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A NEW METHOD OF ASSEMBLING LARGE MAGNETIC BLOCKS FROM PERMANENT NdFeB MAGNETS

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ABSTRACT

The presented technological procedure makes it possible to assemble large magnetic blocks from permanent magnets with a high value of maximum energy product in such a way that the individual magnets or magnetic plates are moved toward each other at a controlled speed in the direction perpendicular to the future common contact surface of these magnets, i.e. parallel to the induction lines crossing this contact surface. Unlike in the previously used way of assembling the blocks, it is thus possible to eliminate the influence of partial demagnetization as the blocks are being assembled and consequently to reach higher values of magnetic induction in the air gap of the magnetic circuit. When applying the new method of assembling the blocks for instance in circuits of magnetic filters for the purification of ceramic suspensions, a prerequisite for the further improvement of the technological parameters of filtration is thus created.

KEYWORDS: Magnet assembly, magnetic circuits, magnetic separation, magnetic filtration, permanent magnets, NdFeB magnets, large magnetic blocks

INTRODUCTION

Magnetic circuits with permanent magnets are used in various branches of industry. They have found wide application for example in the assembly of magnetic filters for the filtration of ceramic casting slips and glazes, in various types of separators for the treatment of mineral resources, in the separation of ferromagnetic admixtures from various materials (for instance in the treatment of glass shards or plastic substances), in the separation or filtration of various raw materials in the food-processing industry, etc.

Large magnetic blocks inserted in this equipment were previously assembled mainly from ferrite permanent magnets, thus from material with a maximum energy product $(BH)_{max}$ reaching values of approximately 30 kJ/m^3. The technological procedure used in the production of these blocks consisted in insertion of more pieces of individual small non-magnetized ferrite prisms in a sealing mold and their sealing with epoxy resin; after the resin hardened and the block was possibly worked into a desired shape, the entire block was magnetized in a magnetic field of a sufficiently high intensity.

As examples of the practical application of large magnetic blocks, it is possible to describe in further detail the already-mentioned magnetic filters, used in numerous industrial factories of ceramics and porcelain in the Czech Republic.

The essential component of these filters is a magnetic circuit assembled from a two-part closed ferrous yoke and equipped with two opposing magnetic poles. Each pole consists of one or more large magnetic blocks arranged in a row. These large magnetic blocks in protective stainless-steel casings are placed in the closed two-part ferrous circuit and have a tub containing a removable cassette with a matrix inserted in the space between them in the area of a relatively homogenous magnetic field (in the separation zone). A magnetic field gradient is created by the insertion of the matrix into the space between the magnetic blocks in the tub. When the suspension passes through the separation zone, the ferromagnetic elements (e.g. ferrous abrasions) are captured in the matrix, whereas non-magnetic elements pass freely. The higher the obtained values of magnetic induction and gradient, the higher the force affecting the magnetic elements unlike the non-magnetic ones, and thus the more efficient and effective the system that can be created (Richards et al., 1997).

The mentioned simple magnetic filter is a kind of equipment which works on the principle of high-gradient magnetic separation (HGMS) in a cyclical, discontinuous regime. During magnetic filtration, it is always necessary, after a certain time period, dependent on the flow of the suspension being purified and on the amount of ferromagnetic admixtures, to stop the flow of this suspension, remove the cassette with the matrix from the filter and rinse it with running water beyond the reach of the magnetic field.

One of the crucial parameters affecting the technological results achieved during magnetic filtration is the value of magnetic induction in the separation zone of the magnetic filter (Gerber and Birss, 1983).

The magnetic induction achieved in the separation zone of the filters with ferrite magnets is relatively low. In the case of a magnetic circuit with two large opposing magnetic blocks, each having a ground-plan surface of 0.15 x 0.1 m and a height of 0.15 m, assembled from small ferrite blocks from material with a maximum energy product $(BH)_{max}$ = 29 kJ/m^3, the magnetic induction in the middle of the air gap of a width of 0.06 m between the covering stainless-steel casings of these blocks reaches the value of approximately 0.2 T, whereas in the case of larger models of filters with several pieces of magnetic blocks in each pole it can even reach 0.23 T.

The development of new, affordable magnets on the basis of rare earths (mainly of the NdFeB type) has made it possible to utilize them in the magnetic circuits of industrial equipment. Permanent magnets of this type were thus first embedded in roll magnetic separators of various manufacturers, where the values of the magnetic induction achieved on the surface of the belt on the cylinder (roller) were 1 T; they were further embedded also in the magnetic systems of drum separators, where the magnetic induction on the surface of the drum attains a value of up to 0.9 T. Apart from other types of magnetic separators (e.g. plate or suspension separators), magnets from rare earths are used mainly in various types of magnetic grates (gratings) and filters, where these magnets are embedded in gridded bars, inserted into the flow of the raw material being purified. Magnetic induction on the surface of the bars reaches in this case 0.6 to 0.7 T.

In all this equipment with magnets from rare earths, a high value of magnetic induction is thus attained directly on the surface of the cylinders, drums, plates or bars, but this induction decreases rapidly as the distance from this surface increases.

With none of the mentioned equipment is the gradient of the magnetic field created using a matrix inserted into a homogenous magnetic field in the separation zone as is the case with matrix separators or filters working on the HGMS principle. The reason is that precisely the creation of this strong homogenous magnetic field throughout the volume of the separation zone when using permanent NdFeB magnets in practice involves certain, not insignificant problems, and is connected with the necessity to solve them.

It is necessary to mention in this connection that both the separation matrix and the ferrite permanent magnets have also been used (besides mentioned simple magnetic filters) in the case of the continuous magnetic separator Ferrous Wheel (Svoboda, 1987, 2004). At the present time the producer mentions that this device might also be equipped with magnets of rare earths.

The new types of NdFeB magnets are characterized by continuously rising values of maximum energy product $(BH)_{max}$ attained (currently of up to ca 420 kJ/m^3) and by continuously and constantly increasing dimensions. It is therefore substantially more difficult to manipulate them in the magnetized state than is the case with ferrite magnets. A condition for the usage of these magnets for the given purpose is to determine a suitable technological procedure for the construction of large magnetic blocks, for their magnetization and for practical control of the increasingly higher forces by which large magnets interact with each other and affect surrounding ferromagnetic objects.

In order to approximate the size of these forces, it is possible to use as an example the attractive force by which two separate plates from NdFeB magnets with the adjacent surfaces of opposite polarity, each with ground-plan dimensions of 0.16 x 0.107 m and a height of 0.03 m, from the material N50 with $(BH)_{max}$ equal to 400 kJ/m^3, described in detail below, are mutually attracted. Based on the generally-known formula, the attractive force is proportional to the product of the area of the air gap S (of the surface of the pole) and the square of the magnetic induction B in this air gap, with this magnetic induction being besides other parameters (remanence B_r, dimensions of the pole) dependent mainly on the distance between the magnetic poles. In the middle of an air gap of a width of 90 mm between the mentioned magnetic plates, a magnetic induction of 0.215 T was measured. It arises from the calculation that when the distance is set at these 90 mm, the plates are attracted with a force of 280 N; when they approach to the distance of 10 mm, this force increases to ca 1900 N. When these two plates are inserted into a closed ferrous circuit (yoke), where the values of magnetic induction attained in the same air gap between the plates approximately double, the poles are then at a distance of 10 mm attracted by a force of ca 7600 N, which increases more when the poles further approach each other.

By constructing small magnet blocks from rare earths or from ferrites, it is possible to assemble larger wholes making it possible to create homogenous, non-homogenous or variable-in-time magnetic fields (Coey and Mhíocháin, 2001). One of the possible methods of assembling magnets into large blocks, after whose insertion into a magnetic circuit it is possible to create a homogenous magnetic field in the air gap between them, was described in the patent application No. PV 2006-264 (Žežulka and Straka, 2006). Based on this method, during the assembly a magnet or a magnetic plate is moved toward another magnet or plate in the direction parallel to the future common contact surface (i.e. perpendicular to the magnetic induction lines crossing this contact surface).

The basic construction element when assembling a large magnetic block is a compact magnetic plate, shown in Fig. 1. This plate is composed of six pieces of small non-magnetized NdFeB blocks with dimensions of 0.05 x 0.05 x 0.03 m, placed in a non-magnetic steel frame and sealed with epoxy resin.

The total ground-plan dimensions of the plate including the peripheral frame are approximately 0.16 x 0.107 m, with a height of 0.03 m and the total weight being 3.7 kg. The individual plates having been magnetized, the separate large magnetic blocks are subsequently either gradually assembled and inserted as wholes into the ferrous closed circuit or are gradually assembled directly in the ferrous circuit. In the latter case, the ferrous circuit is first equipped only with two opposing plates (each large block has one plate). After the dependence of magnetic induction on the width of the air gap B = f(x) has been measured, another plate is added, or more precisely according to the mentioned PV moved from the side, to each plate already in the magnetic circuit (each large block thus consists of two plates with a total height of 0.06 m), which is again followed by a measurement of the dependence B = f(x). The procedure is repeated until up to four plates have been inserted into each large magnetic block.

This separate large magnetic block, consisting of four magnetic plates, with overall dimensions of 0.16 x 0.107 x 0.12 m and a total weight of 14.8 kg, is shown in Fig. 2.

During both the assembly of large magnetic blocks and their insertion into the magnetic circuit, as well as in the case of the gradual insertion of the individual magnetized plates into the magnetic circuit, the basic principle has to be preserved that no component can be inserted into the magnetic circuit being assembled until all the pieces inserted into the circuit in the preceding step have been mechanically secured. In order to prevent damage of the magnets, which are relatively fragile, during assembly, it is also necessary during the insertion of the individual magnetized plates simultaneously with directing their line of motion to control the speed of their being attracted (they must not be pulled freely and swiftly).

The maximum size of the NdFeB magnets or magnetic plates from these magnets for the assembly of larger blocks practically depends on the parameters of the available equipment for their magnetization. The necessary magnetizing equipment, which makes it possible to create a magnetic field with the recommended high intensity of 2000-2400 kA/m in a volume great enough for the insertion of the entire large block with a size similar to large blocks from ferrites, has very high capital demands and thus is far from being commonly available. An additional advantage of the selected solution is hence that it allows the use of an affordable electromagnet with a smaller air gap between the poles for the magnetization of the individual magnets or magnetic plates, through a gradual assembly of which it is possible to create a large magnetic block.

Using the above-described method, three small magnetic circuits for laboratory filters were assembled in the course of the development at the Institute of Rock Structure and Mechanics of the Academy of Sciences of the CR, v.v.i., using magnets with gradually increasing $(BH)_{max}$, each circuit containing one pair of opposing large magnetic blocks. Detailed information and a more comprehensive overview of the work carried out so far can be acquired in the publications listed below.

Already in the case of the first magnetic circuit of this type, a substantial increase of magnetic induction in the separation zone of the filter all the way to values until then attained only using electromagnets was achieved by replacing large blocks with ferrite magnets assembled from magnetic blocks of NdFeB magnets (Žežulka et al., 2004).

In subsequent technological tests of the magnetic filtration of a casting slips and a glazes directly in various industrial ceramics and porcelain works in the Czech Republic, significantly better results were obtained when a filter with NdFeB magnets was used than in the case of the existing filters with ferrite magnets (Žežulka et al., 2005). It was verified that without additional requirements on electrical energy consumption it is hence possible to achieve a more effective purification of the glaze or casting slip being filtered of undesirable ferromagnetic and partially also paramagnetic admixtures and consequently thus also an increase in the quality of the production of porcelain and ceramic products.

THE PRINCIPLE OF THE NEW METHOD

During the assembly of the third laboratory magnetic circuit mentioned in the introduction with NdFeB magnets from the material N50, a certain anomaly occurred after the magnetic blocks were equipped with the fourth magnetic plate (when the height of the block was increased to 0.12 m), which had not been observed before. It arose from the measurements conducted that when the blocks are equipped with a fourth plate, not only is there no further increase in the magnetic induction in the air gap, but in the areas of the widths of the air gaps at approximately 0.06m or narrower the values of this magnetic induction are even substantially lower than those obtained in the case of the blocks with three plates. The known phenomenon of demagnetization, dependent on the direction of the demagnetization field with respect to the easy axis, was preliminarily determined and subsequently confirmed as the cause (Katter, 2005). The demagnetization occurs in this case as a consequence of the way (method) of assembling large magnetic blocks used so far.

When moving another plate toward the firmly fixed plate inserted in the preceding step, a superposition of magnetic fields of the two plates occurs. In practice, a manifestation of this interaction is that at a certain distance from the firmly fixed plate, the plate being moved toward it begins to “rise” and must be directed during its further movement until the moment when the two plates partially overlap and the plate being moved is pulled to the firmly fixed plate. Exactly in the phase where the relatively strong magnetic fields of the opposite direction as against the original direction of magnetization interact, a mutual partial demagnetization of the two plates subsequently occurs.

With the aim to eliminate this demagnetization, a new method for assembling large magnetic blocks was therefore designed, based on which, unlike in the earlier method, magnetic plates are moved toward each other at a controlled speed in the direction perpendicular to the future common contact surface of the two plates, it means parallel to the induction lines crossing this common contact surface (Žežulka et al., 2006, 2007), with the adjacent surfaces of the plates being assembled having the opposite polarity (i.e. the plates attract each other). This method was successfully tested first when smaller NdFeB magnets with ground-plan dimensions of 0.05 x 0.05 m and a height of 0.03 m were assembled and subsequently also when assembling magnetic plates with ground-plan dimensions of 0.16 x 0.107 m and a height of 0.03 m.

The principle of the new method consists in permanent magnets or compact magnetic plates**,** composed of several non-magnetized permanent magnets and subsequently magnetized as a whole, being gradually inserted into a tube (vessel) filled e.g. with hydraulic oil (or another suitable liquid) always in the direction perpendicular to the future common contact surface of these magnets or magnetic plates, with the adjacent surfaces of the magnets or magnetic plates being assembled always having the opposite polarity (i.e. the magnets attract each other). Subsequently, the oil contained in the space between these adjacent surfaces of the magnets or magnetic plates is being discharged at a controlled speed (the speed of their attraction is being controlled by means of the regulated discharge of the oil). The movement of the first magnet or magnetic plate in the tube is limited by the effect of the attractive force of the auxiliary (additional) holding magnet, positioned below the bottom of the tube.

Special equipment was designed, which is shown in Fig. 3, for the implementation of this method. This equipment, arranged on workbench desktop 1 of non-magnetic material (e.g. wood), is composed of non-magnetic stainless-steel bottom plate 2 with tube 3 vertically welded on it likewise of non-magnetic stainless steel. The inner cross-section of this tube corresponds to the outer cross-section of the magnets or magnetic plates being assembled (Fig. 3 shows a ground plan of a rectangular cross-section, but it can also be square, circular, or possibly of another cross-section). The inner dimensions of the tube must during the assembly with a small clearance allow for the free movement of the inserted magnets or magnetic plates 13, 14, 15 in a vertical direction. The front and rear vertical walls of the tube have oval apertures 4, covered with transparent plexiglass 5. This acrylic glass is sealed where touching the tube and attached to it by a cover plate 6 with oval apertures by means of screws, which are not depicted, welded to the tube). In the lateral vertical walls of the tube, circular holes have been made, to which non-magnetic stainless steel output nozzles (sockets) 7, 8, 9 are attached, welded to the walls of the tube with closable non-magnetic slides or valves. The spacing between output nozzles 7 and 8 as well as between nozzles 8 and 9 corresponds to the height of the assembled magnets or magnetic plates. Clevis 11 with an inserted auxiliary holding magnet or magnetic plate 12 is attached below the workbench desktop in a position under the equipment.

The actual assembly of large blocks can be prepared in various ways. One of the possibilities is to insert the first magnet or magnetic plate 13 in a situation when this magnet is beyond the reach of the effect of auxiliary holding magnet 12, thus with magnet 12 removed from clevis 11, or by moving (pushing) the entire equipment away from this magnet in the clevis. The aim is to prevent magnet 13 from falling to the bottom of the tube at too high a speed. That is also the reason why soft (rubber) pad 10, preventing the magnet from being damaged through its free fall to the bottom, has been placed at the bottom of the equipment. After the first magnet 13 has been inserted into the equipment, magnet 12 is placed into the clevis, or the equipment moved along the workbench desktop into a position above the clevis with magnet 12. Having been placed at their positions, the mutually adjacent surfaces of the two magnets have to be of opposite polarity, as is indicated in Fig. 3 (the magnets have to attract each other). In addition, all slides (valves) on the output nozzles (sockets) 7, 8 and 9 need to be closed.

After the preparation has been finished, the equipment is filled with oil up to level 16. The magnet or magnetic plate 14 is subsequently inserted into the equipment in such a manner that the contact surface of this magnet is of the opposite polarity to the contact surface of the magnet or magnetic plate 13. The two magnets or plates attract each other, with the speed of their attraction depending apart from the viscosity of the oil used primarily on the size of the clearances between the outer dimensions of the magnets and the inner dimensions of the tube. Provided that the tube has been produced with sufficient accuracy, it is possible slowly to discharge the oil from the area between magnets 13 and 14 by opening the slide (valve) on output nozzle 7. The position of the magnets and the speed of their attraction can be observed in the oval apertures covered with the transparent plexiglass. By adjusting (turning) the slide (valve) on nozzle 7, it is hence possible to regulate this speed of attraction smoothly and thus let the two magnets approach each other slowly without their being damaged. After the two magnets have completed the process of their mutual attraction, the slide on nozzle 7 is closed.

It is necessary to emphasize that this slow attraction is possible to achieve by means of the mentioned regulation of the discharge of the oil even

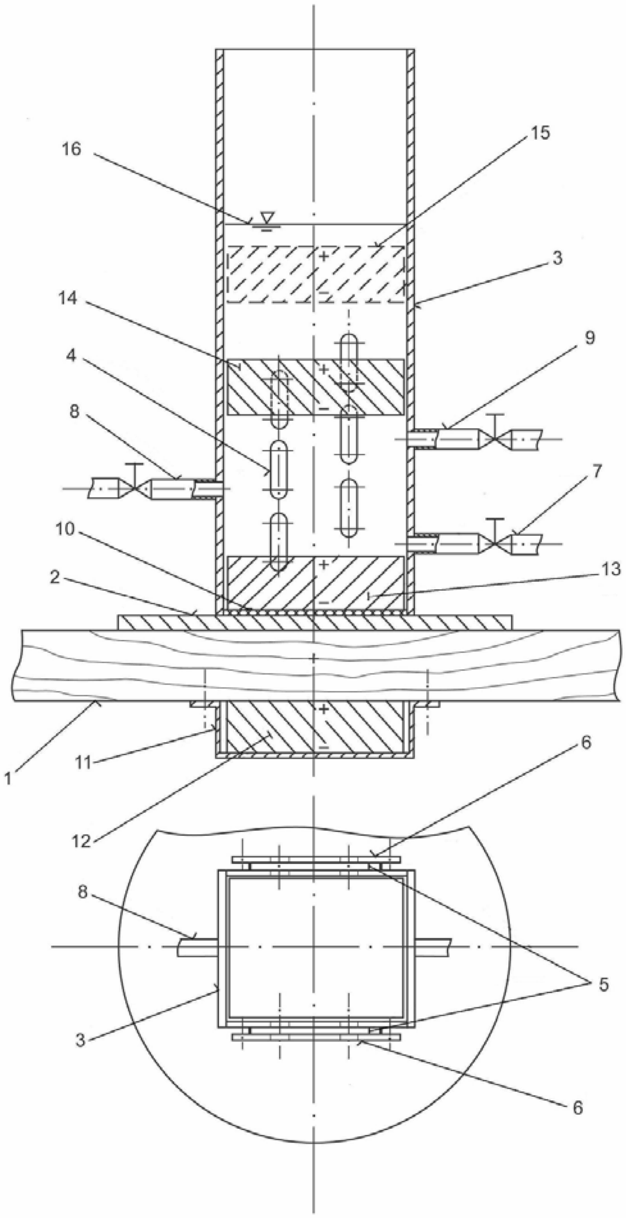

Fig. 3 A scheme of the equipment for the assembly of large magnetic blocks using the new method.

despite the occurrence of the already-mentioned sharp increase in the force by which the magnets are mutually attracted as these magnets 13 and 14 converge.

In this connection, it is also necessary to describe in further detail the purpose of using auxiliary holding magnet 12. The reason is that if this magnet were not used, the equilibrium of forces affecting magnet 13 as magnet 14 is approaching would result in an upward movement of magnet 13 in the tube at a certain distance between the two magnets. During its movement, this magnet would cover the opening into nozzle 7, which would prevent the possibility of regulating the discharge of the oil. After magnet 12 has been placed under the workbench desktop below the equipment, magnets 12 and 13 attract each other (magnet 12 is “holding” magnet 13 at the bottom of the tube) and the movement of magnet 13 upward when magnet 14 is approaching is thus significantly limited.

After magnets 13 and 14 have been assembled, the oil is topped up to its original level and magnet 15 inserted (in Fig. 3 its outline is a dashed line) into the tube again such that the contact surface of this magnet is of the opposite polarity to the contact surface of magnet 14. By opening slightly the slide on output nozzle 8 and subsequently regulating the discharge of the oil like in the previous case, it is possible to achieve a slow attraction of magnet 15 to magnets 13 and 14. After the attraction has been completed, it is necessary to close the slide on nozzle 8 again.

The procedure for the attraction of another magnet, which already is not depicted in Fig. 3, to the magnets already in their positions is the same as in the preceding step. In order to regulate the speed of attraction, the slide on nozzle 9 is used this time.

After the assembly of the block has been completed, it is necessary to remove magnet 12 from clevis 11 and move it beyond the reach of the effect of the assembled magnetic block, or to move the entire equipment with the assembled magnetic block along the workbench desktop beyond the reach of magnet 12. The hydraulic oil is subsequently emptied (or discharged) and the prepared magnetic block removed (turned out) from the tube onto the non-magnetic workbench desktop.

Using the equipment depicted in Fig. 3, it is thus possible to assemble a magnetic block consisting of up to four magnets, or magnetic plates. It is evident that by increasing the height of the tube and equipping it with a corresponding number of additional output nozzles with slides, it is possible analogously to assemble a magnetic block with any required number of magnets or magnetic plates.

It arises from the description above that the mentioned method deals in a new way only with the essential problem of the assembly of large magnetic blocks. For the insertion of these blocks into a ferrous circuit, it is possible to use the procedure mentioned in the introduction.

EXAMPLES OF THE IMPLEMENTATION AND KNOWLEDGE FROM TESTING THE NEW METHOD

In the text above, the method of assembling magnets or magnetic plates of a smaller size into larger magnetic blocks using simple equipment is described. Equipment in the implementation with only one output nozzle with one valve was used to test the new method of assembling blocks from the individual NdFeB magnets with a value of maximum energy product $(BH)_{max}$ equal to 350 kJ/m^3 and with ground-plan dimensions of 0.05 x 0.05 m and a height of 0.03 m. This version is depicted in Fig. 4.

After the function of the above-mentioned simple implementation of the small version of the equipment was successfully tested, further equipment, which is depicted in Fig. 5, was designed and implemented, intended for the assembly of large magnetic blocks of the same size as the blocks assembled earlier (see Fig. 2) and inserted into magnetic circuits. The equipment thus makes it possible gradually to assemble up to four magnetic plates with dimensions of 0.16 x 0.107 x 0.03 m.

Apart from the corresponding dimensional changes in size, this equipment has been modified in other respects as well. The lateral walls of the tube always have, instead of one output nozzle with a valve at a certain height, two opposite nozzles at the same height (symmetrically along the vertical axis of the tube). The nozzles have been attached by hoses of identical length through a three-way pipe (T-piece) to a valve which makes it possible to close and regulate the flow of oil. Through regulation, this solution allows the attainment of the same flow of oil from two symmetrically positioned output nozzles and thus prevents possible jamming of a magnetic plate between the walls of the tube when it is being attracted owing to its low height with respect to the ground-plan dimensions.

A further technical precaution against this possible jamming is to use thin lateral sheet-metal non-magnetic plates, inserted between the walls of the tube and the actual magnetic plate (in Fig. 5 these lateral sheet-metal plates protrude from the upper part of the tube). The dimensions of the inner cross-section of the tube are thus larger by the corresponding thickness of the inserted sheet metal. Should a magnetic plate jam, it is possible to release this magnetic plate by moving these auxiliary sheet-metal plates vertically. Moreover, these auxiliary sheet-metal plates are bent at a right angle at the bottom, allowing thus by pulling upward by two opposing plates to remove both the individual magnetic plates and, mainly, the entire magnetic block from the tube without having to turn the whole equipment.

It may be added here that when large blocks were being assembled, the tendency of some magnetic plates to jam as they were descending to the bottom was actually confirmed. By moving the lateral sheet metal, monitoring the course of the descent of the plate through the openings on the sides and directing it when necessary so that the plane of the plate would always be perpendicular to the walls of the tube, however, it was successfully managed that without problems it safely smoothly landed on the bottom magnetic plate, inserted already in the preceding step.

The equipment is further equipped in its lower part with a nozzle with a valve for discharging oil. This solution makes it possible to simplify the preparation for assembling large magnetic blocks described in text above. Before assembly, the entire equipment can be placed on the workbench desktop directly above holding magnet (magnetic plate) 12 in clevis 11 and fill the tube of the equipment with oil. After magnetic plate 13 has been inserted into the tube, it is possible by controlled discharge of the oil using the discharge slide to make this plate slowly land at the bottom of the equipment as in the case of the assembly of the actual magnetic block.

After the assembly of the entire magnetic block has been completed, it is possible to discharge the oil from the tube of the equipment using the discharge valve, to remove holding magnet (magnetic plate) 12 from the clevis and move it beyond the reach of the effect of the magnetic block. The entire magnetic block can then be removed from the equipment in the way described above by means of the lateral sheet-metal plates. It is thus not necessary to manipulate the actual equipment, shift or turn it in any way.

As has already been mentioned above, the speed of the attraction of the magnets or magnetic plates is substantially affected by the size of the clearances in the tube of the equipment. Precisely the requirement that these clearances be minimized while maintaining the free movement of the magnets or magnetic plates makes high demands on the precision of the production of the individual stainless-steel components of the tube and on the management of the technological procedure of their welding so as to prevent the undesirable considerable shape deformation of the welded product. The size of the clearances in the completed tube can still be further affected by altering the thickness of the inserted lateral sheet-metal plates, whereas at the final stage it is possible to affect the speed of the attraction of the magnets considerably by selecting oil with suitable viscosity for the concrete implementation of the equipment.

In the course of the development, it was also necessary to deal with how to insert the magnetic plates safely into the upper part of the tube of the equipment. Their being held by catch clamps (grips) must make it possible to place the magnetic plate safely on the surface of the oil, i.e. into the area with the effect of the relatively strong dispersive magnetic field of the plate inserted earlier (or of more plates already assembled) and where the plate being newly inserted is thus being affected by an already perceptible attractive force. This holding by the catch clamps must, however, simultaneously make it possible to remove them from the plate easily after the plate is placed on the surface of the oil. Simple magnetic catch clamps making it possible to adjust the holding force have been designed, tested and utilized during further procedures.

WORK PROCEDURE AND OUTCOMES ACQUIRED

In order to be able to assess the influence of the new method of assembling large magnetic blocks on the magnetic induction obtained in an air gap and to compare it with the method used earlier, new magnetic plates of the same size were first produced using the same method as the earlier plates. As the original magnets from the material N50 were no longer available, magnets from the material labeled N52 were used for the production of the new magnetic plates, whose magnetic parameters (mainly remanence and maximum energy product), however, differed from the original material N50 only negligibly. The new magnetic plates were likewise magnetized in the same way as the earlier ones in the same electromagnet by the same magnetic field. The same two-part closed ferrous circuit, originally equipped with magnetic blocks from the material N50, assembled using the method utilized before and dismantled from this circuit before further work began, was employed for further assembly.

The ferrous circuit was first equipped with two new opposing magnetic plates, followed by a measurement of the magnetic induction in the middle of the air gap in dependence on the width of this gap carried out in the same way as in the case of the previous measurements. After it was completed, both magnetic plates were removed from the ferrous circuit, with another plate added to each of them using the new method. Both magnetic blocks, this time each consisting of two plates, were then inserted into the ferrous circuit again and the dependence $B = f(x)$ was measured. The whole procedure was subsequently repeated and the ferrous circuit was gradually equipped with magnetic blocks assembled using the new method from three and finally from four magnetic plates, always followed by a measurement of the dependence $B = f(x)$.

It clearly arises from the results of all the measurements (with the exception of the case of one magnetic plate in each pole, where the influence of the method of the assembly cannot naturally manifest itself) that the magnetic induction in the middle of the air gap between large magnetic blocks assembled using the new method attains higher values of magnetic induction all along the slope in all the measurements when compared to the magnetic induction between the analogous blocks but assembled using the method used earlier. From the further slopes of the dependences $B = f(x)$ for the gradually increasing heights of the blocks, gradually assembled from up to four plates using the new method, a permanent increase of the magnetic induction obtained is evident. Thus unlike in the case of the method of assembly used before, in this case when the blocks are equipped with the fourth plate, the values of the magnetic induction reached no longer decrease, but on the contrary, they are for all the widths of the air gaps even higher (Žežulka and Straka, 2007).

CONCLUSION

This new method, in comparison with the earlier technological procedure, allows for a reduction of the laboriousness of assembly, a shortening of the time necessary for the work and an increase in safety while simultaneously attaining very good magnetic parameters of the assembled large magnetic blocks. Its utilization eliminates the unfavorable influence of partial demagnetization, which occurred when the blocks were assembled using the previous method, and it is thus possible to attain higher values of magnetic induction in the air gap of the magnetic circuit. For this reason, it is suitable to use this method not only for the mentioned assembly of large magnetic blocks from magnetic plates but generally when assembling any two or more magnets with a high $(BH)_{max}$ value into larger wholes, mainly in such cases when it is required that peak magnetic parameters be attained.

On the basis of the knowledge up to now, it may be supposed that with the development of new permanent magnets with increasingly higher values of maximum energy product $(BH)_{max}$, the importance of the selected method for the assembly of these magnets will also continue to increase. This will be so mainly in the cases of such magnet materials where the mentioned increase of $(BH)_{max}$ will not be simultaneously accompanied by a substantial increase in coercivity as the degree of the magnet's resistance to demagnetization.

The mastery of the technology of assembling magnetic circuits from NdFeB magnets in the new way in practice makes its application possible in the existing simple discontinuous magnetic filters, in whose case it is thus possible to attain higher values of magnetic induction in the separation zone. The new technology, however, can be applied also in the development and implementation of other highly effective equipment. These can be, for example, a new type of a magnetic filter not requiring attendants, working in an automatic cyclical regime, hence in comparison with electromagnets having considerably lower capital and operational demands. A need for such equipment, enabling a further increase in production quality, has also begun to appear in the requirements on the part of industrial factories of ceramics and porcelain.

The technology of the assembly of large magnetic blocks from NdFeB material with a high BH_{max} and then assembly of these blocks into a larger pole surface can also be applied in the magnetic systems of plate or belt separators suspended above conveyor belts, for example. These separators are used for the separation of ferromagnetic objects from various materials (from glass shards, plastic substances, etc.) to protect the subsequently used equipment from damage. In view of the higher values of magnetic induction obtained in the separation zone, it would also be possible to expect an increase in the sorting efficiency in this case.

Another very important potential area where the new technology of the assembly of large magnetic blocks could be utilized would be its application in the construction of magnetic circuits of continuous magnetic separators with permanent magnets from the material with a high $(BH)_{max}$, thus not only in magnetic filtration but on a wider scale also for the enrichment of raw materials. It may be successfully anticipated that it would also in this case positively influence the results of the magnetic separation, in regard to the usage of permanent magnets again evidently without any requirements in terms of electrical energy consumption.

It cannot be excluded that apart from the mentioned possibilities for the application in the treatment of raw materials, this technology can be successfully used and of benefit also in other branches, for example in magnetic circuits of rotary machines or in magnetic field generating devices for a magnetic resonance imaging (MRI) equipments, eventually for NMR equipments, too. These questions, however, have remained open for the time being.

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Fig. 1 A compact magnetic plate.

Fig. 2 A large magnetic block.

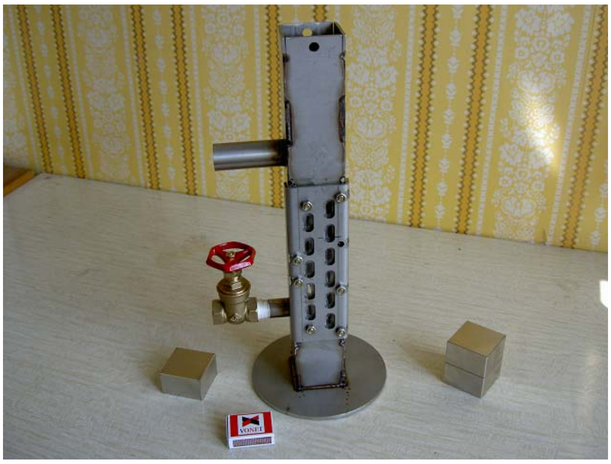

Fig. 4 Equipment for assembling small blocks of magnets with dimensions of 0.05 x 0.05 x 0.03 m.

Fig. 5 Equipment for assembling large magnetic blocks from magnetic plates.