Transaction Paper

A basic triboelectric series for heavy minerals from inductive electrostatic separation behaviour

by D.N. Ferguson*

Synopsis

The separation of certain minerals by electrostatic techniques can be difficult due to their similar electrical conductivity, and any technique to improve this can be useful in certain difficult separation applications. Triboelectric differences between minerals can result in certain minerals acquiring small positive or negative charges prior to inductive electrostatic separation. By changing the polarity of inductive separation, relative changes in mineral recovery can be observed, which may be beneficial. In this brief study a JKTech mineral liberation analyser (MLA) was used to evaluate the effect of polarity change on selected minerals present in the Richards Bay Minerals deposit, and an approximate triboelectric series based on this behaviour is presented.

Introduction

Electrostatic separation is used in many heavy mineral sand operations for the separation of minerals, particularly where other separation means (density, size, magnetic susceptibility) are less effective due to close similarity in such properties, as is experienced with minerals such as rutile and zircon.

Electrostatic separation is achieved by exploiting differences in mineral conductivity giving rise to differences in particle charging and discharging rates. By the appropriate design of equipment an efficient separation can be accomplished. A good review of the fundamentals relating to electrostatic separation is given by Manouchehri *et al.*[1]

There are three major mechanisms for particle charging in commercial electrostatic separators: corona or ion-bombardment charging, inductive charging, and triboelectric charging to a lesser extent. In practice, inductive separation techniques experience some triboelectric charging effects as the overall induced charge level is generally lower than that of corona charging; the frictional effects between particles and the separator surface are therefore more significant.

Triboelectric charging is a complex process caused by the frictional contact between dissimilar materials with differing filled electron levels.[1–2] In simple terms this results in a flow of electrons to equalize electron levels across the two materials while in contact. When the surfaces are separated the charge may be retained by the two materials, with the net result that one material retains a negative charge while the other a positive charge. The extent of charging is dependent on many factors, including the speed and pressure of the contact, ambient conditions, as well as surface contamination such as coatings.

The effect of triboelectric charging during inductive electrostatic separation can be determined by changing the polarity of the induced field and comparing mineral recoveries under both polarity regimes.

The objective of this work was to use this method to better understand the triboelectric behaviour of minerals in the Richards Bay Minerals (RBM) deposit, with the potential that this information could lead to improved electrostatic separations.

Experimental

Two identical splits of 1 000 g each of a dry mill feed sample (55% zircon, 25% rutile) were prepared for separation in a Reichert Mk III electrostatic screen plate (ESP) separator under positive and negative plate polarity at a voltage of 32 kV with a 55 mm electrode gap (minimum point).

* *Richards Bay Minerals, Richards Bay, South Africa.*

 This paper was first published at the SAIMM Conference, Heavy Minerals, 20–23 September 2009.

The ESP, as shown in Figure 1, takes its name from the use of a screen extending from under the plate. Charging occurs in the plate region while non-conductors fall unaffected through the screen, whereas charged conductors are lifted over into the conductor tray.

The screen opening area and feed velocity settings (i.e. feed discharge height) were maximized to the fullest extent offered by the equipment. All other conditions were kept as identical as possible for the two separations.

The separation procedure followed entailed heating the samples in a laboratory-scale fluid-bed heater to 120°C before being introduced into the ESP at feed rate of 1.8 tph/metre. The non-conductors were re-treated as feed a further three times after which they were reheated, again to 120°C. This procedure was repeated every four stages to achieve an effective total of 12 stages of separation for the two samples (positive and negative).

The multiple stage approach was taken to accentuate recovery differences between conductors and non-conductors, as an individual stage of separation is somewhat inefficient. This is apparent in that typical production-scale versions of the equipment combine 5 stages into a single unit. For comparison, a four stage result was also tested and is included for comparison using similar feed stock.

The final conductor and non-conductor samples were analysed by a JKTech mineral liberation analyser (MLA) to quantify the basic mineralogy of each fraction.

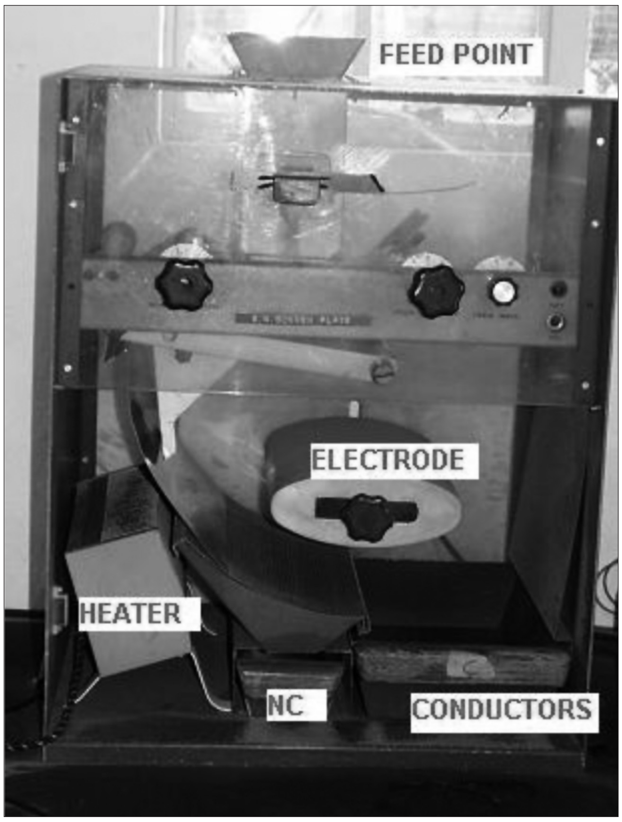

Figure 1—Laboratory-scale electrostatic screen plate separator (ESP)

Results

The recovery of each mineral to the conductor fractions was calculated and tabulated in Table I. In this table, the average recovery between negative and positive polarity has been used to order the minerals into a conductivity series, from least conductive to most conductive. It must be noted that sizing, inclusions and coatings have a significant effect on these apparent conductivities. For example, quartz in this sample is generally finer sized with some quartz present as inclusions in rutile, increasing the apparent conductivity of quartz. For this reason results should be seen as specific to this feed sample, although results may still provide a guide to the behaviour of pure mineral grains.

To give an estimate of the triboelectric effects, the difference between positive and negative conductor recoveries was calculated and then used to order the sequence, and this is shown in Table II. This data presentation gives a simulation of an electrostatic triboelectric series for common minerals in the RBM dry mill feed, much along the lines of the general purpose triboelectric series given in educational textbooks, for example describing the likely charging effect of rubbing fur on Perspex. These tables are useful in giving an indication of which material is likely to acquire positive or negative charge relative to another.

In Table III, a similar ordering of results from the four stage separation is presented, with arrows showing how the individual minerals positions compare to the 12 stage results.

Table I

Recovery of mineral to conductors under negative and positive electrode polarity

Recovery to conductors (%)	Electrode polarity		
	Negative	Positive	Average
Zircon	5.4	25.8	15.6
Aluminosilicates	4.4	28.0	16.2
Tremolite	6.9	28.2	17.5
Actinolite	5.3	31.3	18.3
Pyroxene	6.6	36.2	21.4
Garnet	20.2	25.3	22.8
Tourmaline	15.2	40.0	27.6
Staurolite	24.7	31.3	28.0
Epidote	19.5	40.4	29.9
Hydrous silicates	19.8	42.3	31.0
Monazite	50.6	12.2	31.4
Feldspar	18.4	61.4	39.9
Titanite	36.2	75.3	55.8
Apatite	92.4	22.4	57.4
Quartz	24.4	91.2	57.8
Carbonates	90.5	50.2	70.3
Goethite	78.1	92.4	85.3
Altered Ilmenite	84.6	97.9	91.3
Magnetite/haematite	93.4	96.6	95.0
Spinels	96.2	99.5	97.8
Rutile	97.3	99.3	98.3
Leucoxene	97.4	99.7	98.6
Titanomagnetite	98.4	98.8	98.6
Ilmenite	98.8	99.6	99.2

Discussion

The difference between positive and negative voltage plate separations illustrates that triboelectric charging effects

Table II

Apparent triboelectric series for selected minerals based on inductive separation

Mineral name	Recovery difference (%)	Charge acquired (apparent)	Comment
Apatite	-70.0	+++++++	Strong positive
Carbonates	-40.2	++++	Moderate positive
Monazite	-38.4	++++	Moderate positive
Titanomagnetite	0.4	.	Neutral
Ilmenite	0.8	.	Neutral
Rutile	2.0	.	Neutral
Leucoxene	2.4	.	Neutral
Magnetite/haematite	3.2	.	Neutral
Spinels	3.4	.	Neutral
Garnet	5.1	.	Neutral
Staurolite	6.6	.	Neutral
Altered ilmenite	13.3	-	V. weak negative
Goethite	14.4	-	V. weak negative
Zircon	20.4	--	Weak negative
Epidote	20.9	--	Weak negative
Tremolite	21.3	--	Weak negative
Hydrous silicates	22.5	--	Weak negative
Aluminosilicates	23.6	--	Weak negative
Tourmaline	24.8	--	Weak negative
Actinolite	26.0	--	Weak negative
Pyroxene	29.7	---	Weak negative
Titanite	39.1	----	Moderate negative
Feldspar	43.0	----	Moderate negative
Quartz	66.8	-------	Strong negative

Table III

Comparison of differences—effect of number of stages

Mineral	Difference
Carbonates	-66.0
Apatite	-54.5
Goethite	-13.3
Monazite	-3.4
Altered Ilm.	-2.4
Titanomagn.	0.0
Ilmenites	2.2
Rutiles	4.7
Garnet	5.8
Aluminosilicates	10.0
Epidote	10.7
Kaolinite	11.4
Leucoxene	12.4
Staurolite	12.6
Feldspar	16.7
Spinels***	17.1
Amphiboles**	18.9
Zircons	19.0
Pyroxene	19.5
Tourmaline	23.5
Titanite	24.5
Quartz	49.7

Mineral	Difference	Acquires
Apatite	-70.0	+++++++
Carbonates	-40.2	++++
Monazite	-38.4	++++
Titanomagn.	0.4	
Ilmenite	0.8	
Rutile	2.0	
Leucoxene	2.4	
Magnetite/haem.	3.2	
Spinels	3.4	
Garnet	5.1	
Staurolite	6.6	
Altered Ilmenite	13.3	-
Goethite	14.4	-
Zircon	20.4	--
Epidote	20.9	--
Tremolite	21.3	--
Hydrous silicates	22.5	--
Aluminosilicates	23.6	--
Tourmaline	24.8	--
Actinolite	26.0	--
Pyroxene	29.7	---
Titanite	39.1	----
Feldspar	43.0	----
Quartz	66.8	-------

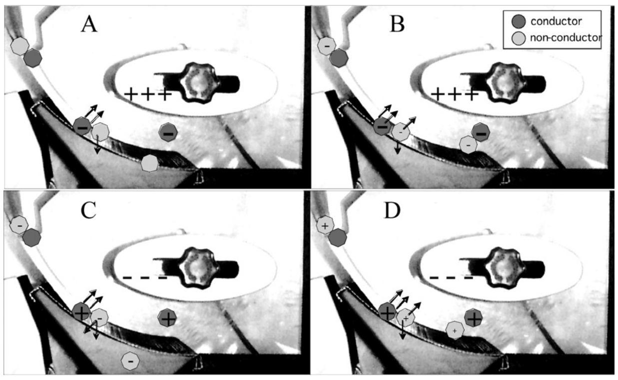

Figure 2. Tribocharge and polarity scenarios. (A) No tribocharge effects give a normal inductive separation; in figures (B) and (D) initial tribocharge increases the apparent conductivity of the non-conductor giving a poorer separation; finally in (C), the initial tribocharge works synergistically with the field polarity in pinning the non-conductor and assisting it to fall through the screen into the non-conductor tray

appear to significantly modify the apparent conductivity of certain minerals under inductive electrostatic separation. The most remarkable effects were seen in apatite, monazite, carbonates (e.g. calcite), feldspar, titanite and quartz. Depending on the polarity chosen, these effects can either enhance or lessen inductive separation and should be considered when conducting inductive separations. Some scenarios are shown conceptually in Figure 2.

As expected, the 12 stage results (Table II) show more significant triboelectric effects than the 4 stage tests (Table III). Despite the smaller differences in conductivity, the triboelectric series is broadly the same and is supportive of this method showing triboelectric differences even after only 4 stages. The 12 stage results are thought to give a better indication of triboelectric differences as minerals with higher conductivities (eg. rutile) are recovered nearly completely to conductors after 12 stages (> 97%) but only partially (70–75%) after 4, allowing differences between non-conductors to be more easily determined.

It is also worth noting that conductive minerals (e.g. ilmenite, rutile, spinel, titanomagnetite, magnetite/haematite) show very little apparent triboelectric effect and this is probably due to faster discharge of the static (i.e. tribo) charge and a more pronounced effect of the induced charge in the presence of the electrical field. Accordingly this technique may be less accurate for determining triboelectric position for very conductive minerals.

It is speculated that the majority of tribocharging that occurs is due to contact with the steel surfaces as mineral slides down the internal chutes of the separator, although interparticle interactions may also contribute some charging. Therefore modification of the internal chute surfaces may provide an opportunity to enhance or reduce tribocharging effects, depending if they are harmful or helpful to the separation being conducted. Tribocharging devices using appropriate surface materials ahead of the separator could also be used to enhance these effects.

Some equipment manufacturers market pure triboelectric separators, such as Outotec's T-Stat separator. Where minerals have very similar conductivities but significant triboelectric differences, such separators may be more effective than the combination of inductive and triboelectric effects. Table II may give some suggestion of candidate mineral separations worthy of testing in this regard. Outotec[4] highlights the particular case of feldspar/quartz separation and this supported by Table II, where the triboelectric series suggests quartz should acquire a negative charge and feldspar a positive charge if contacted together in a tribocharging device.

Data for the positive and negative polarity separation of various other minerals are tabulated by Fraas.[3] This data have been ordered in a similar way for comparison with Table II and are presented in Table IV. This suggests some general agreement with the results shown in Table II, with some exceptions, such as titanite (sphene). The differences are probably attributable to fewer separation stages, mineral sizing, chemistry, degree of liberation, and coating differences, and some minerals may have a wider range of conductivities that may overlap with others. Minerals common to the two tables are indicated in bold type.

The implications of the triboelectric effect for heavy mineral operations is particularly evident in the behaviour of monazite and quartz, both of which are undesirable zircon contaminants. Assuming a zircon circuit design with similar equipment, stages and feed as used in this experiment, the choice of negative polarity would result in nearly a sevenfold higher residual quartz level in the zircon product but with only 44% of the monazite associated with a positive polarity design. This has implications for the design of upstream and downstream circuitry—for example, more or fewer downstream magnetic stages or higher or lower recovery on upstream gravity separation to achieve desired quartz levels in final product.

For existing equipment, polarity change is probably the only change that can be made to exploit this effect cost-effectively, although it will still come at some cost to procure modifications to HT supply units, if not prefitted with selectable polarity.

Table IV

Apparent triboelectric series for other minerals based on the data of Fraas[3]

Mineral name	Recovery difference (%)	Comment (acquired charge)
Siderite	-46	Most positive
Olivine	-15	
Andradite	-14	
Apatite	-13	
Nepheline	-12	
Magnesite	-9	
Allanite	-8	
Staurolite	-7	
Beryl	-4	
Grossularite	-3	
Eudialyte	3	
Sphene	6	
Stilbite	6	
Netafite	8	
Diopside	11	
Cyrtolite	14	
Hornblende	14	
Monazite	16	
Chromite (Spinel)	19	
Euxenite	23	
Scheelite	24	
Microcline	28	
Albite	33	
Quartz	39	
Rhodolite	39	
Actinolite	45	
Hexagonite	47	
Glauconite	78	Most negative

Conclusions

Triboelectric charging can have a significant effect on the relative recovery of minerals under inductive separation and should be considered when performing inductive electrostatic separations. This knowledge can be used to improve separation effectiveness or suggest where pure triboelectric separation may be worth considering. A triboelectric series based on the behaviour under inductive electrostatic separation is presented.

Further research into testing different equipment surface materials is recommended as there may exist opportunity to improve certain separations by such modifications.

References

1. Manouchehri, H.R., Rao, K.H., and Forssberg, K.S.E. Review of electrical separation methods. Part 1: Fundamental aspects. *Minerals and Metallurgical Processing*, vol. 17 no. 1, February 2000.
2. Kelly, E.G. and Spottiswood, D.J. The theory of electrostatic separation: A review, Part II: Particle Charging, *Minerals Engineering*, vol. 2, no. 2, 1989. pp. 200–202.
3. Fraas, F. Electrostatic Separation of Granular Materials, U.S. Bureau of Mines, vol. 603, 1962. p. 82.
4. Sadowski, J., Sherrell, I., and Dobbins, M. Outotec Physical Separation Technology External Newsletter, Issue 2, December 2008. ◆