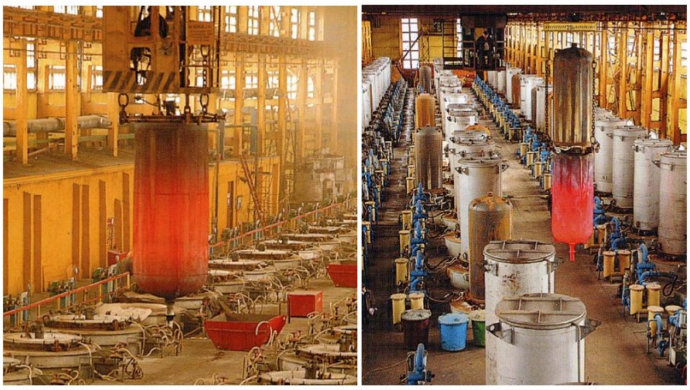


Figure 6. Location of equipment in the areas of reduction (left) and vacuum separation of the metallurgical shop of UKTMC JSC

The location of electric heaters in the furnace, temperature control and regulation systems should ensure the most uniform temperature distribution on the working surface of the muffle. The power of the furnace should ensure that the wall of the muffle is heated to the holding temperature in the shortest possible time. The greatest power is required when heating the reaction mass. During the period of constant speed of distillation, the energy consumption decreases slightly, and then during the period of decrease in speed, the furnace consumes about a third of the original power (idle power).

Separation of 1 ton of sponge theoretically requires 1500 kWh of electricity. In practice, it is spent 3-4 times more. Such a low efficiency of the furnace is due to the periodicity of the process, as well as the long-term distillation of the last portions of magnesium chloride, when almost all the energy is spent on replenishing heat losses through the lining and condenser.

The screen is a thermal insulation between the reaction mass and the condenser. It creates an obstacle to heat radiation from the muffle to the condenser and to the flanges that connect the condenser to the muffle.

Capacitor. The cooled surface of the condenser must be sufficient to remove the heat brought by the precipitated magnesium and magnesium chloride. Very intense cooling of the deposition surface leads to the formation of finely dispersed magnesium, which is capable of spontaneous combustion. Slowing heat removal is also undesirable, since heat removal is the main function of the condenser, contributing to the acceleration of the process. For the convenience of unloading and preventing the formation of spontaneously igniting condensate, sometimes a precipitator shell is inserted into the condenser, where the main amount of vapor is deposited.

As vapors settle and the deposit thickens, the cooled surface heats up due to the difficulty of heat removal.

A difficult operation is the unloading of the condenser, therefore, in apparatuses where the condensate does not melt, a device is provided directly in the condenser-retort that simplifies the unloading of the shell (sector, etc.).

When dismantling the retort, the condensate must not fall into the separated sponge.

When choosing the design of the separation apparatus, the position of the condenser is important: it can be located above, below or to the side in relation to the furnace and muffle. The condenser located on the side has a serious drawback: in this case, a heated steam pipeline is required, through which vapors of magnesium and magnesium chloride must flow from the muffle to the condenser. Vacuum seals must also be heated, which complicates the design of the condenser.

In an apparatus with a lower condenser, part of the magnesium and magnesium chloride can be smelted from the reaction mass. This requires less heat and time than evaporation in the case of separation in an apparatus with an upper condenser. When unloading, there is no danger of contamination of the sponge with crumbling condensate.

However, the gain in power consumption and in the productivity of the apparatus is not as significant as it seems, because the main part of the time in the separation process is spent on the distillation of the last portions of magnesium chloride, and this period in both apparatuses is the same in duration. A significant disadvantage of devices with a lower condenser is the need to use bell-type removable furnaces of complex design.

Figure 7 shows a block of sponge titanium weighing 7 tons produced by UKTMC JSC obtained from a distillation apparatus.

There are two main processes in any optimization problem based on genetic algorithms. First the module of genetic algorithms is designed, and then the tests and evaluations are simulated. The boundary conditions are defined by the parameters of the process under study. Setting the optimization problem to achieve the main goal and possible alternatives is based on the analysis of the structure of the main arrays of production data of the enterprise. The genetic algorithm uses some initial actual array of this data. If this preliminary array is adapted by the model with constraints, there is a return to the genetic algorithms module. If the matching function is satisfied, we get the solution to the problem. In the second generation, the genetic algorithms module processes the first population of parameters and creates a new list of parameters, continuing to search for the necessary mutations until the final version satisfies the matching function or the user-defined algorithm runtime runs out. This type of system using tools and genetic algorithms is planned to be implemented at UKTMK JSC.

Figure 7. Sponge titanium block weighing 7 tons produced by UKTMC JSC

Mathematical model of the neural network system "Receiving titanium sponge JSC "UKTMK". Due to the linearity of the neuron, the output signal y(i) or f(Ti) coincides with the induced local field v(i):

$$y(i) = v(i) = \sum_{k=i}^{m} w_k\,(i) x_k(i) \tag{1}$$

where wl(i), w2(i), ..., wm(i) are m synaptic weights of the neuron measured at time i. In matrix form the output signal y(i) can be represented as the scalar product of vectors w(i) and x(i):

$$y(i) = x^T(i)w(i) \tag{2}$$

where $w(i) = [\mathrm{w}_1(\mathrm{i}), \mathrm{w}_i(\mathrm{i}), \dots, \mathrm{w}_m(\mathrm{i})]^T$.

Since the case of a single neuron is considered, the indexing of synaptic weights does not include an additional index to define the neuron. Neuron output signal y(i) is compared with the corresponding actual output signal d(i) - the data are taken from the PTU (production and technical control) of UKTMK JSC; as a rule, they are different and their difference determines the error signal e(i).

The way to use the error signal e(i) to correct the synaptic weights of a neuron is determined by the cost function used to obtain the adaptive filtering algorithm. This problem is closely related to the problem of production optimization of UKTMK JSC. Therefore it is reasonable to present an overview of some optimization methods, which is applicable not only to linear adaptive filters, but to neural networks in general.

Function E(w) maps elements of vector w to space of real numbers and is a measure of optimality of vector w chosen for adaptive filtering algorithm. It is required to find such solution w*, that

$$\mathrm{E}(\mathrm{w}^*) \leq \mathrm{E}(\mathrm{w}) \tag{3}$$

Thus, it is necessary to solve the problem of unconditional optimization, which consists in minimizing the cost function E(w) with respect to the vector of weights w:

$$\mathrm{E}(\mathrm{w}) \to \min \tag{4}$$

A necessary condition for optimality: $\nabla E(\mathrm{w}^*) = 0$
where ∇ - gradient operator, and ∇E(w) - velocity gradient vector.

$$\nabla \mathrm{E}(\mathrm{w}) = \left[\frac{dE}{dw_1}, \frac{dE}{dw_2}, \dots, \frac{dE}{dw_m}\right]^T \tag{5}$$

A class of unconditional optimization algorithms that are well suited for creating adaptive filters is based on the sequential descent algorithm: assuming an initial value w(0), a sequence of weight vectors w(1), w(2), ..., w(n) is generated such that the value of the cost function decreases with each iteration of the algorithm:

$$\mathrm{E}\big(\mathrm{w}(\mathrm{n}+1)\big) < \mathrm{E}\big(\mathrm{w}(\mathrm{n})\big) \tag{6}$$

where w(n) is the previous value of weights vector, w (n + 1) is the next one. Such an algorithm will converge to the optimal solution w* if certain conditions are met, which are implemented in the following methods of optimization of titanium sponge production of JSC "UKTMK".

Figure 8 shows the algorithm of the neural network "Receiving titanium sponge JSC "UKTMK". Neuron-Ti is a computational unit that receives information, makes program calculations over it and passes it on. They are divided into three main types: input (blue), hidden (red) and output (green).

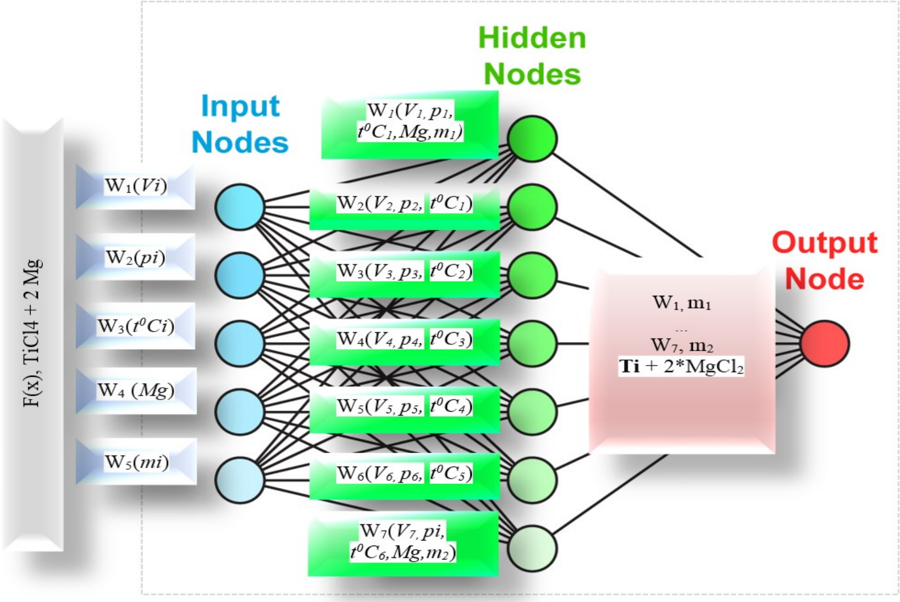


Figure 8. Neural network of magnesium-thermal production of titanium sponge JSC "UKTMK" with activation function f(x): TiCl4 + 2 Mg = Ti + 2 MgCl2, where melting rate (V), system pressure (p), furnace temperature (t0C), raw magnesium (Mg), and charge mass (m) are considered as input parameters

When a neural network-Ti consists of a large number of neurons, the term layer is introduced. Accordingly, there is an input layer, which receives information, n hidden layers (usually not more than 3), which process it, and an output layer, which outputs the result.

Each neuron has 2 main parameters: input data (input data - melting rate (V), system pressure (p), furnace temperature (t0C), raw magnesium (Mg) and charge mass (m)) and output data (output data - Ti/Mg Cl2).

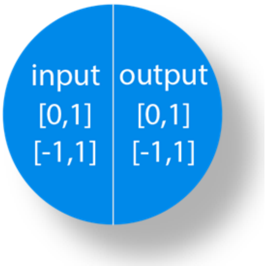
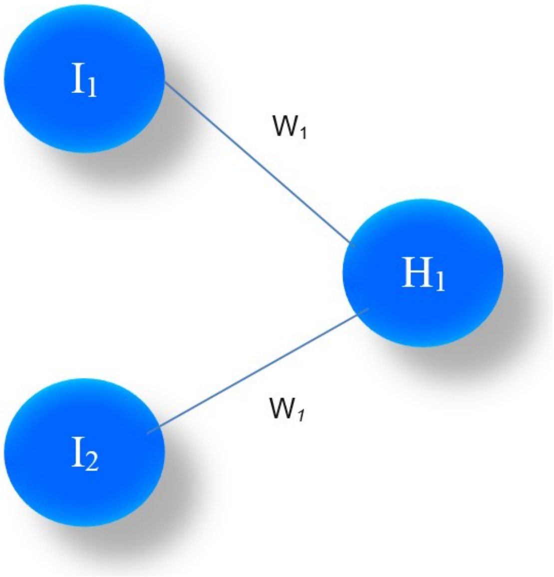


Figure 9. Range of neural network "Receiving titanium sponge JSC "UKTMK" with values [0,1] and [-1,1]

In the case of input neuron: input=output. In the rest, the input field gets the total information of all neurons from the previous layer, and then it is normalized, using the activation function f(x), and gets into the output field.



$$H_{input} = (I_1 * W_1) + (I_2 * W_2) \qquad (7)$$

$$H_{output} = f_{activation}(H_{input}) \qquad (8)$$

Figure 10. Activation function of the neural network "Receiving titanium sponge JSC "UKTMK"

The activation function determines the output value of the neuron-Ti depending on the result of the weighted sum of inputs and the threshold value.

Figure 10 shows a part of the neural network "Receiving titanium sponge JSC "UKTMK", where the letters "I" denote the input neurons (1), the letter "H" - the hidden neuron, and the letter "w" - weights. From the formula we see that the input information is the sum of all inputs multiplied by their corresponding weights. Then we give as input 1 and 0. Let w1 = 0.4 and w2 = 0.7 The input of neuron H1 (2) will be as follows: 1*0.4+0*0.7=0.4. Now that we have the input data we can get the output data by substituting the input value into the activation function:

f(x): TiCl4 + 2 Mg = Ti + 2 MgCl2 (9)

The state of the neuron-Ti is defined as the weighted (w – weights) sum of i input signals x (perceived by the dendrites) and the bias b (4):

$$Ti = \sum_{i=1}^{n} w_i * x_i + w_{i+1} * b \qquad (10)$$

The addition of a bias can be represented as the effect of an additional bias neuron.

The state of the neuron is converted into an output signal (at the axon terminals) using the activation function f:

$$y=f(Ti) \qquad (11)$$

The input signals to the input layer neurons are transferred to their outputs unchanged, which corresponds to a linear activation function:

$$f(Ti)=Ti \qquad (12)$$

A non-linear activation function - "sigmoid", or rather its very popular variant - the logistic function - with a value interval (0; 1) is used for neurons of the hidden and output layer:

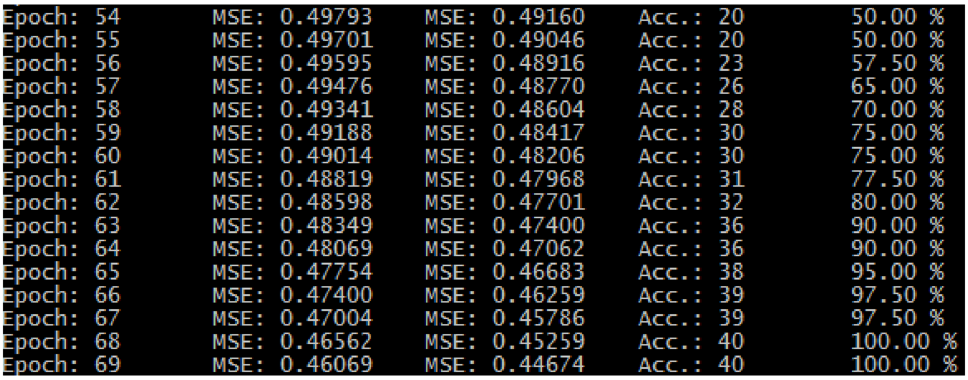
$$f(Ti) = \frac{1}{1+e^{-Ti}} \qquad (13)$$

This choice of activation function is excellent for non-negative ADC samples. But this requires, of course, normalization of input values - divide them by 1024, which guarantees a value less than 1.

Values on output neurons of the output layer define neural network results. Neuron with the maximal output value will indicate a solution (winning class) taken by the network: first class - "titanium with admixture", second class - "titanium purified".

Python - PyTorch, Keras, TensorFlow, CNTK, libraries and Frameworks (JavaScript - Synaptic, Java - Deeplearning4j, C++/CNTK) are often used to solve neural network problems.

After compiling the source code and running the executable, the console displays the learning process - the epoch number (Ti-Epoch), the mean square of the learning and validation errors (Ti-MSE) and the accuracy of the predictions on the validation dataset. A fragment of such a protocol is shown in Figure 11:



```
Epoch: 54       MSE: 0.49793    MSE: 0.49160    Acc.: 20        50.00 %
Epoch: 55       MSE: 0.49701    MSE: 0.49046    Acc.: 20        50.00 %
Epoch: 56       MSE: 0.49595    MSE: 0.48916    Acc.: 23        57.50 %
Epoch: 57       MSE: 0.49476    MSE: 0.48770    Acc.: 26        65.00 %
Epoch: 58       MSE: 0.49341    MSE: 0.48604    Acc.: 28        70.00 %
Epoch: 59       MSE: 0.49188    MSE: 0.48417    Acc.: 30        75.00 %
Epoch: 60       MSE: 0.49014    MSE: 0.48206    Acc.: 30        75.00 %
Epoch: 61       MSE: 0.48819    MSE: 0.47968    Acc.: 31        77.50 %
Epoch: 62       MSE: 0.48598    MSE: 0.47701    Acc.: 32        80.00 %
Epoch: 63       MSE: 0.48349    MSE: 0.47400    Acc.: 36        90.00 %
Epoch: 64       MSE: 0.48069    MSE: 0.47062    Acc.: 36        90.00 %
Epoch: 65       MSE: 0.47754    MSE: 0.46683    Acc.: 38        95.00 %
Epoch: 66       MSE: 0.47400    MSE: 0.46259    Acc.: 39        97.50 %
Epoch: 67       MSE: 0.47004    MSE: 0.45786    Acc.: 39        97.50 %
Epoch: 68       MSE: 0.46562    MSE: 0.45259    Acc.: 40        100.00 %
Epoch: 69       MSE: 0.46069    MSE: 0.44674    Acc.: 40        100.00 %
```

Figure 11. Training protocol for the neural network "Receiving titanium sponge JSC "UKTMK" in 69 iterations (epochs) of training

Changing the starting number affects the initial values of the neural network weights, which leads to small differences in the learning process. With a learning rate coefficient of 0.1, the training is completed (when reaching Ti-MSE = 0.01 on the test set) in about 300 Ti-epochs.

The accuracy of the solutions on the validation dataset is 100 % (the program outputs the number of the winning neuron, starting from 0-"0" - the first neuron, titanium impurity; "1" - the second neuron, titanium purified):

```
0 -> 0
0 -> 0
0 -> 0
…
1 -> 1
1 -> 1
1 -> 1
```

The final weights of the neural network after training are saved for later use in the text file "nn4md.json" in JSON-format.

The application of the neural network system apparatus "Titanium sponge production" in the management of modern production is one of the potentially promising areas of development of automatic control systems of the Joint Stock Company "Ust-Kamenogorsk Titanium-Magnesium Plant" (JSC "UKTMK") involved in the automation of production and manufacture of control system equipment.

The preparation of commercial batches of sponge titanium homogeneous in chemical composition is an important technological operation. The difficulty of averaging lies in the fact that the fractional composition of a commercial batch has a wide range of particle size, which differ significantly in chemical composition and mechanical properties. To average the composition, various mixers and homogenizers are used that do not have moving mixing elements that can cause sparking and ignition of spongy titanium. Drum mixers of periodic action are used, gravitational mixers of continuous action - bunker, tray, cone distributors.

Table 1 shows the chemical composition of the titanium sponge and the Brinell hardness, according to which it is necessary to build neural networks.

Table 1. Chemical composition of titanium sponge and Brinell hardness [10]

Brand	Impurity content, %, no more							HB (10/1600/30), no more
	Fe	Si	Ni	C	Cl	N	O	
USSR (GOST 17746–72)								
TG–90	0,06	0,01	0,05	0,02	0,08	0,02	0,04	90
TG –100	0,07	0,02	0,05	0,02	0,08	0,02	0,04	100
TG –110	0,09	0,03	0,05	0,03	0,08	0,02	0,05	110
TG –120	0,11	0,03	0,05	0,04	0,08	0,03	0,06	120
TG –130	0,13	0,04	0,05	0,04	0,10	0,03	0,08	130
TG –150	0,20	0,04	0,05	0,05	0,12	0,04	0,10	150
TG –TV	2,00	–	–	0,15	0,30	0,30	–	–
USA								
MD	0,12	0,04	–	0,020	0,12	0,015	0,10	120
ML	0,10	0,04	–	0,025	0,20	0,015	0,10	120
SL	0,05	0,04	–	0,020	0,20	0,010	0,10	120
105	0,10	0,03	–	0,03	0,10	0,02	–	105
120	0,20	0,03	–	0,03	0,12	0,02	–	120
160	0,35	0,04	–	0,05	0,15	0,02	–	160

Note.

MD – magnesium-thermal sponge with vacuum separation;

ML – magnesium-thermal sponge with leaching;

SL – sponge obtained by the sodium thermal method with leaching (Na content is not more than 0.19 %.).

The requirements for devices for transporting and dispensing lumpy material are related to the properties of titanium sponge and refer mainly to the material from which parts in contact with sponge titanium should be made: materials should not cause sparking and ignition during friction and should be able to work for a long time in the presence of small sponge particles on rubbing surfaces.

For sponge titanium blocks and large pieces, it is advisable to use manipulators, pushers and addressers. The most suitable unit for handling large material is the “mechanical arm” type manipulator. For medium and small pieces of titanium sponge (size <100 mm), belt conveyors and elevators can be used. In order to reduce the length of transport, vibroconveyors are used.

The continuity and uniformity of the supply of spongy titanium in the process flow depends on the correct choice and calculation of the dimensions of hoppers, gates and feeders. To prevent water formation, stimulators (vibrators, etc.) are installed. The unhindered natural outflow of bulk materials is due to the appropriate dimensions of the outlet openings adopted as a result of operation.

Titanium sponge after averaging is packed in a sealed or dust-proof container: barrels with a capacity of 250 liters or containers with a capacity of 500 liters. Containers with products can be filled with an inert gas to improve the safety of titanium quality.

Considering the structural features of spongy titanium, its physical, chemical and mechanical properties, the following conditions must be met when processing it into commercial products:

– prevent contact of sponge blocks and its pieces with possible sources of contamination: scale, oil from equipment, tool fragments, dirt on vehicles, etc.;

– it is rational to cut the sponge block into categories that differ in quality;

– exclude mixing of different categories of crushed sponge, differing in chemical composition and uniformity;

– to prevent scattering of the sponge; protect moving and rubbing parts of mechanisms from small pieces of sponge and titanium dust;

– to limit the size of the pieces sent to each stage of grinding (organization of the work of crushing plants in a closed cycle).

The technological process of processing sponge titanium blocks into commercial products is built on the principle of mass production by mechanization of labor-intensive preparatory and final operations.

At the final stage of the production of marketable products, a necessary operation is sorting, caused by the fact that, despite visual control at all previous operations, small amounts of defective spongy titanium pieces may be present in the crushed material. Usually sorting is carried out manually on a moving conveyor belt or on sorting tables. The visual control method is subjective and not reliable enough, so it is necessary to improve the sorting process, to create an automated method based on objective data [10].

Results and discussion. There is one big push coming up that will happen in the next few years. They will be the transformation of working with data for industries. The collected information will be used to analyze and detect anomalies in the production cycle, simplifying the management of the conveyor [11]. Modern computers perform mathematical operations at a tremendous speed. Adding numbers at a very high speed is a huge advantage of the computer [12]. Operational analytics is driving the industrial revolution in analytics and is already beginning to push the boundaries of traditional analytics use by companies. Over time, analytics will greatly increase the number of analytic processes that need to be created and the speed at which analytics will be executed [13].

A distributed system is a set of autonomous computing objects that are interconnected and can communicate over a network [14]. One reason for the popularity of neural networks is their remarkable ability to learn from observed examples and draw reasonable conclusions from incomplete, noisy, and inaccurate inputs. A neural network-based solution may look and behave like normal software, but the difference is that a neural network-based implementation is “learned” rather than programmed: the network itself learns to perform a task rather than being programmed directly.

Artificial networks use artificial neurons, which are computer processors. That is, an artificial neural network is a set of interconnected processors that perform several processes simultaneously.

Every kilogram of minerals mined, including titanium-containing raw materials, impoverishes the Earth. Therefore, it is necessary to protect raw materials during processing. The use of neural networks will allow for a deep study of technological parameters and identify the most optimal modes of equipment operation.

Conclusions. Titanium is one of the most common chemical elements both in terms of its content in the earth's crust and the presence of minerals of this metal in many rocks. But do not forget that each resource tends to end. The use of neural networks will make it possible to select the optimal mode of operation of technological equipment, in which the content of low-quality titanium sponge will be minimal in titanium blocks.

The rich potential of new technologies can be unlocked if appropriate tools are available [15]. Neural networks are machine learning tools in which a computer learns to perform a specific task by analyzing training examples. As a rule, these examples are pre-tagged manually. In the object recognition system, it is possible to save the accumulated millions of technological parameters over several decades, which will help to more accurately determine the results. That is, the more input data, the more accurate the result becomes.

This article shows that it is necessary to conduct a large number of chemical analyzes of the extracted titanium block from the retort, including separate analyzes of the skull, the upper and lower crests, and the salable part of sponge titanium itself.

References

1. Marr B., Uord M. Iskusstvennyj intellekt na praktike // Mann, Ivanov i Ferber. – 2020. – S. 6.
2. Klaus SH. CHetvertaya promyshlennaya revolyuciya // Bombora. – 2016. – S. 147.
3. Lekun YA. Kak uchitsya mashina: Revolyuciya v oblasti nejronnyh setej i glubokogo obucheniya // Al'pina PRO. – 2021g. – S. 9.
4. Rafalovich V. Data Mining, ili intellektual'nyj analiz dannyh dlya zanyatyh // Litagent I-Trejd. – 2014. – S. 5.
5. Adzhej A., Dzhoshua G., Avi G. Iskusstvennyj intellekt na sluzhbe biznesa // Mann, Ivanov i Ferber. – 2019. – S. 48.
6. SHumskij S. Vospitanie mashin: Novaya istoriya razuma // Al'pina non-fikshn. – 2021. – S. 50.
7. Tirni B., Kellekher D. Nauka o dannyh // Al'pina Didzhital. – 2020. – S. 3.
8. Brussard M. Iskusstvennyj intellekt. Predely vozmozhnogo // Al'pina Didzhital. – 2020. – S. 136.
9. Kazancev T. Iskusstvennyj intellekt i Mashinnoe obuchenie // Timur Kazancev. – 2020. – S. 2.
10. Lebedev V.A., Rogozhnikov D.A. Metallurgiya tinata // UMC UPI. – 2015. – S. 45 - 58.
11. Blagirev A., Hapaeva N. Big data prostym yazykom // AST. – 2019. – S. 12.
12. Kan K.A. Nejronnye seti. Evolyuciya // LitRes. – 2020. – S. 5.
13. Frenks B. Revolyuciya v analitike // Al'pina Pablisher. – 2020. – S. 30.
14. Lelu L. Blokchejn ot A do YA. Vse o tekhnologii desyatiletiya // Bombora. – 2018. – S. 17.
15. Vajgend A. BIG DATA. Vsya tekhnologiya v odnoj knige // Eksmo. – 2021. – S. 22.
16. DebRoy, T. et al. Additive manufacturing of metallic components – process, structure and properties. Prog. Mater. Sci. 92, 112-224 (2019).
17. Qi, D. et al. Mechanical behaviors of SLM additive manufactured octet-truss and truncated-octahedron lattice structures with uniform and taper beams. Int. J. Mech. Sci. 163, 105091 (2019).
18. Elmer, J. et al. Wire-based additive manufacturing of stainless steel and titanium components. Weld. J. 99, S8–S24 (2020)
19. Bürger, D., Parsa, A., Ramsperger, M., Körner, C. & Eggeler, G. Creep properties of single crystal Ni-base superalloys (SX): a comparison between conventionally cast and additive manufactured CMSX-4 materials.
20. Meid, C. et al. Effect of heat treatment on the high temperature fatigue life of single crystalline nickel base superalloy additively manufactured by means of selective electron beam melting. Scr. Mater. 168, 124–128 (2019).
21. Lee, H. W., Jung, K.-H., Hwang, S.-K., Kang, S.-H. & Kim, D.-K. Microstructure and mechanical anisotropy of CoCrW alloy processed by selective laser melting. Mater. Sci. Eng. A 749, 65-73 (2019).
22. Bahl, S. et al. Non-equilibrium microstructure, crystallographic texture and morphological texture synergistically result in unusual mechanical properties of 3D printed 316L stainless steel. Addit. Manuf. 28, 65-77 (2019).