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A NOVEL ADVANTAGE OF HGMS ORDERED MATRICES

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A novel benefit of an ordered High Gradient Magnetic Separation (HGMS) matrix, made up of parallel ferromagnetic wires is presented. One shows that the magnetic force F_m depends on α, the angle between the wires of the matrix and the applied magnetic field H_0. There is a relation between the tilting angles and magnetic susceptibilities of particles pulled out from the mixture. This relation proves a practical possibility of separating a mixture only by choosing adequate tilting angles; the method is named separation in angular steps. Finally one shows two applications based on this principle: a separator which extracts successively and another one which extracts concomitantly different magnetic fractions from a granular mixture.

Keywords: HGMS; Matrix; Magnetic separation; Ilmenite; Rutile

INTRODUCTION

As it is well known, High Gradient Magnetic Separation (HGMS) is a method usually based on the capture of particles by different kinds of matrix, consisting of disordered or partially ordered ferromagnetic elements.

Ordered matrices are more difficult to achieve, particularly when they are relatively big and made up of small ferromagnetic elements.

However, ordered matrices exhibit some benefits compared to the disordered ones: they have a constant packing factor throughout the entire volume, the local fluid velocity variations are small, the washing

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is easy enough, the ratio between the feeding time and the washing time is high etc.

In this paper we shall substantiate the existence of a new significant advantage of the ordered HGMS matrix consisting of ferromagnetic wires.

Thus, we shall show that it is possible to pull out, from a mixture, different kinds of fractions more or less magnetic, without changing the value of the background magnetic field or the average flow velocity, as it is usually the procedure in HGMS systems.

THEORETICAL CONSIDERATIONS

The HGMS theory indicates that by changing the magnetic force F_m and/or the drag force F_d, which are the main forces acting on a paramagentic particle placed near a magnetized wire, one can extract successively from a mixture, several magnetic fractions with different magnetic susceptibilities.

Practically, for the same construction parameters of the matrix, the variation of the force F_m is achieved by increasing or decreasing the intensity of the applied magnetic field H_0, and the variation of F_d by changing the flow speed of the carrier fluid.

For the ferromagnetic wire–paramagnetic particle system there is yet another possibility to change the value of the F_m force. It consists in different alignments of the wire relatively to the direction of the applied field [1–3].

We deduce that the magnetic force applied on a particle located in the limit layer (at $\theta = 0$) of a saturated buildup, made up of a ferromagnetic wire inclined with an angle α with respect to the applied field H_0 has the form

$$F_m = \frac{4\pi\mu_0 b^3 a^2 \chi_p M_S H_0}{3r_S^3} \sin^2\alpha, \tag{1}$$

where b is the particle radius, a – the wire radius, χ_p – the particle susceptibility and r_S – the distance between the wire axis and the particle. We assumed that *the short range term* is negligible, and in the magnetically saturated wire ($H_0 > M_S/2$) the internal magnetic field has the same direction as the external one.

Relation (1) argues plainly that F_m depends on α: hence, for the magnetic force to be modified it is sufficing to change the value of the angle between the wire and the direction of the applied magnetic field.

EXPERIMENTS

We inspect this theoretical conclusion by capture experiments performed on a rotating HGMS ordered matrix in a transversal flow configuration (Fig. 1).

The matrix consists of wires made of FeNiCo alloy with a diameter of 0.5 mm.

As can be noticed, all the wires are aligned parallel to each other and moreover, the wires residing in the same transversal plane are equidistant, the distance between two neighboring wires being 2.5 mm. The total volume of the matrix is 22 cm^3 and the packing factor of the ferromagnetic matrix is $F = 4.9\%$.

The experiments were performed using rutile particles almost monosided ($-125 + 120\ \mu m$) immersed in distilled water, and the flow was descending.

All the operations of magnetic capture are performed until the matrix saturates with captured material, buildups formed on wires being

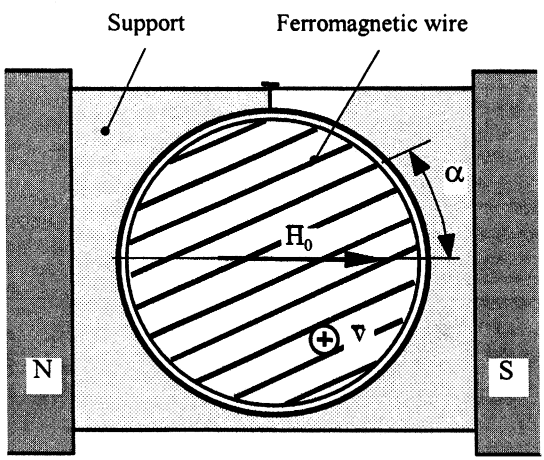

FIGURE 1 The ordered matrix used in experiments (cross section).

saturated buildups. Tests performed for different values of H_0 and v_a were intended to observe the change of the entire quantity of particles captured by the matrix (the saturation mass, m_s) with angle α.

Figure 2 depicts the dependence $m_s = f(\alpha)$ obtained for the mean velocity $v_a = 13.45\,\mathrm{cm/s}$ and five values of the background magnetic field intensity H_0.

The semblance between the experimental curves; both for the presented case and for other two cases ($v_a = 10.10\,\mathrm{cm/s}$ and $v_a = 7.95\,\mathrm{cm/s}$) led us to conclude that m_s depends on α obeying a particular law, the same under given experimental conditions [4].

We found that the simplest function approximating sufficiently well this dependence is $\sin^2\alpha$, therefore one can write

$$m_s(\alpha) = m_{SP} \cdot \sin^2\alpha, \tag{2}$$

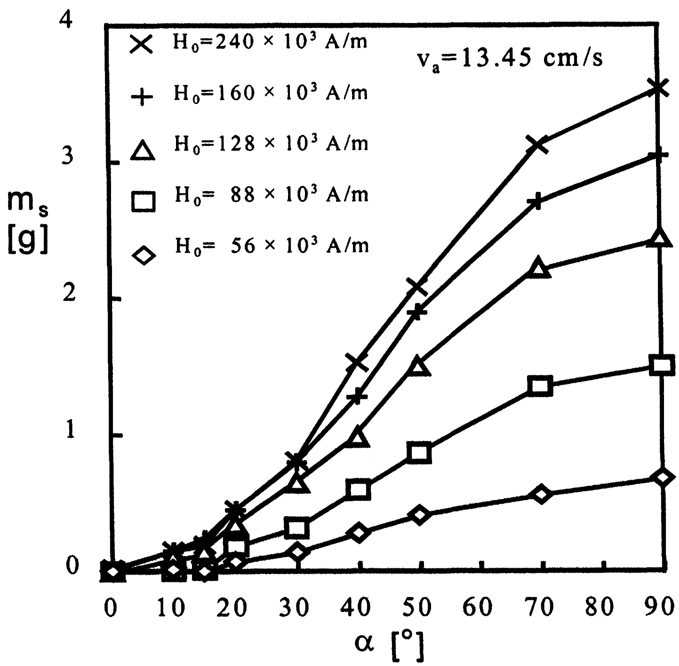

FIGURE 2 The dependence $m_s = f(\alpha)$ obtained for the mean flow velocity $v_a = 13.45\,\mathrm{cm/s}$ and different values of H_0.

where m_s is the saturation mass captured for a certain angle α ($0° < \alpha < 90°$), and m_{SP} is the saturation mass captured at $\alpha = 90°$ (wires perpendicular to the direction of H_0).

DISCUSSION

The decrease of the observed saturation mass with the decreasing angle α is due to a reduction of the magnetic force F_m acting on the particles.

Thus, the quasi-balance between the magnetic force F_m, on one hand, and the sum between the drag force F_d and the gravitational force F_G, on the other hand, is reached at a distance r_S from the axis of the wire, this distance becoming smaller the smaller is the angle α. The balance is achieved through the static friction coefficient μ_S, the force counterbalancing the sum $(F_d + F_G)$, being the friction force $F_f = \mu_S F_m$ (Fig. 3).

We deduced that this distance r_S (at $\theta = 0$), which is the radius of the saturated buildup, reduces with the decrease of α, according to the relation

$$r_S = r_{SP}(\sin\alpha)^{2/3}, \tag{3}$$

where r_{SP} is the saturated buildup radius for $\alpha = 90°$ [5].

Let us consider now a mixture of spherical particles consisting, for instance, of a paramagnetic sort with magnetic susceptibility χ_A, one with susceptibility χ_B ($\chi_B < \chi_A$).

By appropriate choice of H_0 and/or v_a, one can establish an inclination angle α_A so that the deposit formed on the wire contains only particles of the sort with susceptibility χ_A. In this case, a particle P_A (with χ_A, b_A) is held on the buildup limit layer if (Fig. 4)

$$F_{fA} = \mu_S F_{mA} = F_d + F_G. \tag{4}$$

By neglecting the weight and expliciting (4) we obtain

$$\mu_S \frac{4\pi\mu_0 a^2 M_S H_0}{3r_A^3} b_A^3 \chi_A \sin^2\alpha_A = 16\pi \frac{v_a}{R} \eta b_A^2 f_a, \tag{5}$$

where η is the liquid viscosity, f_a is the fraction of the particle surface on which the unit loading (τ_0) is acting and R is the flow tube radius

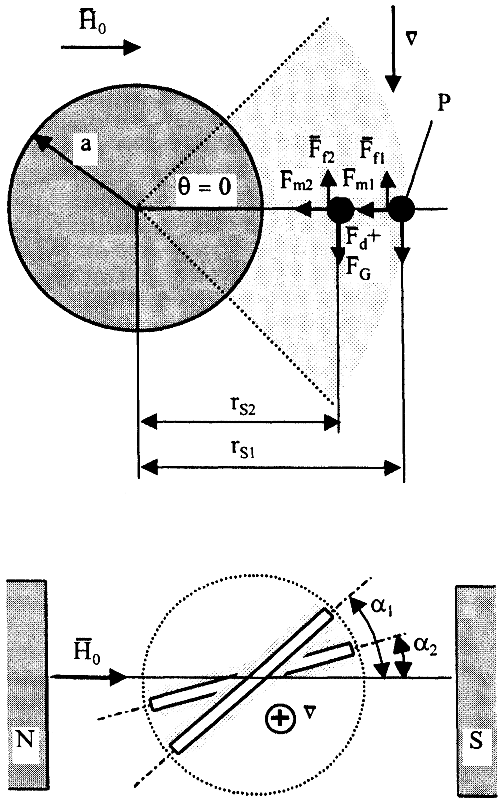

FIGURE 3 For two different angles ($\alpha_2 < \alpha_1$) the particle P takes two different positions and the condition $F_{m1} = F_{m2}$ is achieved for $r_{S2} < r_{S1}$. A small buildup is formed at α_2 and a large one at α_1.

(or equivalent radius of the flow section) [6,7]. It follows from relation (5) that the saturated buildup radius is

$$r_A = k b_A^{1/3} \chi_A^{1/3} (\sin \alpha_A)^{2/3}, \tag{6}$$

where $k = [(\mu_S R \mu_0 a^2 M_S H_0)/(12 v_a \eta f_a)]^{1/3}$ is a constant for given conditions (H_0, $v_a = \text{constant}$).

Once the particles with χ_A are extracted from the mixture, another angle α_B is chosen ($\alpha_B > \alpha_A$) so that the magnetic force F_{mB} allows formation of a new deposit, as large as the first one, yet this time

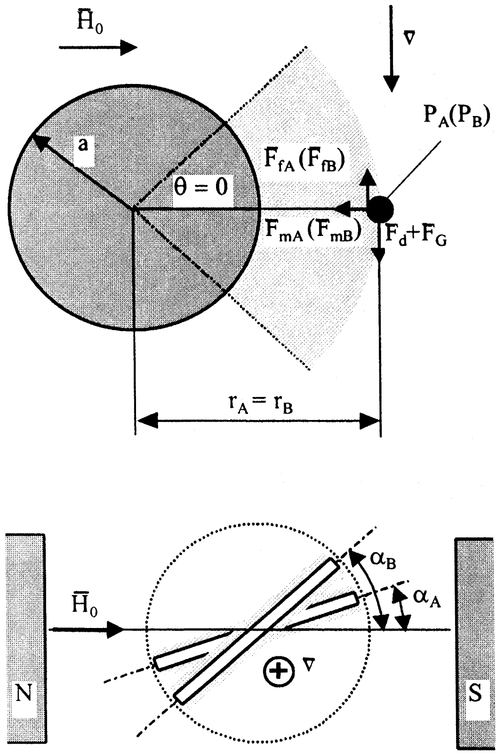

FIGURE 4 Particles P_A (with χ_A) and P_B (with $\chi_B < \chi_A$) can occupy the same position, but for different inclination angles ($\alpha_A < \alpha_B$). The buildups are equal in both cases ($r_A = r_B$).

consisting only of particles with susceptibility χ_B. Particle P_B which occupies the same position that was previously occupied by particle P_A, is situated at a distance r_B from the wire radius given by

$$r_B = kb_B^{1/3}\chi_B^{1/3}(\sin\alpha_B)^{2/3}. \tag{7}$$

The assumed condition $r_A = r_B$ leads to

$$b_A\chi_A \sin^2\alpha_A = b_B\chi_B \sin^2\alpha_B. \tag{8}$$

If H_0 and/or v_a are chosen so that at $\alpha_B = 90°$ the particles with susceptibilities χ_B are extracted from the mixture, it follows that, in order to retain first the particles with susceptibilities χ_A ($\chi_A > \chi_B$), the wires must make with the direction H_0 an angle smaller than 90°, given by

$$\alpha_A = \arcsin\left[\left(\frac{b_B}{b_A}\right)^{1/2}\left(\frac{\chi_B}{\chi_A}\right)^{1/2}\right]. \tag{9}$$

Relation (9) can be written under the general form

$$\alpha_i = \arcsin\left[\left(\frac{b_0}{b_i}\right)^{1/2}\left(\frac{\chi_0}{\chi_i}\right)^{1/2}\right], \tag{10}$$

where b_0, χ_0 are the radius and the susceptibility of particles captured at $\alpha_0 = 90°$, respectively, and α_i is the angle of capture for particles with radius b_i and susceptibility χ_i ($\chi_i > \chi_0$).

Relation (10) shows that a mixture, consisting of components with different susceptibilities, can be separated only by selecting some adequate angular steps: we name this method *magnetic separation in angular steps*.

Practical limits of this method are placed in general limits of the HGMS techniques.

Concerning the selectivity of the method, one can observe that it is better the higher the difference between the capture angles $(\alpha_0 - \alpha_i)$. For pronounced susceptibility ratios (χ_0/χ_i) one admits a relatively large deviation of the particle sizes, but for less pronounced ratios the dimensional deviation of the particles should be smaller.

It is interesting to evaluate the connection between the angular deviation $\Delta\alpha$ and the dimensional deviation Δb, when the spherical particles have their radii between b_0 and $(b_0 + \Delta b)$. If a particle P_{A1} with radius b_0 is captured at an angle α_{A1}, then the capture of a particle P_{A2} with radius $(b_0 + \Delta b)$ is achieved at a smaller angle $\alpha_{A2} = \alpha_{A1} - \Delta\alpha$.

The condition of forming equal buildups $(r_{A1} = r_{A2})$ leads to

$$b_0\chi_A \sin^2(\alpha_{A2} + \Delta\alpha) = (b_0 + \Delta b)\chi_A \sin^2\alpha_{A2} \tag{11}$$

and if we consider $\Delta\alpha \ll \alpha_{A2}$ we finally obtain

$$\Delta\alpha \approx \frac{\Delta b}{2b_0}\operatorname{tg}\alpha_{A2}, \tag{12}$$

or more generally

$$\Delta\alpha \approx \frac{\Delta b}{2b_0}\operatorname{tg}\alpha, \qquad (13)$$

where $\Delta\alpha$ is the angular deviation expressed in radians.

One can notice that angular deviation depends both on the dimensional deviation of the particles and on the value of the capture angle.

Relation (13) indicates that at small capture angles (as is the case for strong paramagnetic minerals ilmenite, chromite etc.), at a constant angular deviation, one can allow relatively large dimensional deviations.

Relation (1) shows the magnetic force acting on a paramagnetic particle is zero for $\alpha = 0°$. Consequently, a paramagnetic fraction captured and retained by an ordered matrix with parallel wires can be washed without canceling the applied field: the matrix rotates until the wires become parallel to H_0 and is maintained this way for washing.

APPLICATIONS

Figure 5 shows a scheme of a magnetic separator proper conception, and named by us *magnetic separator in angular steps* [8].

As can be seen, it consists of a cylindrical canister where the ordered ferromagnetic matrix resides. The matrix is made up of parallel wires arranged in equidistant planes.

The canister is placed between two magnetic poles with plan-parallel faces. The background magnetic field can be generated by an electromagnet or even by a source with permanent magnets.

The canister is sustained and guided by two coaxial bearings, so that it can spin around its axis. At its upper side one can find a driving gear allowing the canister to spin and to connect in such a manner for the ferromagnetic wires to make a certain angle α, its value varying between 0° and 90°.

The operation of the separator is cyclic, the cycle having two or three phases: feeding, possibly rinsing and washing.

The separator divides a mixture of particles into two constituents: one nonmagnetic, with magnetic susceptibility smaller than a specific value

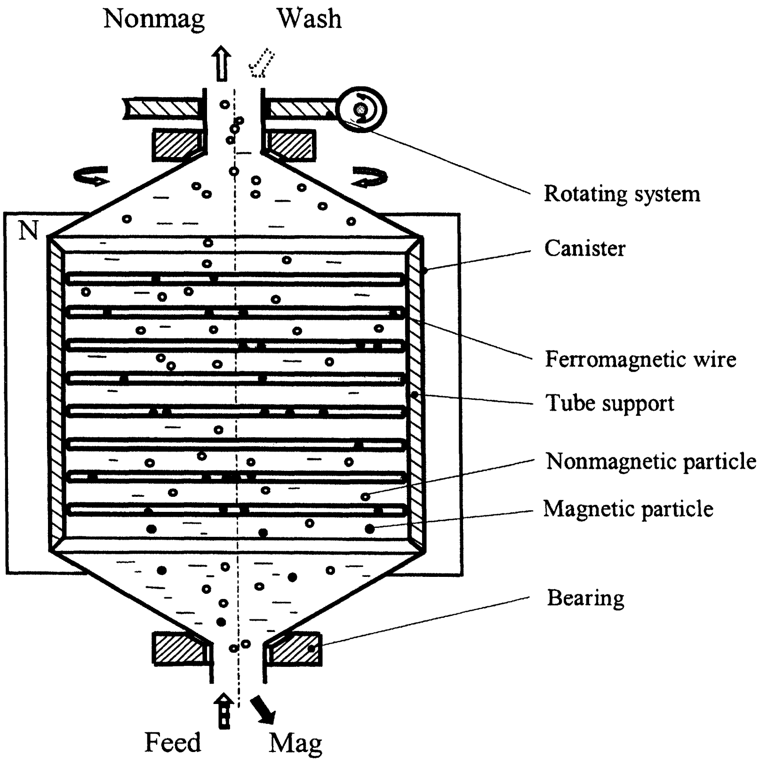

FIGURE 5 Magnetic separator in angular steps.

χ_0 and another one magnetic, consisting of particles with a susceptibility $\chi_p \geq \chi_0$. This partitioning is achieved at suitable values of H_0, v_a and α_0. The same mixture may be also divided into two other fractions delineated by another threshold, χ_0', without any change in the values of H_0 and v_a, but only by choosing a different tilting angle α_0'.

The captured magnetic fraction is washed with a clean liquid (water) after canceling the applied field or rotating the canister until it reaches the position where the wires become parallel to the direction of H_0.

In Fig. 6 one can see a *magnetic separator with multiple matrix*, cyclic as well, based on the same principle. It can divide simultaneously a mixture into several magnetic fractions [9].

The separator consists of a relatively long cylindrical canister, with three identical ferromagnetic matrix M_1, M_2 and M_3, separated by some disks and distance-pieces inside.

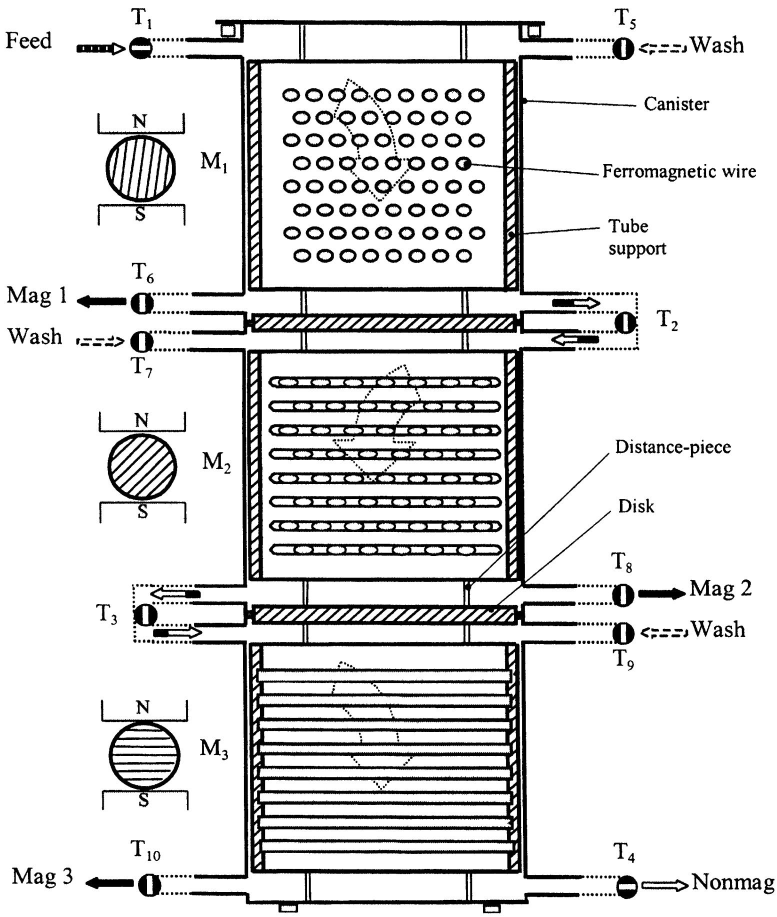

FIGURE 6 Magnetic separator with multiple matrix.

Position of the matrix inside the canister is designed for the wires of the matrix M_1 to be tilted at an angle, say, $\alpha_1 = 10°$ with the direction of the field H_0, wires of the second matrix M_2 at an angle $\alpha_2 = 45°$ with the direction of the field H_0, and wires of the third matrix M_3 to be perpendicular to the field.

During the feeding, the liquid with a mixture is introduced in the canister by tap T_1 and passes through: the matrix M_1, the tap T_2, the matrix M_2, the tap T_3, the matrix M_3 and finally the tap T_4. Thus, the average velocity of the fluid is the same through the three matrices, and the flow is prevalently perpendicular to the ferromagnetic wires (transversal configuration).

Let us assume that one wishes to separate a granular mixture consisting of three different magnetic fractions Mag_1, Mag_2 and Mag_3 (susceptibility of fraction Mag_1 is higher than susceptibility of fraction Mag_2, and Mag_2 has susceptibility higher than Mag_3) and a nonmagnetic fraction *Nonmag*.

In the presence of a magnetic filed, in the matrix M_1, which has the smallest tilting angle ($\alpha_1 = 10°$), only the fraction Mag_1 is retained, in matrix M_2 ($\alpha_2 = 45°$) only the fraction Mag_2, and in the last matrix M_3 ($\alpha_3 = 90°$), the fraction Mag_3, at the exit through T_4 the nonmagnetic fraction being accumulated.

After canceling the applied magnetic field and after a suitable manipulation of the taps $T_1, T_2, \ldots, T_{10}$ the matrices are washed by introducing water through T_5, T_7 and T_9. Thus, in the end, at the exits T_6, T_8 and T_{10} three differently captured magnetic fractions are obtained.

Separation tests accomplished on two types of granular mixtures (alluvial sand) with minerals content (quartz, magnetite, ilmenite, granat, rutile, zircon etc.) from the granulometric classes $-225 + 200\ \mu m$ and $-125 + 100\ \mu m$ proved the accuracy of the principle of magnetic separation in angular steps.

Systematic tests to determine the optimal process parameters (H_0, v_a, α, etc.) where the maximum efficiency in the concentration of ilmenite and possibly rutile may be achieved are being planned.

CONCLUSIONS

The magnetic force of a ferromagnetic wire acting on a paramagnetic particle changes its value depending on the angle between the wire and the direction of the applied magnetic field. As a result, one finds experimentally that an ordered HGMS matrix made up of parallel wires, has the advantage of capturing successively different magnetic fractions by properly choosing the angles (angular steps) without changing the applied field and/or the average velocity.

The tilting angles of the capturing ferromagnetic wires depend on the magnetic susceptibilities of the components of the mixture.

The method is named *magnetic separation in angular steps*. It can be practically materialized by building magnetic separators, which can successively or simultaneously fractionize a granular mixture.

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