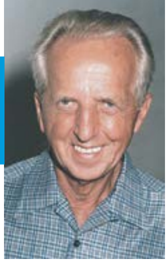

ACADEMIC STUDY
Dr. David Kirk | Coventry University

Back to Basics: Shot Velocity

INTRODUCTION

The aim of this mini-series is to cover the basic scientific principles of shot peening. Fundamental principles are presented together with relevant theoretical explanations. Shot particles themselves, together with the velocity that we give them, are the two essential factors needed to carry out shot peening. Quoting from the song made famous by Frank Sinatra: "They go together like a horse and carriage—you can't have one without the other." This synergy is also encapsulated by the formula, $\frac{1}{2}mv^2$, that represents the kinetic energy for each accelerated shot particle (m being mass and v being velocity).

Shot is accelerated to its required velocity by applying either pneumatic or mechanical force. Pneumatic acceleration is normally achieved using high-velocity air as the fluid or alternatively water. Mechanical force acceleration is normally achieved using a bladed rotating wheel. Unlike shot particles, velocity is not covered by specifications. The Almen strip test can be used to prove, indirectly, that the required velocity has been achieved.

Equations are necessary to show how shot velocity is influenced quantitatively by shot peening variables. We do not need to know how they were derived just as we can use Pythagoras' Theorem without being able to derive it.

GENERATION OF AIR-BLAST SHOT VELOCITY

The generation of air-blast shot velocity can be considered in three stages:

1 - Air stream,

2 - Introduction of shot into the air stream and

3 - Acceleration of the shot particles by the air stream.

A general equation is available that can be used to predict shot velocity based on the effects of shot size and density together with nozzle air pressure and nozzle length.

1 - AIR STREAM

1.1 Compressed air

Our primary need is to have an adequate supply of compressed air. The outlet from an air compressor goes into a ballast tank and thence to an air supply pipe, preferably via a drying unit. The compressed air flows as a stream through the pipe. This can then be connected to a shot feed and nozzle system. Ballast tanks even out pressure fluctuations from the compressor and provide a reservoir of compressed air. One or more pressure control valves, **PCV**, will be present in the air supply line. The compressed air, at a pressure, $\mathbf{p_1}$, is fed into a blast hose of length **L**, at the other end of which is a nozzle where the pressure will then be $\mathbf{p_2}$, see fig. 1. It is the nozzle pressure that is the key factor affecting induced shot velocity.

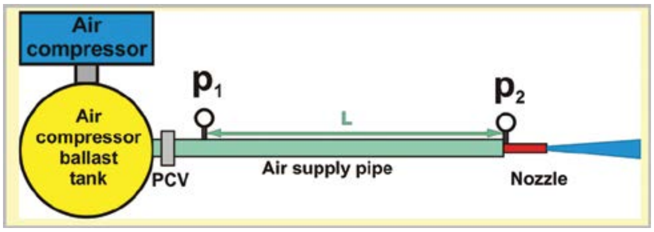

Fig. 1. Air stream generation and supply to nozzle.

Pressure gages normally indicate "relative to atmospheric" rather than "absolute" pressures. That means that without any compression we would have a gage reading of zero. The compression ratio, CR, is given by: CR = (1 + P) to 1 where P is the "relative" gage reading in atmospheres.

Air at atmospheric pressure has a density of about 1.2 kgm^{-3}. If we compress it by applying an outside additional pressure of one atmosphere (14.7 psi) we halve its volume (P = 1 so that CR = 2) and thereby double its density. At a typical applied peening pressure of seven atmospheres (100 psi) we have multiplied its density by a factor of eight to about 100 kgm^{-3} which compares with 1000 kgm^{-3} for water. Air density = CR times 1.2 kgm^{-3}. It is this "heavy air" that we force through air supply pipes. Fig. 2 (page 30) illustrates heavy air production.

We must note that the air pressure at the nozzle is not constant. The air compressor ballast tank, see fig. 1, reduces but does not eliminate the air compressor's set pressure range. Air density is a prime factor in accelerating shot particles. Compare, as an analogy, standing in a street with a wind blowing at 10 $klmh^{-1}$ with standing in a river that is also flowing at 10 $klmh^{-1}$. We would not be blown over by the wind but we would be pushed over by the water's flow.

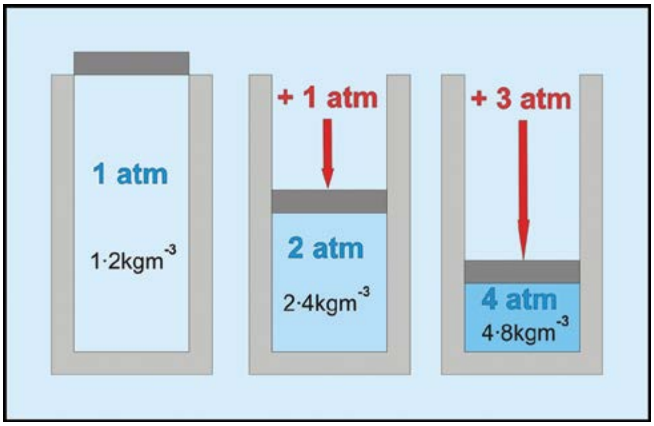

Fig. 2. "Heavy air" production by compression.

The reason lies in the relative densities of the two fluids—1.2 kgm^{-3} for air compared with 1000 kgm^{-3} for water.

1.2 Pipe flow

A useful analogy when considering pipe flow rates is that of electricity. Just as we need a potential difference between the ends of a wire for electricity to flow so we need a pressure difference between the ends of a pipe for air to flow. In fig. 1 (**$p_1 - p_2$**) represents the pressure difference between the ends of the air supply pipe. This pressure difference induces a corresponding air flow rate, **Q**, through that pipe. (**$p_1 - p_2$**) is useful as a process control parameter. Changes in (**$p_1 - p_2$**) can be either abrupt or gradual. For example, if (**$p_1 - p_2$**) = **p_1** we have a burst pipe! If (**$p_1 - p_2$**) approaches zero then the pipe has become blocked with shot at the nozzle. A common example of gradual change is that caused by nozzle wear. As the nozzle diameter increases (**$p_1 - p_2$**) increases (assuming that **p_1** is maintained at a constant value which is normal industrial practice).

It is worth noting that the pressure drop, (**$p_1 - p_2$**), also represents "wasted energy". It follows that we can save energy by reducing (**$p_1 - p_2$**). To a first approximation energy loss increases linearly with pipe length, **L**. Excessive pipe lengths should therefore be avoided. A far more important factor is the internal diameter, **D**, of the supply pipe. The pressure drop for a given flow rate is inversely proportional to **D^4** (very approximately). Doubling the pipe diameter will reduce (**$p_1 - p_2$**) by a factor of about sixteen, whereas halving the pipe's length only halves the pressure drop.

1.3 Nozzle flow

The air stream is accelerated at the nozzle. One mechanism for fluid velocity increase is very familiar. A garden hosepipe has low-velocity water flowing through it until it reaches a nozzle. If that nozzle has a cross-sectional area that is a quarter of the cross-section of the hose then the velocity of water will be increased four-fold at the nozzle. We can apply the same principle to air stream acceleration, up to a certain critical velocity—the speed of sound. Fig. 3 illustrates the basic geometry that is involved.

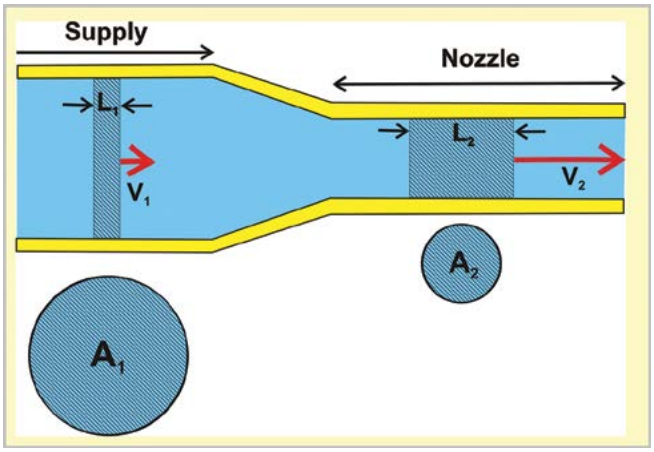

Fig. 3. Acceleration of air stream velocity by peening nozzle.

Consider an imaginary cylinder of air, as shown in fig.3, having a volume $A_1.L_1$ and travelling at a velocity v_1. When this cylinder reaches the nozzle it has the same volume (assuming no density change) but different dimensions, A_2 and L_2, and now has a velocity v_2. Now since $A_1.L_1 = A_2.L_2$ it follows that v_2 must then be A_1/A_2 times greater than v_1. In general: $\mathbf{v_2 = v_1.A_1/A_2}$.

Practical nozzle air pressures are always high enough to produce what is termed "choked flow". Fig. 4 is a simplified schematic representation of how the nozzle air velocity changes with increase of nozzle air pressure. A "sonic barrier" exists at the narrowest part of the nozzle, caused by the difference in pressure in the nozzle as compared with that in the peening unit. This barrier occurs when the air pressure difference is about 1.9 atm. Because all practical peening involves a pressure difference of more than 2 atm (29.4 psi) we have a fixed limited air velocity in the nozzle regardless

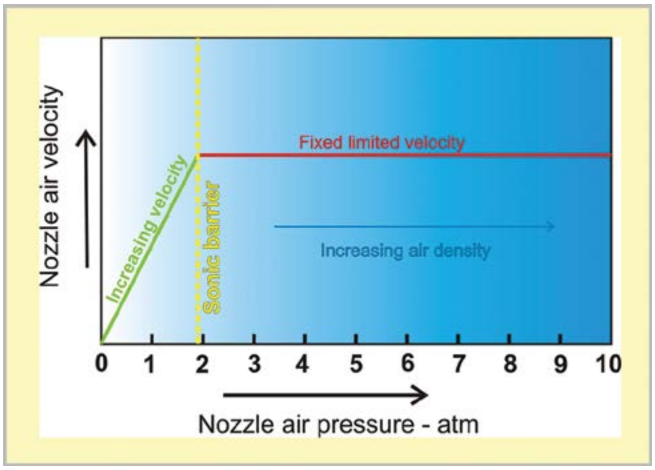

Fig. 4. Schematic representation of velocity variation with air pressure.

of nozzle pressure and nozzle diameter. This fixed limited air velocity is commonly the speed of sound but may vary slightly with nozzle design. The air velocity across the nozzle varies from a maximum of 340 $m.s^{-1}$ (speed of sound in air) to zero at the nozzle wall. An average value of 207 $m.s^{-1}$ within the nozzle reflects this variation.

The constancy of air velocity in the nozzle begs the question: "What effect does air pressure have if it does not affect air velocity?" The answer is that at higher pressures the air is more compressed so that it has a greater density but has the same velocity. Increasing the nozzle pressure increases the "mass flow" of air. Alternatively, we could say "As we increase nozzle air pressure, we are firing heavier air but at a constant velocity."

2 - INTRODUCTION OF SHOT INTO THE AIR STREAM

The three common systems for introducing shot into the air stream are suction-, gravity- and direct-feeding. These are illustrated, schematically, in fig. 5. More detail is available in a previous TSP article ("Generation of Air-blast Shot Velocity", Winter, 2007).

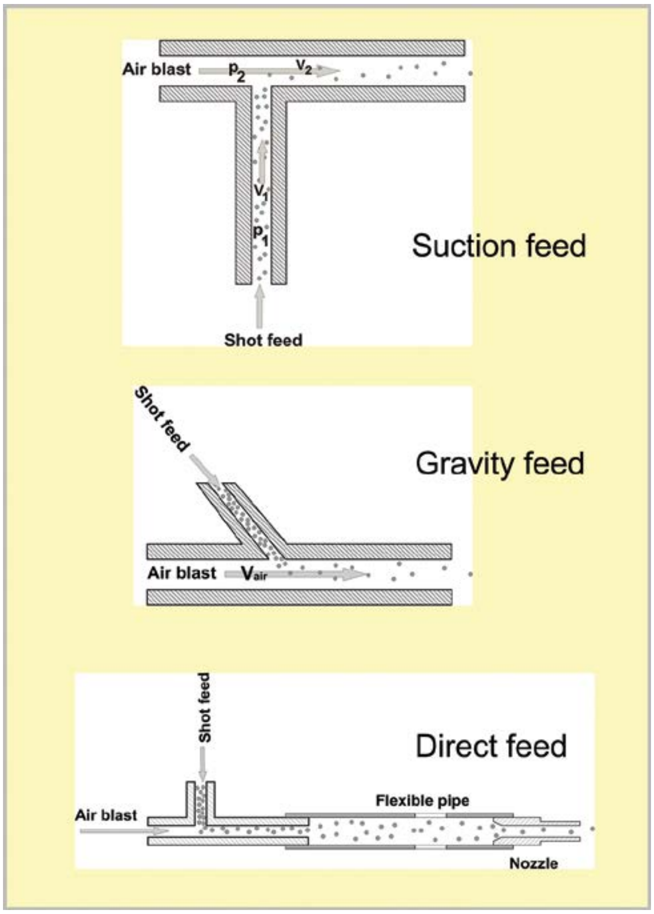

Fig. 5. Shot feed systems.

3 - ACCELERATION OF THE SHOT PARTICLES BY THE AIR STREAM.

Our fast-flowing air stream exerts a force on each shot particle that has been introduced. Acceleration occurs when we have an imbalance of forces. One form of Newton's Second Law is that "Force is equal to mass times acceleration" or:

$$\mathbf{F = m.a} \qquad (1)$$

where **F** is the magnitude of the imbalanced force, **m** is mass and **a** is the consequent acceleration in the direction of **F**.

Fig. 6 represents a model of the air/shot situation in a straight-bore nozzle. On the central axis we have the maximum air velocity. The velocity lowers as we move towards the bore surface. The average air velocity is therefore about 200 ms^{-1} (656 ft/sec) for a straight nozzle.

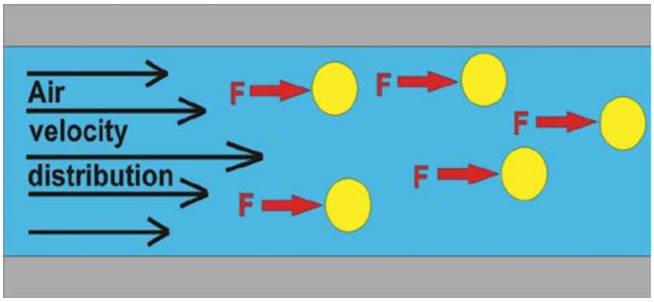

Fig. 6 Model of air/shot situation in a straight-bore nozzle.

With suction- and gravity-feed systems we have the nozzle's limited distance, **s**, in which to accelerate the particles. Direct-feed gives us much more distance in which to generate shot velocity, $\mathbf{v_s}$. The greatest acceleration will, however, occur within the nozzle (where the air velocity is by far greatest).

For nozzle acceleration we have a simple relationship between the three parameters **a**, **s** and $\mathbf{v_s}$:

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

In order to increase the velocity, we can either increase the acceleration or increase the nozzle's length, or both. Shot peening nozzles have a length of the order of 100 mm so that the acceleration has to be very high in order to produce required velocities in the region of 50 $m.s^{-1}$. Substitution of 0.100 m and 50 $m.s^{-1}$ into equation (2) gives us that the acceleration would need to be 12,500 ms^{-2} or 1,250 times normal gravitational acceleration!

An equation for shot velocity was developed and presented in a previous article ("Generation of Air-blast Shot Velocity", Winter, 2007). Fig. 7 (page 34) is an example of curves produced using that equation. Other parameters such as nozzle length, shot size and shot density can be inputted.

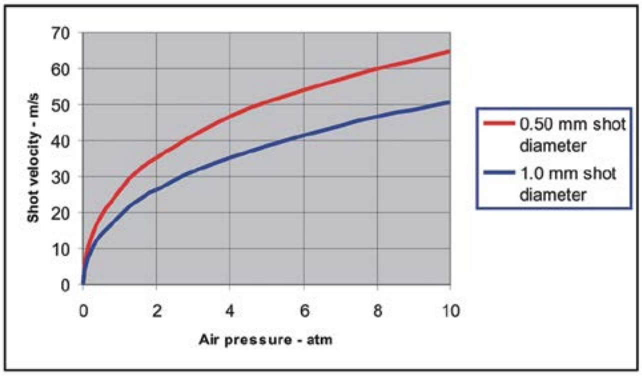

Fig. 7. Curves of nozzle-induced shot velocity versus nozzle air pressure.

GENERATION OF WHEEL-BLAST SHOT VELOCITY

The generation of wheel-blast shot velocity has many of the principles that are embodied in the Bible's story of David and Goliath as illustrated in fig.8. David accelerates a round pebble by rotating a sling. The velocity imparted depended upon the length of the sling and the speed of its rotation. Wheel-blast shot velocity depends on the length of the blades and the speed of the wheel's rotation.

Fig. 8. Image of David slaying Goliath.

Wheel-blast shot velocity is achieved in two stages: accelerator drum and throwing blades.

1 ACCELERATOR DRUM

Shot particles are fed into peripheral slots formed between the rotating accelerator and a stationary control cage. Centrifugal force keeps the particles pressed into the slots as the accelerator drum rotates. At this stage the shot particles have the rotational velocity of the drum. When a slot reaches the outlet slot in the control cage shot particles escape onto a throwing blade for the second stage of acceleration, see fig. 9.

Shot particles trapped in a slot, immediately achieve the drum's peripheral velocity. They are then being acted upon by two forces: centrifugal and gravitational. The centrifugal force, $\mathbf{F_C}$, is given by:

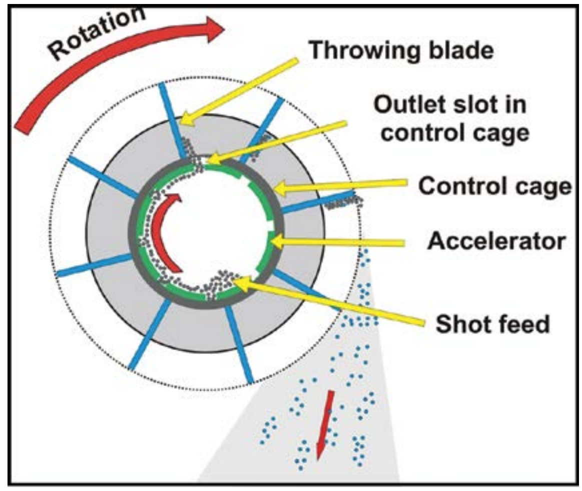

Fig. 9. Principal parts of a Wheel-blast system.

$$\mathbf{F_C = m.V_D^2/S} \qquad (3)$$

where $\mathbf{V_D}$ is the tangential velocity of the drum and $\mathbf{S}$ is the distance of the slot from the axis of drum rotation.

Gravitational force can be ignored as it is about 0.1% of the centrifugal force. We must note, however, that the shot particles are being pressed against the control cage surface with an enormous centrifugal force. They are also being scraped along that surface at high speed. This combination of high force and high speed imposes very severe wear regimes on both particles and drum surface. Finally, when the particles reach an exit slot, they burst out with an acceleration about a thousand times that of normal gravity.

2 THROWING BLADE

When a shot-filled slot reaches the outlet slot of the static control cage some of the shot particles exit onto a throwing blade carried on a rotating drum. This "cohort" of shot particles now immediately adopts the inner tangential velocity of the throwing blade. The cohort of particles is now under immense centrifugal radial acceleration, forcing it along the blade. When the particles reach the tip of the blade, they are flung off to form a shot stream. At the tip of the blade each particle being flung off will have two velocity components, $\mathbf{V_T}$ and $\mathbf{V_R}$. These are vectors which combine to give the shot particle its velocity, V_S, as illustrated in fig. 10 (page 36). $\mathbf{V_R}$ is the radial velocity induced by the centrifugal acceleration and $\mathbf{V_T}$ is the tangential velocity (which is equal to the rotational velocity of the blade tip).

Vectors are anathema to many shot peeners but they needn't be. Professional soccer players, not noted for their mathematical skills, employ vectors intuitively. Imagine one receiving a pass from a teammate. Ordinary players generally stop the ball before kicking it (hopefully to a teammate). This means that they only have to generate a single vector of speed and direction of ball travel. Star players, on the other

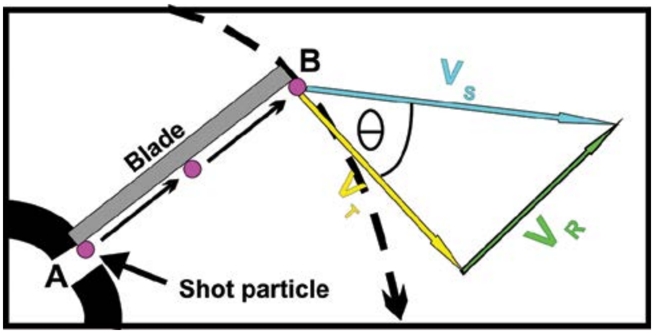

Fig. 10. Shot velocity induced by wheel blasting.

hand, employ what is termed a "one-touch pass". The received pass is not stopped but is immediately kicked. This requires two vectors to be accommodated—speed and direction of received pass and speed and direction imparted by the kick.

The values of $\mathbf{V_T}$ and $\mathbf{V_R}$ combine to form both the velocity, $\mathbf{V_S}$, and movement direction, $\boldsymbol{\theta}$, of the thrown shot particles. Tangential velocity, $\mathbf{V_T}$, is quite easy to estimate, whereas the radial velocity, $\mathbf{V_R}$, requires the application of physical principles (and some simplifying assumptions). Equations (3), (4) and (5) were presented in a previous TSP article (Spring, 2007, "Generation of Wheel-blast Shot Velocity").

$$\mathbf{V_T = 2.\pi.N.R} \qquad (3)$$

where **R** is the radius of the blade and **N** is the number of revolutions per second.

$\mathbf{2.\pi.R}$ is the circumference of the circle traced out by the tip of the blade. If, for example, the circumference was 1 m and the wheel was rotating at 50 s^{-1} then the tangential velocity would be 50 ms^{-1}.

$$\mathbf{V_R = 2.\pi.N(2RL - L^2)^{0.5}} \qquad (4)$$

where **L** is the length of the blade itself.

A combination of (3) and (4) gives us:

$$\mathbf{V_S = 2.\pi.N(R^2 + 2RL - L^2)^{0.5}} \qquad (5)$$

Equation (5) looks complicated, but can easily be employed. The radius of the wheel, **R**, and the length of the blade are fixed so that **N**, the speed of rotation, is the only variable. Hence, for example, when **R** = 0.4 m and **L** = 0.2 m, equation (5) simplifies to $\mathbf{V_S = 2.\pi.N.0.529}$ or $\mathbf{V_S = 0.324N}$.

The **direction** of $\mathbf{V_S}$, $\boldsymbol{\theta}$, is obtained by knowing that:

$$\mathbf{\tan\theta = V_R/V_T} \qquad (6)$$

For example, when $\mathbf{V_R = V_T}$, $\tan\theta = 1$, so that $\boldsymbol{\theta = 45^\circ}$. <u>If</u> $\mathbf{V_R}$ is $\mathbf{0.87V_T}$ then $\mathbf{\tan\theta = 0.87}$ so that $\boldsymbol{\theta = 41^\circ}$.

COHORT MOVEMENT

The forgoing account is based on the movement of a single particle along a rotating, open-ended blade. Each blade is slinging, however, a cohort of particles. Cohorts of particles escaping out of the aperture of the control cage have group features that are important.

Cohort <u>mass</u> is a simple function of the number of blades, speed of wheel rotation and mass thrown per second. For example: an eight-bladed wheel rotating at 50 r.p.s. throws 400 cohorts per second. If we are throwing 120 kg per minute that is 2 kg per second. Dividing 2000 g equally between 400 cohorts gives 5 g per cohort.

Cohort <u>number</u> depends on the shot size. S230 shot has an average mass of 1.48 mg per particle. Dividing 5 g by 1.48 mg gives 3380 particles per cohort.

These estimates of the mass and number and volume of each cohort allow us to envisage the shot stream generation.

Fig. 11 is a schematic representation of the several significant positions of a shot cohort. The shot particles exit onto the throwing blade at slightly different times. The time taken for the first particle to travel from the exit slot to the blade tip determines the position of the head stream and that for the last particle determines the position of the tail stream.

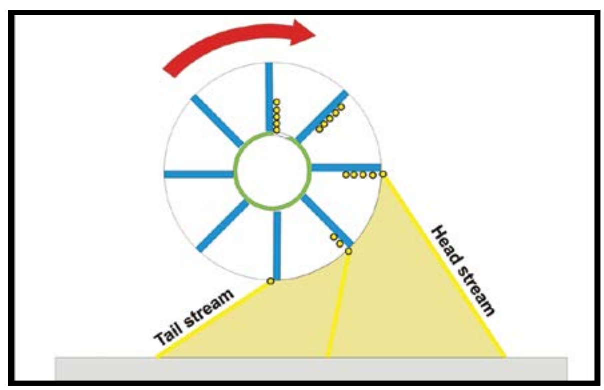

Fig. 11 Schematic representation of shot cohort movement positions.

The time difference (between first and last thrown particles) determines the angular range over which the cohort is thrown for a given wheel speed.

DISCUSSION

Shot velocity is one of the prime factors that need to be controlled if peening is to attain required levels of intensity. This article has only considered the velocity generated at either the peening nozzle's exit or the tip of wheel-blast blades. The velocity will, however, change slightly before reaching a component. Such changes will be explained in a future article in this series.

The velocity control measure for air-blast peening is air pressure whose effect is to vary its density. With wheel-blast peening the velocity control measured employed by peeners is the wheel speed. For both types of peening the shot flow rate will have a secondary effect.