Principles of Spiral Gravity Classification

by David Kirk

INTRODUCTION

Gravity separation of shot particles is of fundamental importance for peening. From a commercial viewpoint it is the basis of several methods for separating acceptable from unacceptable shot shapes i.e. classification. The commonest such method is probably spiral gravity separation. This method has a long and successful history and is used in a number of industries on a variety of particle types.

In use, shot particles can either fracture or wear. Fracture is the primary cause of a particle adopting an unacceptable shape. Wear, on the other hand, tends to improve the shape of particles – conditioning of cut steel wire being a classic example. The primary objective, therefore, is to separate broken particles from unbroken particles.

The fundamental principles of spiral gravity separation are analyzed in this paper. Fig.1 illustrates the essence of the situation. A sphere placed on a downward slope gains a rolling forward velocity. The downward slope is also inclined towards the central axis so that an inward force, F_{INWARD}, acts on the rolling particle.

This gravitational force increases with the slope angle, β. An opposing outward centrifugal force, $F_{OUTWARD}$, acts on the sphere. The centrifugal force increases with the square of the forward rolling velocity. If the outward force is greater than the inward force then the sphere will move outwards on the path shown. The dotted line indicates a constant track of radius R which would be followed *if* the two forces remained equal to one another.

This article analyses the geometrical and physical features of spiral gravity separation. Several simplifying assumptions are used in order to keep the applied mathematics at a digestible level. The motion of even a single particle pulled by gravity down a spiral slope is difficult to analyze, especially if the particle can have an arbitrary shape. Friction and energy losses further complicate the picture. Millions of particles are involved during spiral gravity separation. The analysis presented here does, however, allow quantitative assessments to be made of the classification process.

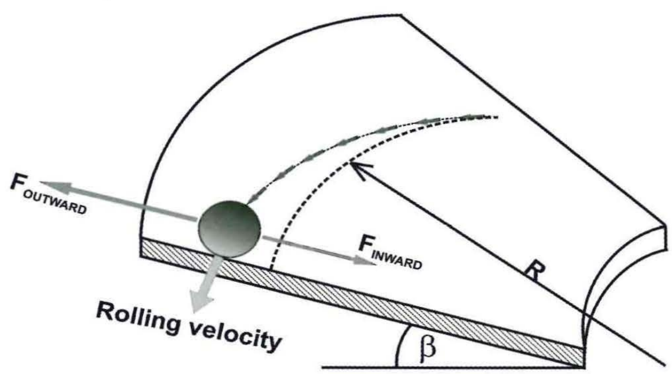
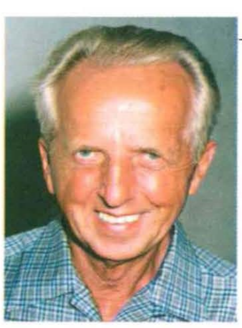


Fig.1 Section of spiral gravity separator showing major force elements.



Dr. David Kirk, our "Shot Peening Academic", is a regular contributor to The Shot Peener. Since his retirement, Dr. Kirk has been an Honorary Research Fellow at Coventry University, U.K. and is now a member of their Faculty of Engineering and Computing. We greatly appreciate his contribution to our publication.

GRAVITATIONAL ACCELERATION DOWN A FLAT SLOPE

Spherical and near-spherical shot particles will roll down a steep slope at an increasing velocity under the action of gravity. Particles that can be classed as being unacceptable will tumble down a slope and can achieve a substantial forward velocity.

(a) Rolling

Fig.2 is an illustration of a sphere which generates increasing forward and rotational velocities as it rolls down a steep slope whose angle is α. The acceleration, **a**, is related to gravitational acceleration, **g**, by the relationship that:

$$\mathbf{a = S.g.\sin\alpha} \qquad (1)$$

where **S** is the shape factor for the rolling body, having a value of 5/7 for a perfect sphere and having lower values for any other shape.

2/7 corresponds to the fraction required to generate rotational energy.

The particle's forward velocity, **v**, increases with the distance travelled, **s**, under constant acceleration. For a particle starting at rest the governing equation is that:

$$\mathbf{v^2 = 2.a.s} \qquad (2)$$

Substituting the value of **a** from equation (1) into (2) yields the important equation:

$$\mathbf{v^2 = 2.S.g.\sin\alpha.s} \qquad (3)$$

The time, **t**, that a sphere takes to roll a given distance is given by:

$$\mathbf{t = 2s/v} \qquad (4)$$

(b) Tumbling

Tumbling motion depends on the precise shape of the particle, slope angle and on interaction with other particles. Stationary particles on a slope will be struck by another descending particles causing

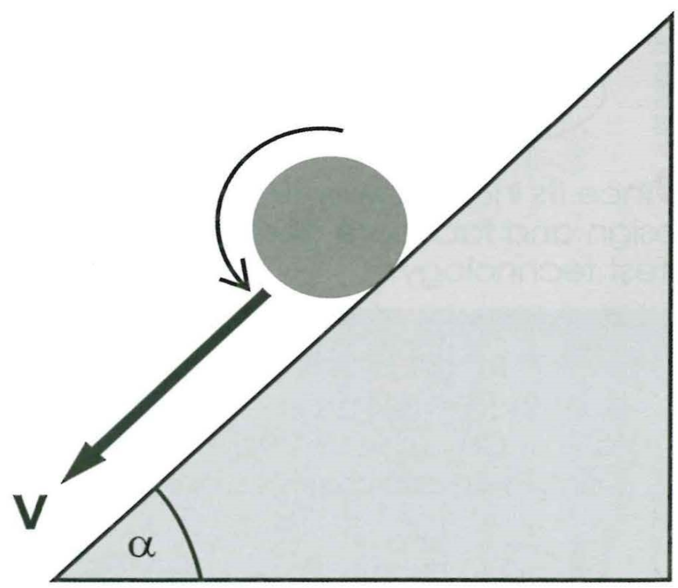


Fig.2 Sphere generating forward and rotational velocities.

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them to make further progression. All this makes the dynamics of the motion fiendishly complicated. Simple experiments can, however, determine the important characteristic features of tumbling motion. Consider, for example, a wooden plank inclined at predetermined angles (by leaning against a wall) together with a miscellaneous collection of irregular shapes. With the plank inclined at an angle of 45° every shape tumbles down the slope with increasing velocity. At an inclination of 20° none of the irregular shapes will move at all. For each shape there is a critical angle ("Angle of Repose") above which tumbling will be initiated. A slightly more complicated experiment involves a hard plastic sheet supported along one edge. The weight and flexibility of the thin sheet yields a slope of decreasing angle – as shown in fig.3.

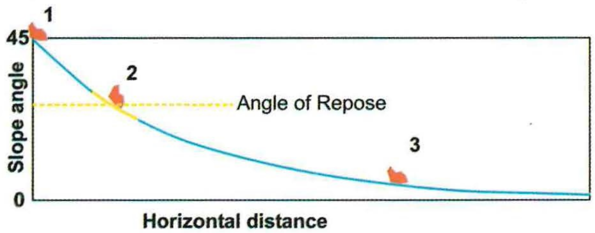

Fig.3 Irregular shape at various positions on a slope of decreasing angle.

An irregularly-shaped particle placed at position 1 will always tumble down the slope, *but will slow down at low angles* and come to rest at some position such as 3. Position 3 increases with increase in the size of the irregular particle – for a given shape. This effect is equivalent to the well-known general observation that 'larger rocks fall further than smaller rocks'. When initially placed at position 2, however, the particle remains stationary – the corresponding angle generally being called the "angle of repose".

GEOMETRY OF SPIRAL SEPARATORS

Fig.4 illustrates the magnitude of the problem that has to be addressed when considering the geometry of industrial spiral gravity separators. The characteristic features are a steep downward slope where the helix is attached to a central vertical column and a much shallower slope at the edge of the helix. For the separator shown, there are five concentric 'left-handed' helix slopes which are fed with shot independently.

One effective way of gaining a quantitative insight into spiral separator geometry is to consider the construction of a simple model separator. All that is needed is a cardboard disc, with a hole, glue and a vertical tube. Fig.5 shows the required shape of the disc.

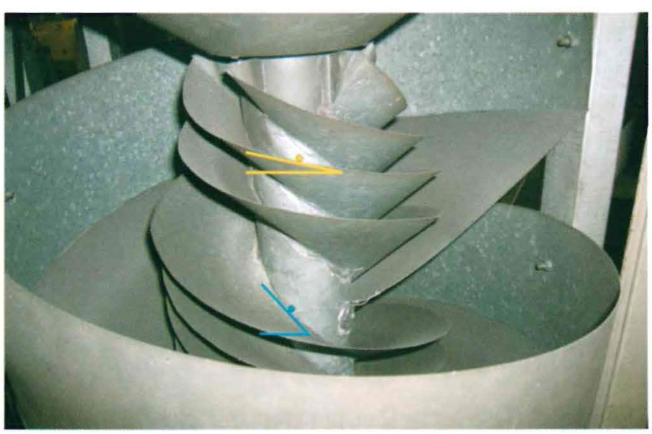

Fig.4 Photograph showing steep inner and shallow outer slopes of a spiral gravity separator.

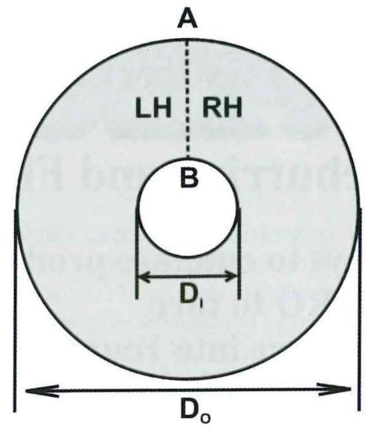

Fig.5 Disc element of simple spiral separator with cut to be made along AB.

Having made the cut along AB if we lift up the right-hand edge relative to the left-hand edge we have generated a 'right-handed' helix. The term 'right-handed' comes from the similarity with a screw that progresses inwards if turned clockwise by a right-handed person. Conversely lifting up the left-hand edge generates a 'left-handed' helix. As we continue to displace the edges the inner diameter, D_I, decreases until it grips a vertical tube of diameter D along a helical path, see fig.6. The cardboard helix can then be glued in position to complete the model.

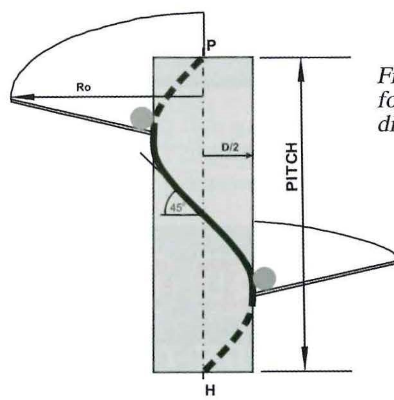

Fig.6 Left-handed helix formed around a cylinder of diameter, D.

Quantification of the parameters involved in spiral separator geometry only requires the application of basic mathematics. The helical path, P-H, shown in fig.6 is the hypotenuse of a right-angled triangle, see fig.7. $AB^2 = AC^2 + BC^2$. If the required slope angle α is to be 45° then the pitch has to be equal to the cylinder circumference i.e. AC = BC, so that $AB = AC\sqrt{2}$. Now the helical path length is the circumference of the hole shown in fig.5. Hence, for a 45° inner slope (see fig.4, blue angle), D_I is given by $D\sqrt{2}$ where D is the diameter of the supporting cylinder shown in fig.6. The circumference $BC = \pi.D$ so that the pitch is then also $\pi.D$ and the helical path length is $\pi.\ D\sqrt{2}$.

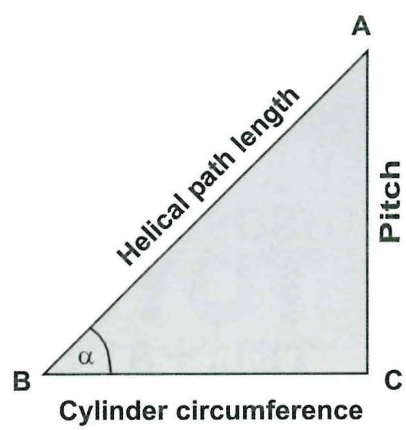

Fig.7 Helical path as the hypotenuse of triangle formed by required pitch and cylinder circumference.

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The outer edge of the sheet forms another helix with the much longer path length of $\pi.D_O$ (see fig.5). This helix has a slope that depends on the magnitude of D_O and the pitch. As an example if the cylinder diameter is 100mm, the formed spiral diameter is 500mm and a 45° inner slope is involved then the downward slope of the outer edge would be 11.3° (see fig.4, yellow angle). The formed spiral would also slope inwards towards the supporting cylinder. This is the important angle β of fig.1 and is given by:

$$\tan\beta = \frac{\pi.D_1}{2(D_2-D_1)} \quad (5)$$

where D_1 is the cylinder diameter and D_2 is the formed helix diameter.

For the previous example of D_1 = 100mm and D_2 = 500mm then β = 21.4°.

Commercial separators usually have an added geometrical feature – a steady increase in the radius, r, of the formed helix – without affecting the steep downward slope adjacent to the supporting cylinder. The shape of the blanked-out sheet elements is then as shown in fig.8.

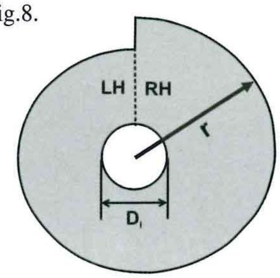

Fig.8 Variable radius, r, of helix element.

INWARD AND OUTWARD FORCES ON ROLLING SHOT PARTICLES

(a) Inward force

The inward force on a downward rolling shot particle is *constant* for a given inward slope angle,β. This force is called a "centripetal force" (because it acts inwards). Since force is equal to mass multiplied by acceleration we have that the centripetal force, C_P, is given by:

$$C_P = \text{mass}.g.\sin\beta \quad (6)$$

A steep inward angle, β is maintained for the first revolution of the helix spiral (see fig.4) in order to constrain the downward path of all shot particles to be around the centre cylinder. Thereafter the outer diameter of the spiral D_2 increases which decreases the value of β.

(b) Outward force

As rolling particles progress in a circular path around the central cylinder (as well as progressing downwards) they become subject to an outward centrifugal force, C_F. The corresponding outward acceleration is equal to $\mathbf{v^2/r}$, where **v** is the particle's forward velocity and **r** is the radius of the circular path. Rolling particles increase their velocity as they travel down the helix becoming subject to a rapidly increasing outwards force since:

$$C_F = \text{mass}.\ v^2/r \quad (7)$$

(c) Net outward acceleration of rolling shot particles

Fig.9 indicates the opposing forces acting relative to a steep helix surface. The net force determines whether the particle will move outwards or whether it will move inwards. C_F acts perpendicular to the cylinder axis so that it has to be resolved along the surface in order to directly oppose C_P. The net force on the particle is therefore $\mathbf{C_F.\cos\beta - C_P}$. For large values of β the net force tends to be inwards.

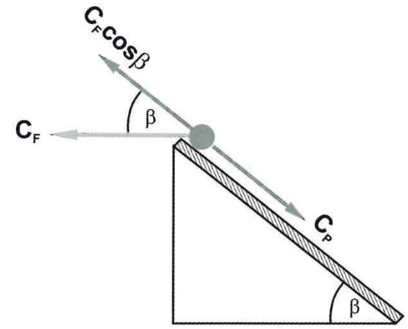

Fig.9 Radial forces acting on descending spherical particle.

The particle mass is the same for both forces. Hence, using equations (6) and (7), the net acceleration, $\mathbf{a_{net}}$, becomes:

$$a_{net} = \cos\beta.v^2/r - g.\sin\beta \quad (8)$$

The effect of net radial acceleration on a descending, rolling, shot particle is illustrated in fig.10.

A particle on 'section 1' is subject to a large inward acceleration (shown as a red vector arrow) so that it is pressing against the support cylinder. As the particle generates downward velocity the consequential centrifugal force reduces the inward acceleration component so that when it reaches section 4 there is zero radial acceleration. Thereafter the net acceleration is outwards so that the particle moves further and further away from the support cylinder. At section 7 it has moved over the edge and is collected separately (from 'reject' particles).

TUMBLING REJECT PARTICLES

Particles that are destined to be rejected also generate substantial downward velocity. This, in turn, induces a centrifugal force. The crucial difference is that the downward acceleration is *rapidly* reduced to zero – because outward radial movement reduces the downward slope for the particle. As a consequence, irregular particles do not generate sufficient velocity, and therefore net radial acceleration, to move them outwards and over the edge of a helix. Hence, these ' reject' particles can be collected separately at the bottom of each helical slope.

As noted previously, large irregular particles tumble faster than small irregular particles. This characteristic is accommodated in commercial separators by using larger diameter helixes for larger grades of shot. With larger diameters the average 'β angle' is reduced and radial travel distances increased, providing greater obstacles for outward-moving, larger, irregular particles.

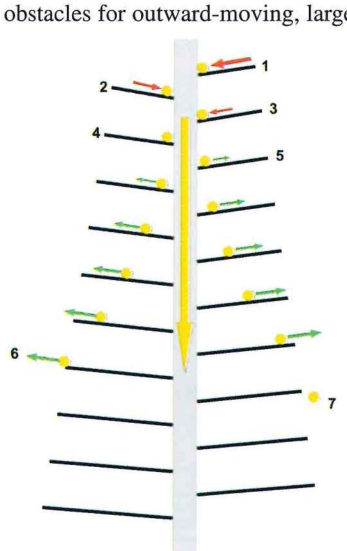

Fig.10 Schematic 'tree' of helix sections showing outward movement of a descending spherical shot particle.

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INPUT AND OUTPUTS

Controlled input of shot at the top of a spiral classifier is essential for its effective operation. Each spiral can only accept a very low rate of shot input. Fig.11 indicates one commercial solution to this problem. Shot is fed via a simple gate valve onto a cone which distributes the flow to five separate spirals. Alternative solutions are to employ a Magnavalve®, rather than a gate valve, to accurately control the shot flow or to use a vibrating inclined feed spout.

Fig.11 Cone distribution of shot to five separate spirals.

The output from the spiral separator consists of separate streams of acceptable and rejected shot particles. Fig.12 shows an example of output separation for a commercial unit.

Fig.12 Segregation of acceptable and rejected shot fractions.