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Recent developments in magnetic methods of material separation

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Abstract

Magnetic techniques are the cornerstone of material manipulation and over the last 30 years these methods have undergone dramatic developments. Advantages of magnetic methods of material treatment are numerous and the spectrum of applications of this technique is formidable. Numerous technological milestones and key drivers of innovations in magnetic separation have resulted in a wide range of magnetic techniques that are available for application in various industries. This paper reviews the current status of magnetic separation and outlines the future trends in research and development.

Keywords: Magnetic separation; Fine particle processing; Recycling; Industrial minerals; Iron ores; Non-ferrous metallic ores

1. Introduction

The ancient Greeks were familiar with some phenomena of magnetism as early as 550 BC. Socrates observed that *this stone Euripides called the magnet does not simply attract the iron rings, it also imparts to the rings a force enabling them to do the same thing as the stone itself* ... (Livingston, 1997). It was believed that the force exerted without touching is delivered by magnetic effluvium flowing between lodestone and iron. The practical significance of magnetism, and of magnetic separation in particular, was recognised only as late as the middle of the 19th century. Ball, Norton, Edison and others demonstrated the possibility of separation of coarse strongly magnetic iron ores from "non-magnetic" gangue. Since the end of the 19th century the separability of magnetic from less magnetic materials was demonstrated in numerous applications by a broad range of magnetic separators. However, only recent considerable progress in the understanding of the fundamentals of magnetism and development of permanent magnetic materials allowed magnetic separation (MS) to be applied to materials ranging from coarse to colloidal and from strongly magnetic to diamagnetic.

2. Principles of separation by magnetic force

When a magnetisable particle is placed in a non-homogeneous magnetic field, it is acted upon by the magnetic force given by

$$\vec{F}_{\mathrm{m}} = \frac{\kappa}{\mu_0} VB\vec{\nabla}B \tag{1}$$

where κ is the volumetric magnetic susceptibility of the particle, μ_0 is the magnetic permeability of vacuum, V is the volume of the particle, B is the external magnetic induction and $\vec{\nabla}B$ is the gradient of the magnetic induction. Magnetic force is thus proportional to the product of the external magnetic field and the field gradient and has the direction of the gradient. In a homogeneous magnetic field, in which $\vec{\nabla}B = 0$, the force on a particle is zero.

In a magnetic separator several competing forces are acting on the particles. These are, among others, the force of gravity, the inertial force, the hydrodynamic drag, and surface and inter-particle forces. This situation is shown schematically in Fig. 1. The force of gravity can be written as

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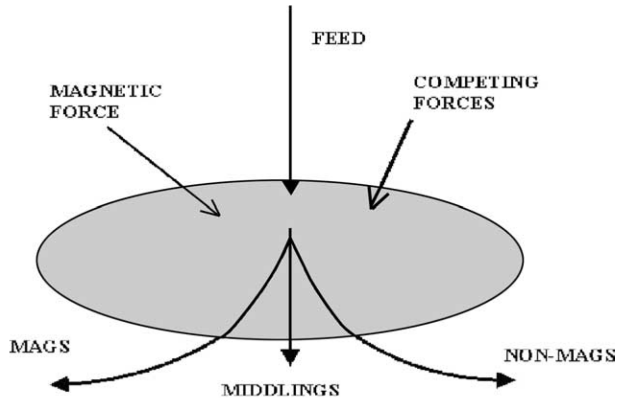

Fig. 1. Schematic diagram of the process of magnetic separation.

$$\vec{F}_g = \rho V \vec{g} \tag{2}$$

where ρ is the density of the particle while g is the acceleration of gravity.

The hydrodynamic drag is given by

$$\vec{F}_d = 6\pi\eta b \vec{v}_p \tag{3}$$

where η is the dynamic viscosity of the fluid, b is the particle radius and v_p is the relative velocity of the particle with respect to the fluid.

Magnetic particles will be separated from "non-magnetic" (or more magnetic particles from less magnetic particles), if the following conditions are met:

$$F_m^{mag} > \sum F_c^{mag} \quad \text{and} \quad F_m^{non\text{-}mag} < \sum F_c^{non\text{-}mag} \tag{4}$$

where F_c is a competing force while F^{mag} and $F^{non\text{-}mag}$ are forces acting on magnetic and "non-magnetic" particles, respectively.

In order to achieve high recovery of magnetic particles, the magnetic separating force must thus be greater than the sum of the competing forces, as shown in Eq. (4). If, however,

$$F_{mag} \gg F_{comp}$$

selectivity of separation will be poor, as no distinction will be made between various magnetisable particles. The selectivity of the process will be critically determined by the relative values of the magnetic and competing forces. And these are affected by a correct choice of a separator itself and its operating conditions.

Although the conditions of efficient separation are clearly defined, a complication arises because the relative significance of the forces is determined mainly by the particle size. It can be seen from Eqs. (1)–(3) that while $F_m \propto b^3$ or b^2, the competing forces have the following dependence on particles size: $F_d \propto b^1$ and $F_g \propto b^3$. In dry magnetic separation where F_d is usually negligible, the particle size, as a rule, does not affect the efficiency of separation significantly because of the same particle size dependence of the magnetic force and of the force of gravity. On the other hand, in wet separation where the hydrodynamic drag can be important, selectivity of the separation will be influenced by particle size distribution. With decreasing particle size the relative importance of the hydrodynamic drag increases in comparison to the magnetic force.

Table 1
The effect of particle size on separability

Particle size [a.u.]	Magnetic susceptibility [a.u.]	Magnetic force [a.u.]
10	1	1000
1	1000	1000

The non-selective nature of the magnetic force is illustrated in Table 1. It can be seen that the same magnetic force is exerted on a coarse, weakly magnetic particle as on a small, considerably more strongly magnetic particle. Both particles will appear in the same product of separation unless the competing forces affect particles of different sizes in a different manner.

2.1. Generation of the magnetic field and its gradient

Although permanent magnets have been used to generate the magnetic field in magnetic separators for many decades, their popularity further increased when inexpensive ferrite magnets, with high-energy product and coercive force, became available. Later a new generation of permanent magnet-based roll magnetic separators appeared when powerful rare-earth permanent magnets were developed. A peak magnetic field of 1.9 T, with very high gradient, can be generated on the surface of such rolls.

In the early days, iron-core electromagnets were used to generate the magnetic field in magnetic separators. Although these magnets still play an important role, their significance has diminished with the advent of permanent magnets and air-core solenoid electromagnets, either resistive or superconducting. The main drawback of the iron-core magnets is that the achievable magnetic field is limited by the saturation magnetisation of iron. Moreover, the scale-up of these magnets is also restricted, resulting in a decreased magnetic field and an increase in mass of the equipment, even at the modest width of the working space, typical of a separator. The magnetic field generated by these magnets usually does not exceed 1 T.

On the other hand, resistive solenoid magnets can create a magnetic field as high as 2 T in large volumes of the working space. These magnets thus allowed the building of large high-intensity magnetic separators capable of treating as much as 100 t/h of material. Superconducting magnets extended the range of the available magnetic field to 5 T or higher, although the need for magnetic induction greater than 2 T has never been convincingly demonstrated in most applications (Svoboda, 1987, 1994).

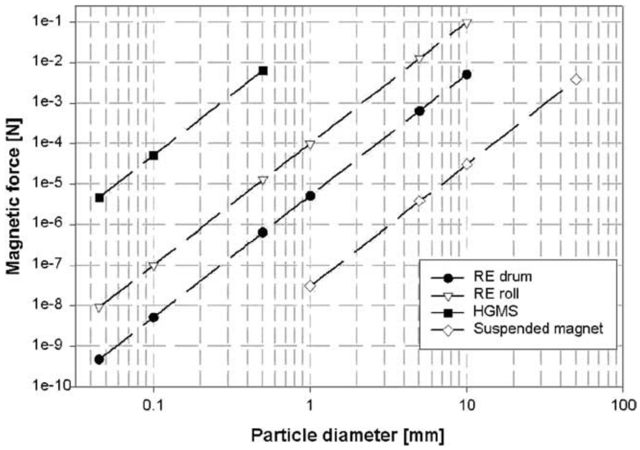

Fig. 2. Magnetic force generated by various magnetic separators, on a hematite particle, as a function of particle size.

There are two fundamental methods of generating the gradient of the magnetic field, which, as follows from Eq. (1), is equally important for the efficiency of magnetic separation. By a judicious arrangement of permanent magnet elements or by a suitable shaping or positioning of the pole pieces it is possible to exploit a variation of the magnetic field as a function of distance from the magnetic field generating element. This, the so-called open-gradient arrangement, is used in most drum, roll and plate magnetic separators. The magnetic field gradient of approximately 1 T/m can be achieved in a suspended magnet, while in rare-earth permanent magnet rolls, the value of the field gradient is of the order of 100 T/m.

A significant increase in the magnetic field gradient can be achieved by placing ferromagnetic bodies (such as balls, mesh or steel wool) into the magnetic field of a separator (Frantz, 1937). These bodies (usually called a matrix), generate, when magnetised, a high local field gradient of the magnitude as high as 5×10^4 T/m. This innovation extended considerably the range of the magnetic force and thus the applicability of magnetic separation to many weakly magnetic or even diamagnetic minerals of the micrometer size. Fig. 2 illustrates the range of magnetic force generated different classes of magnetic separators.

3. Review of magnetic separators

Various classification schemes of magnetic separators have been introduced and probably the most practical and logical is the one that classifies separators as either dry or wet. At the same time, these separators can operate with a low-intensity or high-intensity magnetic field (Svoboda, 1987). This scheme does not take into consideration the gradient of the magnetic field, an equally important parameter in magnetic separation. It can be, however, safely assumed that low-intensity separators usually generate a low magnetic field gradient while high-intensity separators can be, in general, classified as high-gradient machines. There are, however, exceptions to this rule.

The choice of the class of a separator is dictated by numerous considerations, the most important being the particle size distribution, distribution of magnetic properties of particles to be separated from one another, and by the required throughput of the machine.

3.1. Dry low-intensity magnetic separators

The main application of dry low-intensity magnetic separators is either the removal of tramp iron and of strongly magnetic impurities or the concentration of a strongly magnetic valuable component. Suspended magnets, magnetic pulleys and plate and grate magnets are usually employed to perform the former task while magnetic drums are used mainly for the latter application. Fig. 3 illustrates a typical suspended (or overband) magnet while Fig. 4 depicts a magnetic pulley.

3.2. Wet low-intensity magnetic separators

By far the most frequently used wet low-intensity magnetic separators are drum separators. With the

Fig. 3. Suspended magnet for the removal of tramp iron (courtesy of Steinert GmbH).

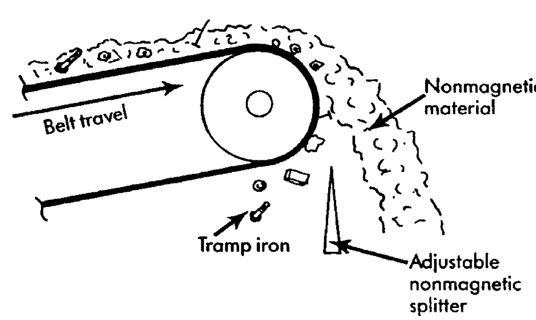

Fig. 4. Magnetic pulley for separation of strongly magnetic materials.

advent of ferrite permanent magnets, permanent magnet-based units almost completely replaced the electromagnetic drum concept. These separators are used mainly for the recovery of heavy medium, such as magnetite or ferrosilicon used in dense medium separation. Plant installation of such a separator is shown in Fig. 5.

Concentration of strongly magnetic ores, such as magnetite, is another application. The availability of rare-earth permanent magnets and their improving affordability further extends the applicability of drum magnetic separators to medium or even weakly magnetic materials.

There are two basic designs of permanent magnet drum separators, namely radial and axial configurations, as illustrated in Fig. 6. In a radial configuration, the polarity of permanent magnets alternates across the drum width, while in an axial arrangement, the poles alternate along the circumference. Radial configuration is usually used in those applications where the recovery of the strongly magnetic material is important. On the other hand, the axial configuration is preferred when the quality of the magnetic product is of significance. The tumbling motion of particles over the rows of the magnet with alternating polarity facilitates the release of entrained non-magnetic particles and thus improves the grade of the magnetic concentrate.

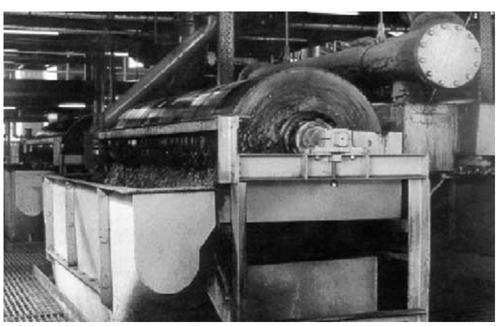

Fig. 5. Low-intensity wet permanent magnet drum separator.

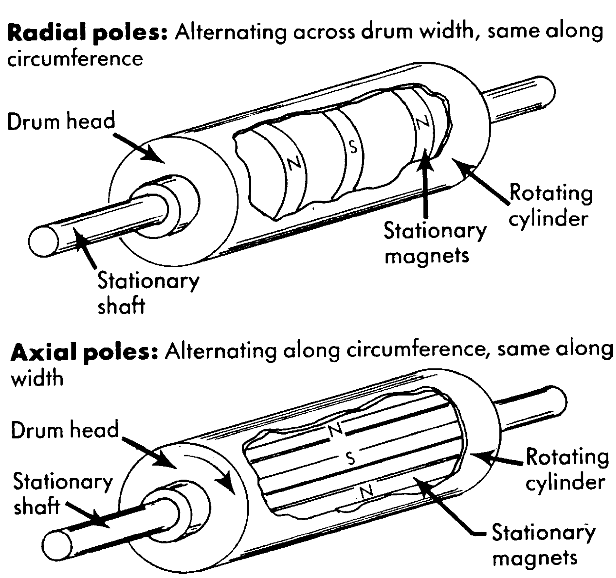

Fig. 6. Pole configurations in drum magnetic separators.

3.3. Dry high-intensity magnetic separators

It appears that the minerals industry has always had a great need to beneficiate coarse weakly magnetic minerals. A wide spectrum of magnetic separators for this application has been developed and used on an industrial scale over the last 50 years. A cross-belt separator and an induced magnetic separator shown in Fig. 7 used to be particularly popular electromagnet-based machines.

However, the development of permanent magnetic materials and an improvement in their magnetic properties over the last 20 years, proved to be one of the main drivers of innovation in dry magnetic separation. Fig. 8 illustrates the history of improvement of the energy product of permanent magnets. With the advent of rare-earth permanent magnetic materials it became possible to construct magnetic roll separators that generate a magnetic force that exceeds that produced by electromagnetic high-intensity separators.

Although the magnetic field cannot be easily varied, by a judicious selection of the permanent magnetic material and by optimising the geometrical configuration of such a roll, it is possible to design rolls for treatment of materials of different size ranges and magnetic susceptibility distributions. A permanent roll separator shown in Figs. 9 and 10 has significantly lower mass and size than an induced magnetic roll separator. The absence of an air gap means that large particles can be treated.

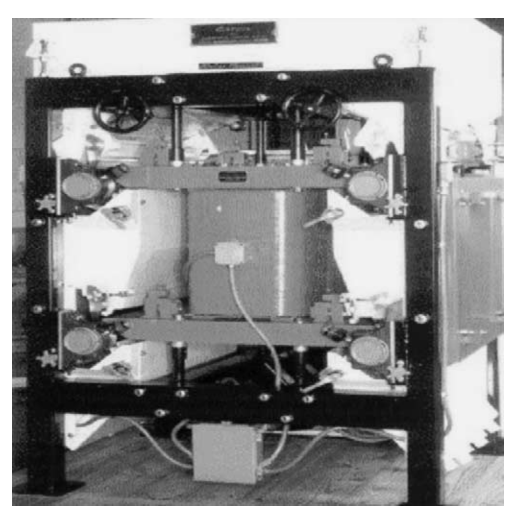

Fig. 7. The Carpco induced magnetic roll separator.

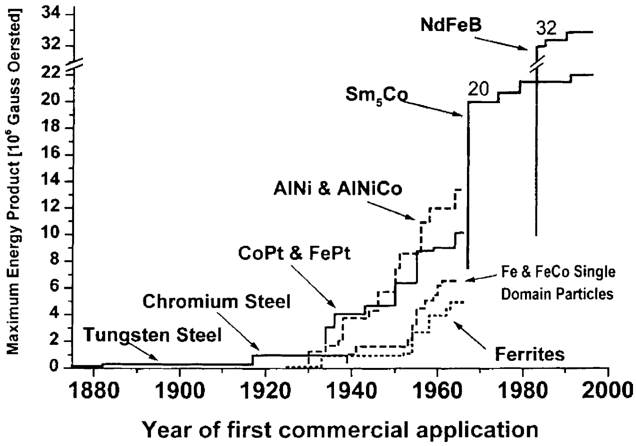

Fig. 8. Progress in development of permanent magnetic materials.

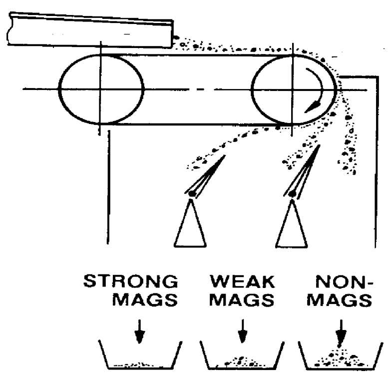

Fig. 9. Permanent magnetic roll separator.

The considerable technical and commercial success of permanent magnet roll separators is a result of two factors. The first is the availability of a large variety of magnet grades and sizes and the decreasing cost. The second aspect that is playing an important role is the availability of electromagnetic modelling software that allows the optimisation of the design, as is illustrated in Fig. 11.

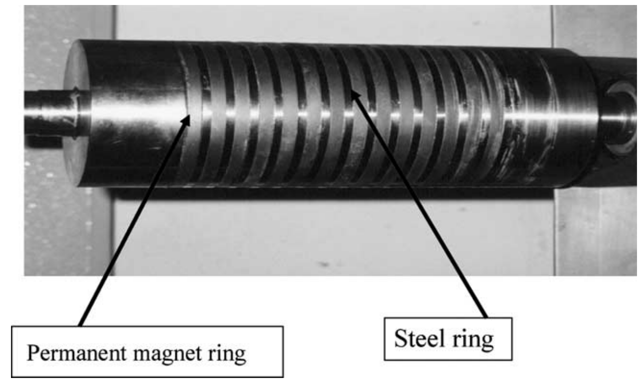

Fig. 10. Details of a permanent magnet roll.

3.4. Wet high-intensity high-gradient magnetic separators

The introduction of a matrix into a circuit of magnetic separators resulted in a dramatic extension of the applicability of magnetic separation to materials that were previously considered too fine and too feebly magnetic. This development was achieved by Jones (1960) who combined Frantz' idea (Frantz, 1937) of a magnetised matrix with a high magnetic field. One of the more advanced designs based on Jones' concept was, for instance, the SALA HGMS shown in Fig. 12. Although numerous cyclic and continuous wet high-intensity high-gradient magnetic separators (WHIMS or HGMS) were designed and built, only a few met the requirements of the mining industry. Kaolin purification, iron-ore and beach sand beneficiation are examples of successful applications.

Poor selectivity and matrix blockage were often responsible for the declining reputation of HGMS. This problem was successfully addressed by the VMS separator (Cibulka et al., 1985) developed in the Czech Republic and shown in Fig. 13. The conventional horizontal rotor was replaced by a vertically rotating ring and reverse flush was introduced. The VMS separator was further upgraded by introducing a bottom feed into

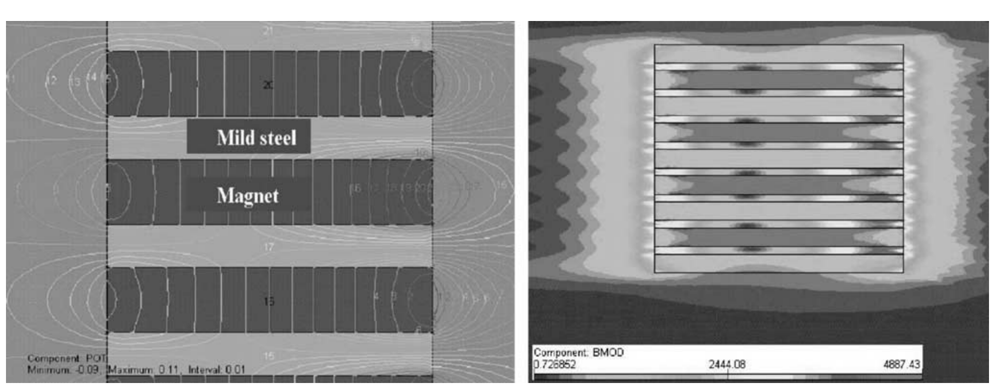

Fig. 11. Modelling of the magnetic field distribution around a magnet roll.

Fig. 12. SALA 480 HGMS in operation.

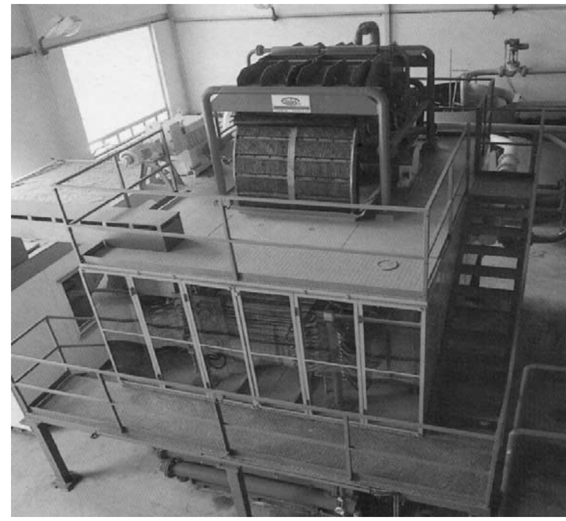

Fig. 14. VMS HGMS with bottom feed.

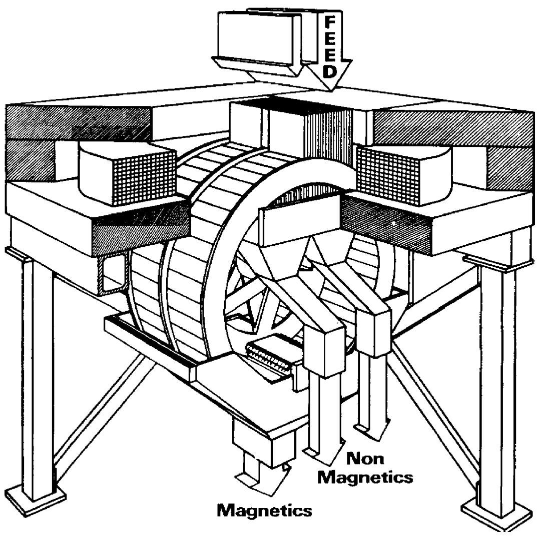

Fig. 13. Schematic diagram of VMS HGMS.

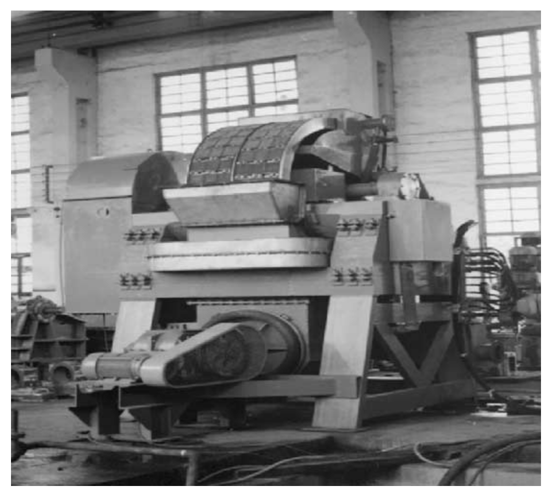

Fig. 15. SLON pulsating high-gradient magnetic separator.

the separator and a continuous control of the slurry velocity through the matrix (Fig. 14).

This concept was developed further in the SLON magnetic separator (Xiong, 1994). In this separator, developed in China and shown in Fig. 15, a slurry within the matrix is exposed to pulsation, which results in a better separation selectivity.

3.5. Superconductivity in magnetic separation

Although the technological significance of superconductivity is considerable, its importance for magnetic separation does not seem to represent a major breakthrough. Since the need for magnetic induction exceeding 2 T is not obvious (Svoboda, 1994), the main advantage of superconducting magnets is thus the reduced energy consumption and lower mass. Superconducting magnets also allow the generation of a high magnetic force in a large volume without using matrices, by employing open-gradient configurations of the coils (Good and Kopp, 1984).

Purification of kaolin by removing quasi-colloidal, very weakly magnetic iron and titanium oxides is the main application of the superconducting HGMS. Fig. 16 shows a continuous superconducting HGMS that uses the concept of a reciprocating matrix. Operating at a magnetic field of 5 T generated in the bore, of diameter of 1000 mm, this Outokumpu-Carpco machine can process up to 100 tons of slurry per hour.

3.6. Eddy-current separators and separation in magnetic fluid

Magnetic technology has responded to the environmental and economic needs to recycle metals and metallic products, and efficient eddy-current separators

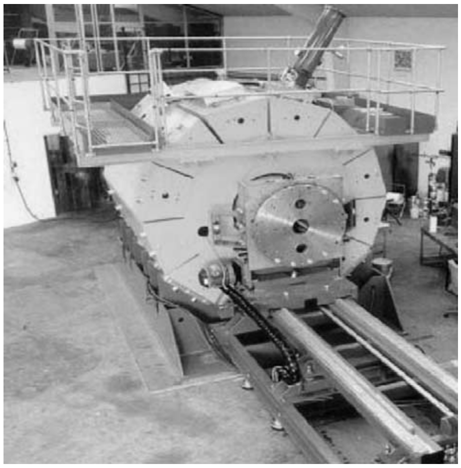

Fig. 16. Superconducting HGMS Cryofilter (courtesy of Outokumpu Technology, Carpco Division).

have been developed. By exposing the non-magnetic electrically conductive particles of non-ferrous metals to an alternating magnetic field, eddy currents generate their own alternating magnetic field opposing the external field. The resultant magnetic repulsion produces spatial displacement of components of the mixture, depending on their conductivity and density (Schloemann, 1982).

Most designs of eddy-current separators employ rotating drums fitted with earth permanent magnets, arranged with alternating polarity. A schematic diagram of such a separator is shown in Fig. 17. The common drawback of most commercial eddy-current separators is a poor separation of particles smaller than 5 mm. Therefore, recent developments have been directed towards efficient separation of small non-ferrous metal particles (Zhang et al., 1999). These developments allow the application of the eddy current technique to the separation of metal particles as small as 0.1 mm.

Selective recycling and separation of individual non-ferrous metals can be achieved using magnetic fluids as a separating medium. When a magnetic fluid is placed in a non-homogeneous magnetic field it exhibits an apparent density different from its natural density. This apparent density can be controlled through a wide range of values, exceeding densities of all known elements and materials. Numerous ferrohydrostatic (FHS) separators have been designed over the last 20 years for separation of non-ferrous metals from automobile scrap and for recovery of gold, platinum-group metals and diamonds (Fujita, 1996; Svoboda, 2000). Although this effort has demonstrated that it is possible to achieve a high selectivity of separation at industrially meaningful rates, wide-scale implementation of FHS has not yet happened. The availability of cost-effective, environmentally and user-friendly magnetic fluids that can be easily recycled is likely to enhance the significant potential of FHS.

4. Future trends in magnetic separation

Magnetic separation and magnetic techniques in general have been applied, with variable success, in numerous areas of engineering and science. This technique has at its disposal the magnetic force, which can be selectively controlled over a wide range of values and is universal in nature since all matter possesses magnetic properties.

Fig. 17 illustrates the current research and development trends and the future focus (Svoboda, 2001). Several areas that are likely to receive attention can be identified, such as improved understanding of the theoretical and operational principles of HGMS, judicious and justified incorporation of superconductivity, with particular emphasis on both high-temperature superconductivity and the inclusion of advanced permanent magnetic materials into new magnet design.

As is shown in Fig. 18, magnetic separation methods that have been conceived empirically and applied in practice, such as superconducting MS, small particle (<5 mm) eddy-current separation and biomedical MS, are being studied from a more fundamental point of view and further progress can be expected in the near future.

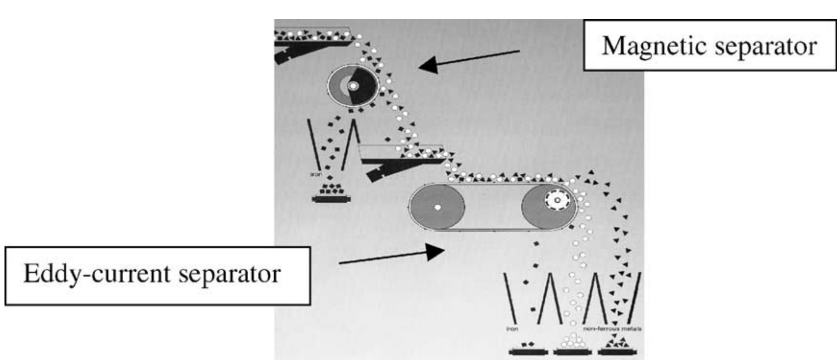

Fig. 17. Drum eddy-current separator for the recovery of non-ferrous metals.

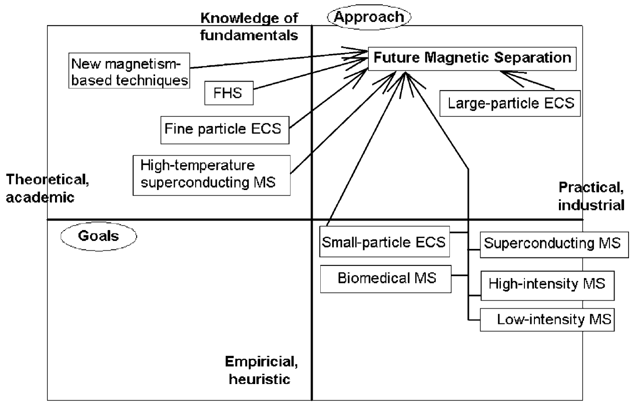

Fig. 18. The future trends in magnetic separation.

On the other hand, techniques such as fine particle (<1 mm) eddy-current separation, ferrohydrostatic separation and high-temperature superconducting MS, that received attention on an academic level, are entering the development stage. It can also be expected that novel magnetism-based methods will be investigated, either theoretically or empirically. Processes such as magnetic flocculation of weakly magnetic materials, separation by particle rotation, magnetic flotation or magnetism-assisted gravity separation are just a few examples. For successful development and implementation of these novel methods a research process that combines a deep knowledge of scientific fundamentals with a clearly defined use in a production environment, is essential.

5. Conclusions

Magnetic separation is an inherent part of numerous material treatment processes. This technique has at its disposal the magnetic force, which can be selectively controlled over a wide range of values. Enormous effort has been expended over the years in order to convert this feature, and a wealth of novel designs and ideas, into workable techniques and to introduce them into material treatment operations. It is hoped that in the future less reliance on an empirical or heuristic approach and a better environment for innovation, will facilitate research and the development of novel magnetism-based technologies in numerous areas of human endeavour.

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