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METHOD OF SEPARATING MAGNETIC MATERIAL

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Our invention relates to material treatment and the material treated. It relates more in particular to the treatment of a material such as an ore or the like by a process involving magnetic separation to concentrate a portion of such material.

For convenience, our invention will be described in connection with the separation of different constituents of ores and the like, and modifications and details of the process and products involved will then be disclosed. In considering the invention from the standpoint of mineral separation, it is to be noted that substantially all magnetic separation employed heretofore has depended primarily upon the utilization of the characteristic of magnetizable materials known as permeability. Separations that depend for their results on permeability of materials or differences of permeability are necessarily limited in their applications.

The principal object of our present invention is the utilization of a characteristic of material not heretofore employed in separation processes.

Another object is the provision of means for developing modified magnetic characteristics of materials which will permit their ready separation by subsequent treatment.

Another object is to utilize differences in coercive force of materials to effect a separation of such materials.

Another object is the provision of a method for modifying the coercive force of materials;

Another object is the production of material having high coercive force.

Another object is the provision of improved means for employing magnetic properties in removing impurities from materials such as ores or minerals.

Heretofore all commercial methods for separating minerals have employed direct current magnets or have employed magnets in such a way as to utilize the magnetic permeability of the material to be separated. This is a specific measurable magnetic property usually represented by the symbol μ. For example, the attraction of the mineral particle in air for a magnet has been determined to be proportional to the quantity μ minus one.

The complete magnetic nature of a substance, however, is not expressed by its permeability. The degree and tenacity with which its magnetism is retained after a magnetizing field is removed are also important. These properties are proportional to characteristics of magnetizable materials termed "remanence" and "coercive force". Our invention is directed to the development of a suitable remanence and coercive force in materials and the utilization of these factors in magnetic separation processes.

For further explanation of the character of remanence and coercive force as it affects our invention, we wish to remind those skilled in the art that the tenacity with which a material retains its magnetism is often expressed by the so-called hysteresis loop which shows the magnetic induction resulting from increasing and decreasing a magnetizing field cyclically. For convenience, the general configuration of the hysteresis loop is expressed in terms of intercepts on the axes. The induction remaining when the field is reduced to zero is called the remanence, and the field which would be necessary to neutralize this induction is termed the coercive force of a particular material. The tenacity with which magnetism is retained is accordingly determined by the coercive force, and the strength of the remanent magnetism by the remanence. Since in small particles the demagnetizing factor is very great, we are in the present invention more concerned with the control of coercive force than with the remanence.

An important aspect of our invention is the discovery that the coercive force of minerals varies widely and is particularly susceptible to change by suitable heat treatment. We have also found that this coercive force may be utilized in a number of ways to effect separations of two or more materials which were not readily separable prior to our invention. In a large class of substances, the coercive force developed or increased therein in accordance with our invention permits the formation of small permanent magnets and the resulting permanent magnetism can be used to advantage in separation processes. We have found further that these properties are associated with activity in an alternating magnetic field in such a way that strongly active materials have a high coercive force and, as a rule, considerable remanence. This activity in an alternating current field manifests itself by a behavior which may be termed "jumpiness". The individual active particles, for example, if supported on a plane surface and brought into the field of an alternating magnet will jump and vibrate on the plane surface at a relatively high rate which in many cases is comparable to the rate of change of the polarity of the magnet. We conceive that this property which we term "activity" may be due to the alternate repelling and attracting action of the alternating mag-

netic field. We have found, as will be shown further hereinafter, that if the alternating magnetic field is too intense, activity will be cut down. This we conceive to be due to a partial demagnetization of the individual magnet particles.

The first step in our process consists in providing suitable coercive force and remanence in the materials to be treated. We have found that we may divide most minerals, for example, into a number of classes and in general each class is susceptible to treatment by a uniform process to develop high coercive force. Although all of the members of a single class may be capable of treatment by substantially the same process to develop high coercive force and remanence, the duration and control of the treatment and the nature of the mineral itself may be employed to produce a final result in which all of the members of a single class may be made to differ in coercive force. The result is that we may treat a mixture of minerals which may be minerals of different classes or minerals of the same class to develop a differential in coercive force and remanence and make it possible to secure a separation.

For purposes of explanation, minerals containing iron, nickel, manganese and/or cobalt may be considered to represent the minerals which can be separated or concentrated by our process. It may be stated, however, that it is immaterial whether the iron, nickel, or cobalt are present as normal constituents of the minerals or as impurities. Minerals of this class often contain iron, nickel or cobalt in combination with other metallic elements. We have found that when the other metallic element present has an atomic weight greater than 40, the mineral may be treated to obtain a high coercive force, while minerals with associated elements which have an atomic weight below 40 do not become highly coercive by the same treatment.

For our purpose, we may classify minerals as follows:

Class A

Materials naturally possessing high coercive force and remanence (and their artificial analogues)

Lodestone (roasted iron oxides)

Pyrrhotite (roasted iron or copper pyrites)

Class B

Materials naturally possessing high coercive force but low remanence

Hematite

Chromite

Mica

Class I

Metals, alloys, sulphides, arsenides and antimonides

Pyrite, FeS_2

Marcasite, FeS_2

Sternbergite, $Ag_2SFe_4S_5$

Millerite, NiS

Niccolite, NiAs

Breithauptite, NiSb

Pyrrhotite, Se_nS_{n+1}

Troilite, FeS

Polydymite, Ni_4S_5

Bornite, Cu_3FeS_3

Chalcopyrite, $CuFeS_2$

Arsenoferrite, $FeAs_2$

Marmatite, (Fe, Zn) S

Molybdenite, (Fe present)

Leucopyrite, $FeAs_2$

Arsenopyrite FeS_2FeAs_2

Safflorite, $CoAs_2$

Rammelsbergite, $NiAs_2$

Metallic iron

Heusler's alloys

Powdered nickel-iron alloy (78% nickel)

Cobalt nickel pyrite

Smaltite, $CoAs_2$

Cobaltite, $CoAs_2$

Gersdorffite, NiAsS

Corynite, $NiS_2.Ni(AsSb)_2$

Ullmannite, $NiS_2.NiSb_2$

Pentlandite, (FeNi) S

Chalmersite, $Cu_2SFe_4S_5$

Lollingite, $FeAs_2$

Glaucodot, (Co, Fe) AsS

Stannite, $SnS_2.Cu_2S.FeS$

Frankeite, $Pb_5Sn_2Sb_2S_{12}$(Fe present)

Class II

Oxides of the general formula R_2O_3

Hematite, Fe_2O_3

Ilmenite, $(FeTi)_2O_3$

Heterogenite, $CoO.Co_2O_36H_2O$

Psilomelane, $H_4MnO_5(Fe_2O_3)$

Diaspore group

Gothite, $Fe_2O_3H_2O$

Limonite, $2Fe_2O_33H_2O$

Turgite, $2Fe_2O_3H_2O$

Martite, Fe_2O_3 (isometric)

Pyrolusite, $MnO_2(Fe_2O_3)$

Xanthosiderite, $Fe_2O_3.2H_2O$

Skemmatite, $3MnO_2.2Fe_2O_3.6H_2O$

Class III

Aluminates, ferrites, carbonates, tungstates, columbates and tantalates

Hercynite, $FeOAl_2O_3$

Dysluite, (Zn, Fe, Mn) O.(Al, Fe) $_2O_3$

Magnetite, FeO, Fe_2O_3

Ferrozincite, $ZnO.Fe_2O_3$

Ferrozincite, $(ZnO.Fe_2O_3)$

Franklinite, (Fe, Zn, Mn) O.(Fe, Mn) $_2O_3$

Copper ferrite, $CuO.Fe_2O_3$

Jacobsite, (Mn, Mg) O.(Fe, Mn) $_2O_3$

Chromite, $FeOCr_2O_3$

(FeMG) O.(Cr, Fe) $_2O_3$

Pseudo Brookite, $Fe_4(TiO_4)_3$

Tantalate Niobate Tungstate group

Columbite-Tantalite, $FeO.(TaCb)_2O_5$

Samarskite, $3FeOCe_2(NbTa)_6O_{18}$

Wolframite, (FeMn) $O.WO_3$

Ferberite, $FeO.WO_3$

Molybdite, $3MoO_3.Fe_2O_3.7\frac{1}{2}H_2O$

Hubnerite, $MnO.WO_3$

Siderite, $FeOCO_2$

Oligonite, $(FeOMn)O.CO_2$

Rhodochrosite, $MnCO_3$

Class IV

Silicates

Pyroxene group

Bronzite, $(MgFe)SiO_3$

Hypersthene, $(FeMg)SiO_3$

Augite, $(Ca, Mg, Fe)(SiO_3)_2$

Aegirite, $NaFe(SiO_3)_2$

Rhodonite, (Mn, Zn, Fe, Cu) SiO_3

Amphibole group

Anthophyllite, $(MgFe)SiO_3$

Actinolite, $Ca(MgFe)_3(SiO_3)_4$

Hornblende, $Ca(MgFe)_3(SiO_3)_4$

Glaucophane, $NaAl(SiO_3)_2.(Fe, Mg)SiO_3$

Iolite, $H_2(Mg, Fe)Al_3Si_{10}O_{37}$

Garnet group

Garnet, $Fe_3Al_2(SiO_4)_3$

Chrysolite group

Chrysolite, $(Mg, Fe)_2SiO_4$

Mica group

Biotite, $(HK)_2(MgFe)_2(AlFe)_2(SiO_4)_3$

Any of the materials set out hereinabove may be treated by our process, as will appear clear hereinafter. Other materials not specifically listed may also be treated, usually by means of a first step involving the introduction of a magnetizable material not normally present in the substance. In our process, as in all processes involving separation, the materials are first treated to form relatively small particles. Usually in the case of minerals, preliminary metallurgical treatment will have required the formation of small particles, and so our process does not, as a rule, involve additional grinding. We may treat finely divided ores or minerals ground in any of the usual ways. We find, however, that exceptionally good results are in most cases obtainable when the material has previously been broken down by an explosion shattering process, as described in the co-pending application of Dean and Gross, Serial No. 612,524 filed May 20, 1932.

In developing high coercive force in materials, we have proceeded on the conception that this high coercive force is associated with the dispersion in one substance of a second phase in a very finely divided state. This second phase must be that state which exists at the grain boundaries in multicrystalline solids or discontinuities in the crystal lattice or metallic structure. Either the matrix or the dispersed phase, or both, may be magnetic. The treatments which we employ to control coercive force are essentially treatments to control the dispersion of constituents of the mineral or the like.

For the purpose of description, our method may be classified according to two general steps of treatment. They are as follows:

A. Formation at a temperature below that of substantial crystal growth of a solid.

B. Treatment which involves first forming a solid solution and then dispersion of one of the constituents of the solid solution in finely divided state in the other.

This latter treatment may be considered as involving four steps as follows:

1. Heating to form a solid solution;
2. Quenching to obtain a supersaturated solid solution;
3. Aging to allow the supersaturated solution to obtain a more stable state and resulting in the separation of a finely dispersed phase; and
4. Annealing to agglomerate a dispersed phase.

The point in this latter method where the process is stopped depends upon the result desired. After step 2, the coercive force is low; after step 3, the coercive force is high; and after step 4, again low.

To apply the first mentioned method (designated A), a suitable heat treatment is most commonly used. In some cases, the mineral or the like may be treated directly by heating in one or more steps and with suitable control of the furnace atmosphere where this is required. In other cases, a preliminary treatment is required to form a solid capable of decomposition at a temperature below that of substantially crystal growth.

As an example of the second mentioned method (designated B), a mixture of hematite and magnetite has been "homogenized" by heating for one hour 1450° C. The mixture was then quenched in cold water thereby producing a solid solution in a metastable condition. Subsequent aging in vacuo for thirty minutes at any temperature between 500° C. and 1000° C. produced a substantially four-fold increase in coercive force. Another example involved the treatment of basic open hearth slags which, in a quenched condition, have a low coercive force and apparently contain metastable solid solutions. Aging for one hour at 600° C. caused a substantial increase in coercive force.

In order to avoid an extremely long and detailed description of details of treatment, we give below a table showing the application of various heat treatments to different minerals and the like and the resultant activity in both a direct and alternating field, the latter being produced by a single phase, 60 cycle, alternating current and a laminated core electromagnet having a field strength of about 50 gauss. Activity may be considered as a direct indication of coercive force and remanent magnetism. The data given in the table will be discussed hereinafter.

Referring to the table, it is at once evident that minerals of Class A usually require no treatment. They have been known to possess permanent magnetism and we claim no heat treatment or separating process as applied directly to these materials except as included in the appended claims. Insofar as we may separate these materials from other magnetic materials, or insofar as we may employ a different method of separation, my invention applies to them. In this connection we are familiar with British Patent No. 224,924 to Mordey, as well as other patents and literature references relating to the Mordey development. In this connection, we wish to state that we employ an entirely different mechanism, as further details of this specification will show.

Minerals of Class B likewise require no treatment, but on account of their very low remanence, require high fields to obtain the advantage of their high coercive force. By treating these minerals in accordance with our invention, however, the use of lower field strengths is permitted.

Referring further to the table, it will be seen that in Classes I and II, heating produces at once a high remanence and coercive force material, according to our method A. Control of temperature and atmosphere can be employed further to modify coercive force in different minerals of the same class.

In the case of minerals of Class III, it is necessary first to produce a solid, capable of partial decomposition below the temperature of crystal growth, e. g., by oxidizing the mineral or by driving off CO_2. We then produce a dispersion and a resultant magnetic substance having high coercive force by partial reduction according to method A. This treatment likewise renders these minerals of higher permeability and may be used to make possible their separation by well-known direct current methods.

Minerals of Class IV are characterized by requiring repeated and drastic treatments to secure high coercive force. In this class of materials, we may, for example, employ the heating, quenching and aging steps.

From the appended table and the disclosure hereinabove, methods of treatment for separating different minerals may be readily determined. We shall give hereinbelow a number of examples showing the application of my invention to different minerals and the like.

Example 1

In the treatment of chromite to secure high coercive force in accordance with the general treatment A previously discussed, we heat the ore or mixture of minerals which may have resulted

Test No.	Mineral		Notes	Heat treatment				
	Class	Designation		Step	Temperature, °C.	Time	Atmosphere	Method of cooling
1	I	Sponge iron	Reduced in H_2	Single	650	5 min	Air	Air.
2	I	Iron-silicon filings	Annealed	do	950	10 min	do	Do.
3	I	Iron-cobalt (large piece).	Not hardened	Three	850		do	Do.
4	I	Permalloy dust		Single	950	10 min	do	Do.
5	I	Iron	Nitrided	Two		4 hrs	NH_3	NH_3.
6	I	Troilite	FeS	Single	650	5 min	Air	Air.
7	I	Pyrite	FeS_2	do	650	5 min	do	Do.
8	I	Marcasite	FeS_2	do	650	5 min	do	Do.
9	I	Pyrrhotite	Fe_7S_8	do	650	5 min	do	Do.
10	I	Chalcopyrite	$CuFeS_2$	do	600	1 min	do	Do.
11	I	do		do	600	2 min	do	Do.
12	I	do		do	600	5 min	do	Do.
13	I	do		do	600	1 hr	do	Do.
14	I	do		do	950	10 min	do	Do.
15	I	do		do	950	1 hr	do	Do.
16	I	Bornite	Cu_5FeS_4	do	600	5 min	do	Do.
17	I	Pentlandite	(FeNi)S	do	600	5 min	do	Do.
18	I	Arsenopyrite	FeAsS	do	600	5 min	do	Do.
19	I	Molybdenite	MoS_2(some Fe)	do	600	5–15 min	do	Do.
20	I	do		do	750	2 min	do	Do.
21	II	Hematite	Fe_2O_3	do	500	30 min	H_2	Furnace.
22	II	Hematite+sponge iron.		do	650	5 min	Closed crucible	
23	II	Martite	Fe_2O_3 (isomet.)	do	500	30 min	H_2	Furnace.
24	II	Limonite	$2Fe_2O_3.3H_2O$	do	500	30 min	H_2	Do.
25	II	Gothite	$Fe_2O_3.H_2O$	do	500	30 min	H_2	Do.
26	II	Turgite	$2Fe_2O_3.H_2O$	do	500	30 min	H_2	Do.
27	II	Ilmenite	$(FeTi)_2O_3$	do	600	15 min	Air	Air.
28	II	do		do	500	30 min	H_2	Furnace.
29	II	Psilomelane	H_4MnO_5	do	500	30 min	H_2	Do.
30	II	Pyrolusite	MnO_2	do	500	30 min	H_2	Do.
31	III	Lodestone			950	5 hrs	Air	Air.
32	III	do	$FeO.Fe_2O_3$		1300	1 hr	Vacuum	
33	III	do			A+B {950, 500}	5 hrs, 30 min	Air, H_2	Air. Furnace.
34	III	Fe_3O_4	Hayden artificial, high purity, low coercive force.	Single	950	1 min	Air	Air.
35	III	Fe_3O_4		do	950	6 min	do	Air.
36	III	Fe_3O_4		do	950	30 min	do	Do.
37	III	Magnetite	$FeO.Fe_2O_3$ (low coercive force).	do	950	10 min	do	Do.
38	III	do		do	950	10 min	do	Water.
39	III	do		do	950	2 hrs	do	Air.
40	III	do		do	950	2½ hrs	do	Furnace.
41	III	do		do	500	1¼ hrs	H_2	Do.
42	III	do	Ox.+red		A+B {950, 500}	10 min, 30 min	Air, H_2	Air. Furnace.
43	III	Magnesio-ferrite	$MgO.Fe_2O_3$	Single	950	10 min	Air	Air.
44	III	Ferberite			950	10 min	do	Do.
45	III	do			950	45 min	do	Do.
46	III	do	$FeO.WO_3$		{950, 500}	45 min, 30 min	do, H_2	Do. Furnace.
47	III	do			500	45 min	H_2	Do.
48	III	do			500	2 hrs	H_2	Do.
49	III	Chromite			950	10 min	Air	Air.
50	III	do	$FeO.Cr_2O_3$		950	30 min	do	Do.
51	III	do			{950, 500}	1 hr, 30 min	do, H_2	Do. Furnace.
52	III	do			500	1 hr	H_2	Do.
53	III	Franklinite	(Complex ferrite of Zn, Fe and Mn.)		950	10 min	Air	Air.
54	III	do			950	30 min	do	Do.
55	III	do			{950, 500}	30 min, 30 min	do, H_2	Do. Furnace.
56	III	do			{950, 500}	2 hrs, 30 min	Air, H_2	Air. Furnace.
57	III	do			{950, 950}	1 hr, 4 min	H_2, Air	
58	III	do	Equal amount pyrite		600	5 min	do	Air.
59	III	do	do		950	5 min	do	Do.
60	III	Siderite	$FeO.CO_2$		500	30 min	H_2	Furnace.
61	III	Rhodochrosite	$MnO.CO_2$		500	30 min	H_2	Do.
62	III		$MnCO_3$ (chemically pure)		500	30 min	H_2	Do.
63	III	Tantalite-Columbite	$FeO.(TaCb)_2O_3$		{950, 500}	12 hrs, 30 min	Air, H_2	Air. Furnace.
64	IV	Augite	(Ca, Mg, Fe) (SiO_3)		{950, 500}	12 hrs, 30 min	Air, H_2	Air. Furnace.
65	IV	Rhodonite	(Mn, Zn, Fe, Cu)SiO_3		500	30 min	H_2	Do.
66		Olivine			{950, 500}	1 hr, 1 hr	Air, H_2	

Test No.	Magnetic properties				Coercive force (measured in oersteds)	Induction (measured in gausses)	Density (grams of mineral powder per cubic centimeter)
	Untreated		After treatment				
	D. C. suscept.	A. C. activity	D. C. suscept.	A. C. activity			
1	Strong	None	Strong	100%			
2	do	do	do	100%			
3	do	do	do	100%			
4	do	do	do	100%			
5	do	do	do	100%			
6	None	do	Moderate	100%			
7	do	do	do	100%	600	180	1.5
8	do	do	do	100%			
9	Weak	Moderate	do	100%			
10	None	None	do	75%			
11	do	do	Strong	90%			
12	do	do	do	100%	350	100	1.81
13	do	do	do	90%			
14	do	do	Very strong	10%			
15	do	do	do	None			
16	do	do	Moderate	100%			
17	do	do	do	100%			
18	do	do	do	100%			
19	do	do	Weak	Slight	300	240	3.11
20	do	do	Moderate	Moderate to strong			
21	do	do	do	100%	370	1,100	3.04
22				100%			
23	None	None	Moderate	Strong			
24	do	do	do	do			
25	do	do	do	do			
26	do	do	do	do			
27	Weak	Few particles		100%			
28	do	do		100%			
29	None	None	Moderate	100%			
30	do	do	do	100%			
31	Strong	Strong	do	Moderate			
32	do (even stronger after D. C. activation.)	do		None	100	400	3.0
33	do	do			2	1,500	3.0
34	do	do	Strong	Strong			
		None	do	10%			
35	do	do	do	100%	100	1,200	3.0
36	do	do	do	30%			
37	do	do	do	100%			
38	do	do	do	100%			
39	do	do	Moderate	Moderate			
40	do	do	do	do			
41	do	do	Strong	Weak			
42	do	do	do	100%			
43	do	do	do	Moderate			
44	do	do	Weak	None			
45	do	do	do	Few particles (weak).			
46	do	do	Moderate	100%			
47	do	do		50%			
48	do	do		75%			
49	Very weak	do	Weak	None			
50	do	do	Moderate (so was gangue).	do			
51	do	do	Moderate	100%			
52	do	do	do	Very little			
53	Weak	do	Weak	None			
54	do	do	do	Few particles			
55	do	do	do	25%			
56	do	do	do	25%			
57				100%			
58	Weak	None	Weak	None			
59	do	do	Strong	do			
60	None	do	Moderate	Strong			
61	Weak	do	do	Small amt.—strong			
62	None	do	Small amount	Small amount			
63	do	do	do	do			
64	do	do	do	do			
65	Weak	do	Weak	Small amt.—strong			
66			Moderate	None			

* The percentages listed show the proportions of A. C. active material present.
† The blank spaces in the foregoing table indicate incomplete data.

from an intermediate metallurgical process to a temperature of 950° C. for one hour in an atmosphere of air and then in a reducing atmosphere at 500° C. for thirty minutes.

The first operation is readily conducted by placing the material, which has previously been crushed and pulverized so that it will all pass through a screen of 48 meshes to the linear inch, in a refractory container and then by exposing the ore to the air by an occasional stirring or rabbling while heating at 950° C. during a period of one hour. The heating is easily performed with an open muffle furnace but any available source of heat that produces the specified temperature with adequate exposure to air is satisfactory. The reducing roast may be performed by placing the product in a refractory boat or iron container and inserting in a heat resistant, gastight tube such as an iron pipe. A flow of hydrogen producing two or three bubbles per second at the exit end is maintained during the heating and cooling of the charge. The portion of the tube containing the material from the roast is heated so that a temperature of 500° C. is maintained for thirty minutes in the environment of the charge. Easiest control of heat is obtained by using an electric resistance heating unit, but the same result is accomplished in other ways. After cooling in the reducing atmosphere, the chromite is rendered of high coercive force and after exposing to a strong direct magnetic field is active in a 60-cycle alternating magnetic field of 50 gauss field strength.

The chromite is then in condition to be separated by the alternating magnetic field while associated minerals, as, for example, olivine, are unaffected by such a field. In some cases we have obtained better results by using a plurality of such oxidation and reduction steps.

Example 2

Chalcopyrite is separated from ferberite by a comparatively simple treatment. The material is roasted in air at 600° C. while stirring for a period of five minutes. The cooled product is exposed to a strong direct magnetic field and then treated on an alternating field magnetic separator of 60 cycles. The chalcopyrite is active in an alternating magnetic field of 50 gauss field strength and jumps while the ferberite under these conditions of treatment is non-active.

Example 3

We have also found that by treatment of a substantially homogeneous ore to render part of it active in an alternating magnetic field, the impurities may be segregated in the active or non-active portion. For instance, an ore may be partially activated and impurities segregated into either the activated or unactivated portion. We may consider an iron ore from Negaunee, Michigan, which contains 1.6% sulphur. By giving this material a reducing roast at 400° C., 93% of the sample became active in a 60-cycle alternating magnetic field of 50 gauss field strength and contained only 1.18% sulphur. The residual 7% analyzed 4.58% sulphur.

Example 4

In another case, pyritic gold ore was subjected to roasting and subsequently separated into an active portion and a non-active portion. The non-active portion contained 1.29 oz. gold per ton and the other only .29 oz.

Example 5

We have also found that our method of producing high coercive force in minerals and the like may be applied to metallic iron by dispersing it in mercury. This may be accomplished by any of several ways known in the art. The mercury content of the mixture may be removed or reduced to any amount desired by distillation. Iron produced in this way has a coercive force above 250 and may be compacted into strong permanent magnets.

Methods for preparing iron amalgams are described in H. O. Hofman's "General Metallurgy", McGraw Hill Book Company, New York, 1913, page 510; in United States Patent No. 1,602,404 issued October 12, 1926 to Joseph C. W. Frazier; and in Kolloid Zeitschrift, vol. 52, page 31, 1930.

Example 6

The liquid iron amalgams we have also used to extract gold from ores and for this purpose they have the advantage that any finely divided mercury formed during the amalgamation may be separated from the ore by magnetic means.

Example 7

Untreated hematite is separated from silica gangue by subjecting to an alternating magnetic field of 500 gauss and a frequency of 25 cycles.

It is clear from the above that the broad conception of our invention is in the formation of a high coercive force in certain materials and converting the same into permanent magnets by exposing the small particles to a direct current magnet. Materials so prepared have a use in the arts as, for example, in forming permanent magnets by molding discrete particles, all of which are permanent magnets, into a larger magnet structure, thus securing certain obvious advantages in the manufacture of commercial permanent magnets. The magnetized particles have other uses in the arts.

According to features of our complete process, these small permanent magnets are employed in a separation process. The separation processes involved may be modified in many respects. In general, however, they involve three types of treatments resulting from three characteristics at once apparent. These are as follows:

(a) The attraction of the magnets for each other;

(b) The attraction of the magnets for a highly magnetic material such as soft iron; and

(c) The activity of the magnets in an alternating magnetic field.

We shall now consider the general types of processes utilizing these characteristics:

Example 1

We separate roasted hematite from ordinary magnetite by magnetizing the mixture and then sifting it through a screen of a mesh so that all of the material will just pass through in an unmagnetized condition. Since the hematite particles agglomerate, they form composite particles of a size to be retained on the screen, while the non-magnetized magnetite will remain in the form of small particles which will pass the screen.

Example 2

We may utilize the principle involved in Example 1 in a froth flotation process to separate permanently magnetized material from material which is not magnetized. We thus separate

hematite which can be made to agglomerate in the manner indicated from silica.

Example 3

By employing the characteristic (*b*) set out hereinabove, we may obtain a direct separation of permanent magnetic particles by passing them over a rotating soft iron pulley. The permanent magnets adhere to the surface and are removed by a scraper while the other material falls off the pulley. By such methods, we have separated sponge iron from its associated gangue obtaining products containing 9.32% insoluble and 1.25% insoluble, respectively, for the particles which will fall off the pulley or drum and those which will stick. These figures, of course, are merely illustrative and do not represent the maximum separation possible.

Example 4

According to Example 4, we separate two materials, both of which may be magnetic, but only one of which is in the form of permanent magnets, by subjecting them to the influence of an alternating magnetic field. For example, roasted hematite is separated from magnetite by depositing the same onto a moving non-metallic belt in which the axes of the pulleys are tilted horizontally to make the belt slope laterally. The slope is such that gravity is not quite sufficient to cause downward movement of the material laterally of the belt. If now the particles are subjected to an alternating magnetic field, as, for example, by placing the magnets immediately under the belt, the roasted hematite becomes active and moves down the slope laterally of the belt, while the magnetite will adhere to the belt and be deposited after passing over the pulley. This example will be further understood by a more complete reference to the use of the activity of the permanent magnets as described hereinabove.

In making use of the activity in an alternating magnetic field to separate permanently magnetic particles, we do not attempt to make the particles traverse any appreciable distance by means of this activity but superpose this activity on a system of forces in balance acting on all the particles of the mixture to be separated. Thus the particles may be held on a surface with the force of friction just greater than that of gravity. By applying an alternating field, the permanently magnetic particles are activated and their friction is decreased, hence they move away from the others under force of gravity.

A balance may be struck in this way between any two forces acting in opposite directions one of which is affected by the activity in an A. M. field. Examples of the forces affected by the A. M. field are friction, magnetic and electrical forces. These may be opposed with gravity, centrifugal force, or the force of moving water or air.

A detailed explanation of one preferred form of our invention to the separation of minerals will make the above points clear.

In this preferred method of application of our invention to the separating of minerals, the ore or mineral treated by the methods indicated is subjected to the action of a direct magnetic field and then to an alternating field of less intensity than the coercive force of the mineral so arranged that the particles which are active in that field may be separated from the non-active particles. In some cases the use of preliminary treatment with the direct magnetic field may be dispensed with and higher intensities of alternating field may be used.

In one preferred form of our invention, the minerals and the like to be separated are fed onto a non-magnetic supporting surface, the latter being inclined to the horizontal and capable of movement relative to an alternating magnetic field in such a way that the material is caused to separate into two or more fractions by virtue of the jumping motion of some of the particles under the action of an alternating magnetic field, combined with the force of gravity acting on these moving particles resulting in their jumping down the slope and across the supporting surface and thus becoming separated from the particles which are less mobile, the latter remaining substantially in their original portion on the supporting surface.

With regard to the frequency and field strength of the alternating current to be employed, we have found that in general the higher the frequency, the more rapid is the motion of the particles but the more limited is the field strength which can be used. We have found that the field strength is limited by two factors. It must be high enough to prevent the particles sticking together and still below that at which activity ceases. These limits we have called the lower and upper sticky limits. We have found that in general the lower limit increases with frequency and the upper limit decreases, so that with some minerals, no satisfactory range exists at frequencies higher than 15. Other minerals show a satisfactory field range at the highest frequencies tried (1000 cycles).

The practical carrying out of the process of our invention can be made clear from a reference to specific methods employed, all utilizing the same general principles but each requiring more or less modified apparatus.

According to one method, we utilize an endless belt passing over two pulleys whose axes are parallel to each other but inclined to the horizontal whereby the top of the belt slants laterally, but longitudinally is in substantially a horizontal plane. Associated with the surface of the belt, that is, immediately under the same or otherwise suitably positioned, we place one or more, preferably a plurality, of alternating current magnets suitably designed in accordance with the character of equipment and specific details of the process involved. A comminuted ore material, the mineral bearing portion of which is to be concentrated, is now delivered to the top of the belt so as to be conveyed substantially the full length thereof, it being assumed, of course, that the material has previously been prepared in accordance with the processes described hereinabove. If the material has not previously been magnetized, it is usually necessary to subject it to a charge of direct current magnetism as it is being delivered to the belt. In the simplest form of process, the belt constitutes a non-magnetic conveyor and is continuously operated to move the material from one end thereof to the other. As the conveyor and the material start to pass through the alternating fields created by the magnets, the portion of the material capable of accepting a permanent magnetism becomes active and jumps more or less violently, depending upon the frequency of the current, as previously set out. The active material thereby is freed from the force of friction resulting from its contact with the belt at each jumping movement and accordingly moves with considerable rapidity down the slope of the belt where it is delivered into a trough or bin. The remaining portion of the material moves along the belt and

may be discharged off the end thereof as it passes over the pulley and thence be delivered to a second bin or trough. When two or more active components are present, they may be successively subjected to stronger fields or fields modified in respects other than intensity, thereby attaining more than two constituents comprising at least two active constituents and a non-active constituent which may be a non-metallic material. It is, of course, obvious that even a very active material may be separated from a slightly active material by making only one separation, the slightly active material being allowed to pass continuously along the belt conveyor and delivered to a trough or bin in the same way that entirely inactive material would be handled.

Following a process of this kind, we have been able to heat treat a chromite ore and produce a concentrate containing approximately 65% of Cr_2O_3, a very high grade product, while previous attempts at concentrating the same ore by usual concentration methods did not produce concentrates appreciably better than 50% Cr_2O_3. Various modifications of this method may be employed and the same method may be employed with modified apparatus. The apparatus may also be modified to operate on wet material.

With regard to the alternating field system, strength and frequency of the alternating current, distances between the magnet poles and the surface supporting the material being treated, and distance from pole to pole, we have found that the most effective arrangement of the alternating field magnetic system is obtained when single phase current is used and when the magnets are wound in such a direction that adjacent poles have unlike polarity at any given time. The magnet cores should be laminated and may consist of individual cores which may be placed with their lower poles on a single iron plate, or the magnet system may be constructed from a single laminated core having multiple poles on a common base.

The slope of the conveyor surface and the speed of belt travel should be adjustable to suit the material being treated.

A demagnetizing coil may be placed between the direct current magnetizing field and the alternating current separator so that materials below any given coercive force may be demagnetized and thus rendered inactive in the A. C. field.

According to another method, a drum is employed formed of magnetic material, and the material to be separated is delivered to the drum through a suitable delivery chute. The material which has accepted a permanent magnetism will adhere to the drum, while the particles which do not constitute small individual magnets will fall off the surface of the drum and be deposited into a bin provided for the purpose. Those particles which adhere to the drum are removed therefrom by a scraper or some other suitable means in such a way as to be deposited in a separate bin.

According to another process, the material to be separated is in more or less of a pulp condition with a considerable portion of water. A metal disc revolving in an alternating magnetic field on a vertical axis is provided and the material fed to the disc near the center thereof. That portion of the material which is magnetic but of low coercive force will resist movement toward the outside of the disc, but the active and non-magnetized material, moved partly by centrifugal force and partly washed by water with which the material is associated or added water, will be moved off the periphery of the disc. At another location, the material which has adhered to the disc can be removed by subjecting it to the action of a stream of water moving at a comparatively high rate of speed. In still other separations, the comminuted material to be separated is suspended in water whereby the active material will agglomerate and can readily be separated from the non-agglomerated material, according to many different principles.

With regard to the phase relationships of the alternating current employed in connection with our invention we prefer to use a single phase current and when we have specified alternating current in the foregoing description a single phase current has been in mind. However, it is possible to employ currents having any type of phase relationship in carrying out our invention. We are familiar with apparatus described in earlier patents for the separation of magnetic materials by making use of their motion in a polyphase, moving magnetic field. We do not claim processes based on this motion except where such motion is greatly aided and augmented by the superposition of activity which is due to high coercive force and remanence of the material being treated, in which case our invention is applicable to polyphase fields and limited only by the appended claims.

With regard to the field strength to be used it will be clear that this depends upon the separation which it is desired to make and upon the previous direct current activation, if any, of the material to be treated as well as on the properties of the individual material. In this connection we have found that the relative coercive force of minerals either treated or untreated is not necessarily the same at all field strengths. Accordingly under some conditions one mineral may be active in an alternating current field and the other mineral unactive while under other conditions the reverse may be true. As an example we have found that magnetite has a higher coercive force than reduced hematite in very weak fields. Accordingly if a mixture of magnetite and reduced hematite be activated in a weak direct current field and subsequently subjected to the action of a weak alternating current field the magnetite and not the hematite will be active. In this case the fields to be employed are of the order of five gauss.

Apparatus utilizable for separating materials by the methods described hereinabove is shown in Transactions A. I. M. E., volume 112, page 534 et seq.

What we claim as new and desire to protect by Letters Patent of the United States is:

1. The method of separating minerals containing a paramagnetic substance which comprises subjecting subdivided particles thereof to a heat treatment to impart thereto a high coercive force, converting the treated mineral particles into permanent magnets, and then effecting the desired separation by an action including the subjection of the mineral particles to an alternating magnetic field the strength of which is not greater than the coercive force of the magnetized particles.

2. The method of separating minerals containing a paramagnetic substance which comprises subjecting subdivided particles thereof to a treatment to impart thereto a high coercive force, converting the treated mineral particles into permanent magnets, and then effecting the desired

separation by an action including the subjection of the mineral particles to a single phase stationary alternating magnetic field the strength of which is not greater than the coercive force of the magnetized particles.

3. The method of separating minerals containing a paramagnetic substance which comprises subjecting subdivided particles thereof to a heat treatment to impart thereto a high coercive force, converting the treated mineral particles into permanent magnets and then effecting the desired separation by an action including the subjection of the mineral particles to a single phase stationary alternating magnetic field the strength of which is not greater than the coercive force of the magnetized particles.

4. The method of separating minerals which contain iron and at least one other metal, said method comprising subjecting subdivided particles of the mineral to a treatment to impart thereto a high coercive force, converting the treated mineral particles into permanent magnets and then effecting the desired separation by an action including the subjection of the mineral particles to an alternating magnetic field the strength of which is not greater than the coercive force of the magnetized particles.

5. The method of separating different mineral particles from each other or from other particles of material with which they may be associated wherein at least one mineral has a paramagnetic constituent, comprising heat treating the mineral, in subdivided form, to impart a high coercive force to particles thereof, converting said particles into permanent magnets, and then separating the magnetized particles by subjecting the material to a magnetic separation treatment.

6. The method of separating mineral containing a paramagnetic substance particles which comprises treating them to impart high coercive force thereto and to form permanent magnets therein capable of becoming active in an alternating magnetic field, and subjecting said minerals simultaneously to alternating magnetism having a field strength not greater than the coercive force of said mineral particles, and to a force opposed thereto.

7. In the separation of mineral particles which are in the form of permanent magnets from other particles, the step comprising subjecting the mineral particles to an alternating magnetic field of an intensity not greater than the coercive force of the magnetized particles and insufficient for their demagnetization whereby a jumping action of the permanent magnet particles within the field is produced.

8. In the separation of mineral containing a paramagnetic substance particles, the process which includes the steps of preliminarily magnetizing some of the particles to form permanent magnets thereof, then subjecting the particles to an alternating magnetic field of an intensity not greater than the coercive force of the magnetized particles and insufficient for their demagnetization whereby a jumping action of the permanent magnet particles is produced within the field, and then separating the jumping particles from the stationary particles.

9. In the separation of mineral containing a paramagnetic substance particles, the process which includes the steps of converting some of the particles to a state of high magnetic coercive force, subjecting the mineral particles to a magnetizing action whereby magnetization of some of the particles to form permanent magnets is effected, subjecting the mineral particles to an alternating magnetic field of an intensity not greater than the coercive force of the magnetized particles and insufficient for their demagnetization whereby a jumping action of the permanent magnet particles within the field is produced and then separating the jumping particles from the stationary particles.

10. In the separation of mineral containing a paramagnetic substance particles, the process which includes the steps of converting some of the particles to a state of high magnetic coercive force, subjecting the particles to a magnetic field of constant polarity to form permanent magnets of the high coercive force particles, placing the particles in an alternating magnetic field of an intensity substantially less than the coercive force of said permanently magnetized particles and thereby producing a jumping motion of the permanent magnet particles within the field and then separating the jumping particles from the stationary particles.

11. A process of separating mineral containing a paramagnetic substance particles which comprises converting some of the particles to a state of high magnetic coercive force, subjecting the particles to a magnetic field of constant polarity to form permanent magnets of the high coercive force particles, placing the particles in an alternating magnetic field of an intensity substantially less than the coercive force of said permanently magnetized particles and thereby producing a jumping motion of the permanent magnet particles within the field, and then separating the jumping particles from the stationary particles by subjecting the mixture to the opposing action of gravity and friction so balanced that the frictional force will predominate on the stationary particles and gravity on the jumping particles.

12. The process described in claim 7 including the step of separating the jumping particles from the stationary particles by superposing the jumping motion upon a system of forces which are in balance, at least one of said forces being affected by the jumping motion whereby separation is effected.

13. The process described in claim 8 wherein the separation of the jumping particles from the stationary particles is effected by superposing the jumping motion upon a system of forces which are in balance, at least one of said forces being affected by the jumping motion whereby separation is effected.

14. The process described in claim 9 wherein the separation of the jumping particles from the stationary particles is effected by superposing the jumping motion upon a system of forces which are in balance, at least one of said forces being affected by the jumping motion whereby separation is effected.

15. The process described in claim 10 wherein the separation of the jumping particles from the stationary particles is effected by superposing the jumping motion upon a system of forces which are in balance, at least one of said forces being affected by the jumping motion whereby separation is effected.

16. The process of treating a copper ore containing a substance susceptible to magnetization which comprises subjecting the ore in particle form to an oxidizing roast whereby a high coercive force is imparted thereto, converting the particles into permanent magnets, and then subjecting the mixture of particles to the action of

an alternating magnetic field the strength of which is not greater than the coercive force of said magnetized material whereby separation of the materials is effected.

17. The process of separation of minerals or other substances possessing different magnetic properties which includes causing comminuted material containing minerals possessing high coercive force and which are in the form of permanent magnets to pass onto a non-magnetic supporting surface, and subjecting said material to the action of an alternating magnetic field having a strength not greater than the coercive force of the magnetized mineral particles, the supporting surface being inclined to the horizontal at an angle less than that at which inert material moves down the slope and capable of movement relative to said alternating magnetic field in such a way that the material is caused to separate into fractions by virtue of the jumping motion of certain particles caused by the action of the alternating magnetic field combined with the force of gravity acting on these moving particles resulting in their jumping down the slope and across the supporting surface and thus becoming separated from those particles which are less mobile.

18. The method of separating mineral particles which have high coercive force and are in the form of permanent magnets which comprises superposing their activity in a single phase alternating magnetic field, having a strength not greater than the coercive force of the magnetized mineral particles, on a system of forces in balance whereby one of said forces is unbalanced by the activity of magnetized particles in the alternating magnetic field, the unbalancing of the forces serving to effect a separation of the mineral particles.

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