Generation of Wheel-Blast Shot Velocity

by David Kirk

INTRODUCTION

Shot velocity is of primary importance because it governs the kinetic energy of the impacting shot and hence the peening intensity. Wheel-blast shot acceleration is much more energy-efficient than air-blast shot acceleration – which accounts for its continued appeal. A variety of wheel types have evolved but the mechanics involved are generally similar. Normally, blades attached to a rotating wheel throw shot at components. Shot velocity is achieved in two stages: accelerator drum and throwing blades. Particles are fed into peripheral slots formed between the 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 some shot particles escape onto a throwing blade for the second stage of acceleration, see fig.1.

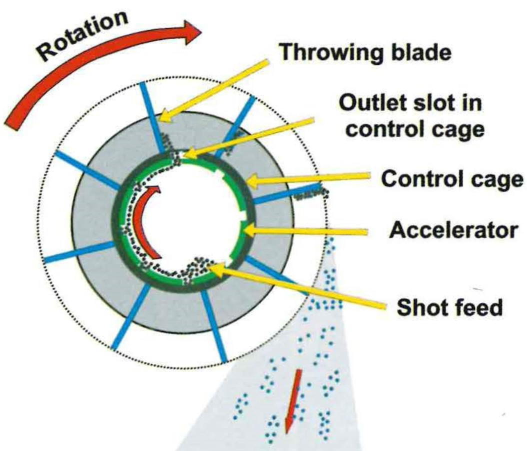

Fig.1 Wheel-blast system with 'open' throwing blades.

This article is an account of the mechanics involved in generating the final shot velocity. Equations are presented that allow estimates to be made of the thrown shot velocity, direction and angular range when leaving the wheel. These equations accommodate the variations in wheel speed and diameter, blade length, number of blades and control cage that occur with different wheel designs.

It is shown that the radial velocity is a large percentage of the tangential velocity. The ratio of radial/tangential velocity determines the direction of individual thrown shot particles.

ACCELERATOR DRUM

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 gravitational force, F_g, will vary from $+m.g$ to $-m.g$ (where m is the mass of the particle and g is gravitational acceleration) as the drum rotates. At the bottom of each rotation $+m.g$ is acting in an 'outwards' direction whereas at the top we have $-m.g$ (gravity is then pulling the particles in an 'inward' direction). The centrifugal force, Fc, is given by:

$$F_C = m.V_D^2/R \qquad (1)$$

where V_D is the tangential velocity of the drum and R is the distance of the slot from the axis of drum rotation.

The total outward force on a particle, F_{OUT}, is given by:

$$F_{OUT} = F_C + F_G \qquad (2)$$

The relative magnitudes of F_C and F_G are of obvious importance. If, for example, we have an accelerator drum of 100mm radius rotating at 50 r.p.s. then V_D is some $31.4m.s^{-1}$. Using this value in equation (1) gives F_C as 9870 $m.s^{-1}$ so that (2) gives:

$$F_{OUT} = m(9870 \pm 9.8)ms^{-2} \qquad (3)$$

It follows from the value given in (3) that gravity is a negligible factor (0.1%) and can therefore be ignored for estimation purposes. Conversely, we must note that 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.

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, V_T and V_R. These are vectors which combine to give the particle velocity, V_S, as illustrated in fig.2. V_R is the radial velocity induced by the centrifugal acceleration and V_T is the tangential velocity (which is equal to the rotational velocity of the blade tip).

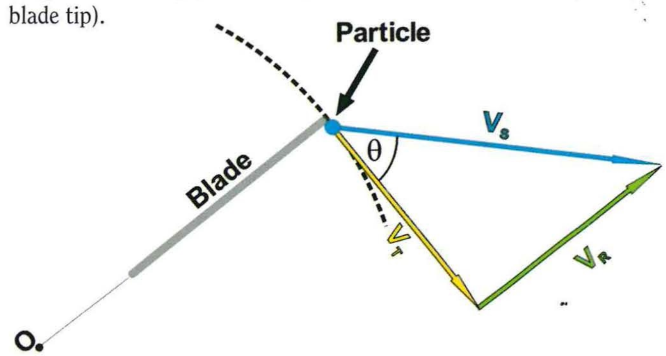

Fig.2 Individual particle leaving blade tip with vector-combined velocity, Vs.

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GENERATION OF WHEEL-BLAST SHOT VELOCITY

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The values of V_T and V_R determine both the velocity and movement direction, θ, of the thrown shot particles. Tangential velocity, V_T, is quite easy to estimate, whereas the radial velocity, V_R, requires the application of physical principles (and some simplifying assumptions).

TANGENTIAL VELOCITY COMPONENT, V_T.

Consider a single blade of length, L, rotating about an axis, O, such that the tip sweeps a radius, R, as shown in fig.3. The shot particle at the tip of the blade is being pushed by the blade with a velocity, V_T, as it leaves the blade. We can assume that the blade is rotating about the axis at a known, fixed, number of revolutions per second, N r.p.s. (= r.p.m./60). Now since velocity equals distance/time we know that in one 360° revolution the tip of the blade will have travelled a distance $\pi.2R$, the circumference of the circle. We multiply that circumference by the number of r.p.s., N, to give the required value of V_T as:

$$V_T = 2\pi.R.N \qquad (4)$$

As an example, if R = 0.250m and N = 50 r.p.s. then V_T = 78.5m.s^{-1}

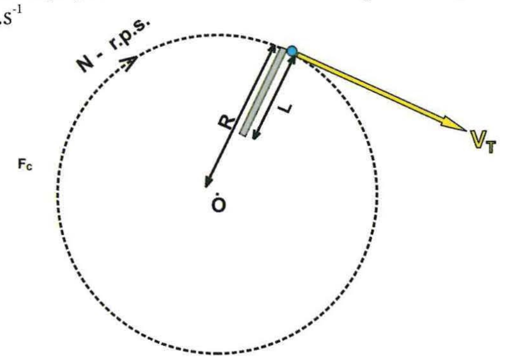

Fig.3 Generation of tangential velocity, V_T.

It is important to note that the tangential velocity, V_T, is constant for all of the particles thrown from the tip of a given 'open' blade rotating at a fixed rate.

RADIAL VELOCITY COMPONENT, V_R.

Shot particles emerging from the accelerator drum come into contact with a rotating blade at a point where it has a tangential velocity, V_A, see fig.4. Tangential velocity, v_x, at any distance, x, from a centre of rotation induces a centrifugal acceleration, a_x, given by the equation:

$$a_x = v_x^2/x \qquad (5)$$

where x is any notional distance from the centre of rotation, O.

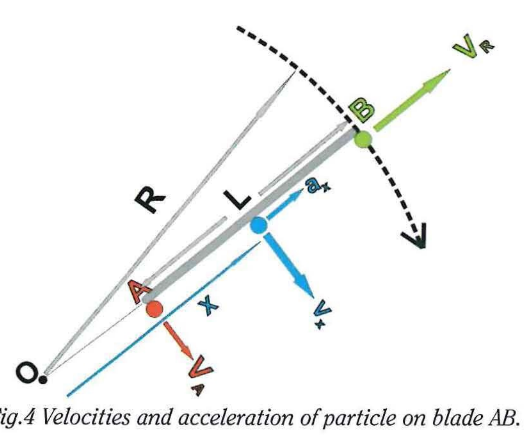

Fig.4 Velocities and acceleration of particle on blade AB.

This is the basic centrifuge principle. Note that lower case is conventionally used for values that vary, such as v_x, as opposed to upper case (capitals) for fixed values - such as V_A and V_R.

The acceleration of shot particles *along* the throwing blade will vary from $V_A^2/(R\text{-}L)$ at A to V_B^2/R at B. Estimation of the velocity of particles under *constant* acceleration is simple - as compared to when varying acceleration is involved. With variable acceleration we have to invoke integral calculus. Fortunately the calculus required is not difficult.

If we plot radial velocity, v, against radial velocity, v, from 0 to V_R, we have a straight line relationship. The triangular area under that straight line is $V_R^2/2$ (half the base times the perpendicular height). Expressing that in integral calculus notation we have that:

$$\int_0^{V_R} v.dv = V_R^2/2 \qquad (6)$$

Now $v.dv = dv(dx/dt) = (dv/dt).dx = a_x.dx$. We know that $a_x = v_x^2/x$ and that $v_x = 2\pi N.x$. Hence, $v.dv = a_x.dx = (2\pi N)^2.x.dx$. Equation (6) can therefore be re-written to give:

$$(2.\pi.N)^2 \int_{R-L}^{R} x.dx = V_R^2/2 \qquad (7)$$

The $(2\pi N)^2$ factor appears outside the integration symbol because it is a constant quantity. Integration of x.dx gives $x^2/2$ so that (7) yields the important relationship:

$$V_R^2 = (2\pi N)^2(2.R.L - L^2) \text{ or} \qquad (8)$$
$$V_R = 2\pi N(2.R.L - L^2)^{0.5}$$

Note that raising to the power of 0.5 is the same as taking the square root. For a given bladed wheel, R and L are fixed, known, quantities – for example 0.25m and 0.15m. Substituting those values into equation (8) gives that V_R = **1.44.N**. V_R is a linear function of wheel rotation speed, N, for a given bladed wheel. For N = 20 r.p.s., R = 0.25m and L = 0.15m then V_R = 28.8 m.s^{-1}. When N is doubled to 40 r.p.s. V_R is doubled to 57.6m.s^{-1}. The corresponding values for V_T are 31.4 and 62.8 m.s^{-1} respectively.

COMBINED SHOT VELOCITY, V_S, AND DIRECTION, θ.

The velocity for an individual particle, V_S, is obtained by combining the two contributing vectors V_T and V_R, as shown in fig.2. These vectors are at 90° to one another so that:

$$V_S^2 = V_T^2 + V_R^2 \qquad (9)$$

Using the values for V_T and V_R from equations (4) and (8) respectively, we obtain our second important relationship:

$$V_S^2 = (2\pi N)^2(R^2 + 2.R.L - L^2) \text{ or} \qquad (10)$$
$$V_S = (2\pi N)(R^2 + 2.R.L - L^2)^{0.5}$$

Equation (10) simplifies enormously for given bladed wheel values, R and L. Using, again, R = 0.25m and L = 0.15m, (10) becomes: V_S = **2.13.N**.

The direction of V_S, θ, is obtained by knowing that:

$$\tan\theta = V_R/V_T \qquad (11)$$

Now, when $V_R = V_T$, $\tan\theta = 1$, so that $\theta = 45°$. *If* V_R is $0.87V_T$ then $\tan\theta = 0.87$ so that $\theta = 41°$. Finally *if* $V_R = 0$ then $V_S = V_T$ and $\theta = 0°$.

EFFECTS OF BLADE/RADIUS ASPECT RATIO

The ratio of blade length, L, to wheel radius, R, can be termed the "blade/radius aspect ratio". Expressed as a percentage, commercial accelerator-fed machines have wheels with aspect

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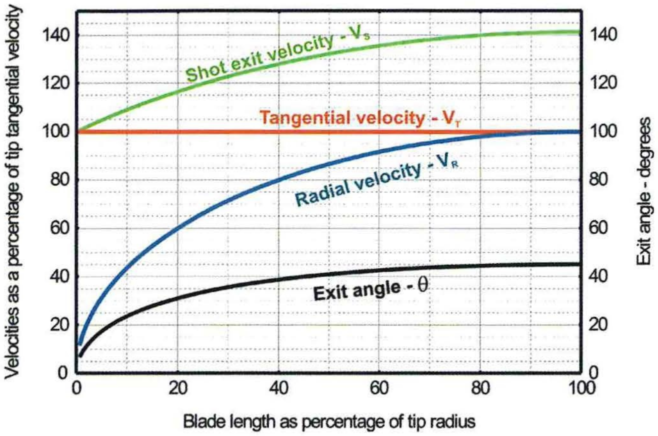

Fig.5 Effects of blade/radius ratio on induced velocities and exit angle.

ratios within a range of 30 to 70. The ratio for a particular machine/wheel affects both the shot's exit velocity, Vs, and the exit angle, θ. Fig.5 illustrates the effects of aspect ratio on shot velocity components and exit angle. The curves were derived by plotting equations (4), (8), (10) and (12) against aspect ratio. Within the aspect ratio range of 30 to 70 the thrown shot velocity is predicted to vary from about 123 to 138% of the tangential velocity. The corresponding exit angle range is from 36 to 44°.

COHORT MOVEMENT

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

Cohort *mass* 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 120kg per minute that is 2 kg per second. Dividing 2000g equally between 400 cohorts gives 5g per cohort.

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

Cohort *volume* is mass/(density x 'packing factor'). For one solid piece volume is mass/density. A cohort of particles has a fraction of empty space between particles. For estimation purposes we can assume that the 'packing factor' is 0.5 (half solid, half space). Hence 5g of steel shot with a density of 7.86 x 10-3g/mm^3 would occupy a volume of $5/(7.86 \times 10^{-3} \times 0.5)$ = 1270 mm^{-3}(1.27cc).

These estimates of the mass, number and volume of each cohort allow us to envisage the scale of cohort movement from control cage to blade tip.

Our first problem is to get the cohort out of a slot and onto a blade. **The particles in the slot have very high tangential velocity but zero radial velocity.** Fig.6 is a schematic representation of the elements involved in cohort transfer. Only a fraction (shown blue) of the particles pressing in an accelerator slot will escape as it passes the exit slot. The remainder (shown yellow) will be carried past the exit slot to be subsequently 'topped up'. This remainder, being under enormous centrifugal acceleration, helps to push shot particles out of the slot. The cohort of particles that does escape is collected by the throwing blade. The collected particles are then subject to the radial acceleration described previously. It is also noteworthy that the time available for the cohort to exit is of the order of a thousandth of a second.

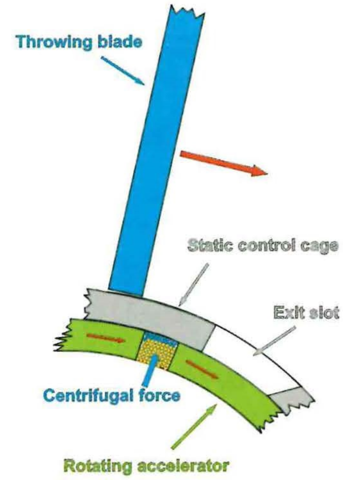

Fig.6 Elements involved in shot cohort transfer to throwing blade.

With an eight-slot, 200mm diameter, accelerator the slots will be of the order of 10mm wide by 50mm across. This *area* of 500mm^2 contains a cohort *volume* of the order of 1000mm^3. It follows that each cohort is about 2mm deep. S230 shot has a diameter of about 0.7mm so that an S230 cohort is a layer about three particles deep. This layer reaches the outlet slot just before the blade root - in order to give time for the escaping shot to exit onto the blade face. Synchronisation of slot, outlet and blade is vital for effective wheel blast operation.

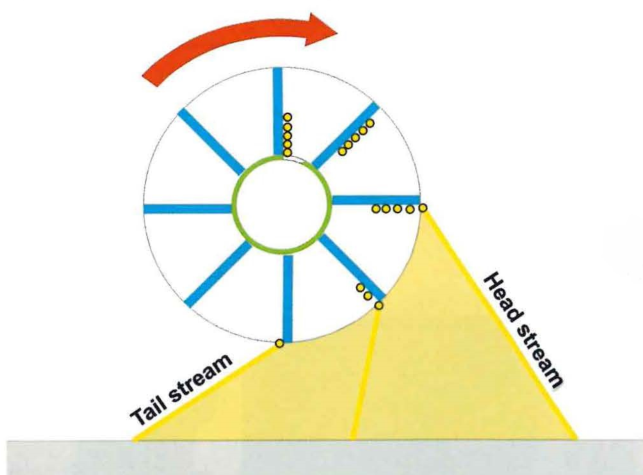

Fig.7 Schematic representation of shot cohort movement positions.

Fig.7 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. This means that there will be an initial cohort spread along, as well as across, the blade. A blade 50mm wide by 150mm long has an area of 7,500mm^2. It follows that a cohort of, say, 3,500 S230 shot particles will be present, on average, as a monolayer. The radial spread will increase as the cohort moves towards the blade tip. That is because centrifugal acceleration increases towards the blade tip - so that the leading particles are travelling faster than those at the rear. 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.

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

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TIME FOR SHOT TRAVEL

The time, T, needed for an individual shot particle to travel the full length, L, of a blade is given by:

$$T = L / V_{AVR} \quad (12)$$

where V_{AVR} is the average radial velocity.

Radial velocity, v_{RX}, varies with distance, x, along the blade according to the equation:

$$v_{RX} = 2\pi N[x^2 + 2x(R - L)]^{0.5} \quad (13)$$

The average radial velocity, V_{AVR}, is obtained by integrating equation (13) over the length of the blade and then dividing that 'area' by L:

$$V_{AVR} = \frac{2\pi N}{L}\int_0^L [x^2 + 2x(R-L)]^{0.5} \quad (14)$$

Substitution from equation (14) into equation (12) gives:

$$T = L^2 / \{2\pi N \int_0^L [x^2 + 2x(R-L)]^{0.5} dx\} \quad (15)$$

If L = R. Equation (15) simplifies enormously when L = R to give $T = 1/(\pi N)$. One revolution takes a time 1/N so that T is always $1/\pi$ of a revolution – about one-third. Referring to fig.7 that is equivalent to the first particle joining a blade at about 11 o'clock and being thrown off at 3 o'clock. If, for example, n = 50 r.p.s then T = 1s/50π or 0.0064s.

Generally L is substantially less than R, so that equation (15) has to be solved 'as is'. Two solution routes are available. The first route is to use a mathematical software program, such as Mathcad, which will solve the integral iteratively and do the necessary arithmetic automatically. The second route is to invoke the very complex integral calculus solution of the integral. Both routes give identical answers. T reduces progressively with decrease in blade length, L. T/N is the fraction of a revolution during which the leading particle travels along the blade and is independent of the wheel radius. Table 1 shows how T/N varies with blade aspect ratio, L/R. The highlighted 60% ratio is typical for commercial wheels with a corresponding one-sixth of a wheel revolution.

DISCUSSION

This account has concentrated on the two components of thrown shot velocity – tangential and radial velocities, V_T and V_R. The thrown shot velocity, V_S, will have a *minimum of* V_T and a *maximum of* $V_T.\sqrt{2}$. The maximum would require that $V_R = V_T$, which in turn requires that the throwing blades have the same radius as that of the wheel. The tangential velocity component is an easily-predictable, stable, factor whereas the radial velocity component depends upon the ratio of blade length to wheel radius and on other factors. Predicted times for shot to travel along the blades explain both the need for pre-positioning of the control cage exit slot and why there is an angular spread between the exiting of first and last particles in a given 'cohort'.

The equations presented for radial velocity and time for shot travel have assumed that *all* of the centrifugal acceleration is converted into shot movement. 100% conversion would require that there is no air resistance as particles travel along the blades and no particle/blade friction. Both air resistance and friction are present. The radial velocity component will, therefore, be somewhat lower than the theoretical prediction. Measurements of exit velocity and direction, together with analysis of manufacturers' data sheets, indicate that an empirical correction factor of 0.8 would reasonably accommodate air resistance and friction effects.

All of the radial velocity component will be lost if caging around the blades extends beyond the head stream position for an open wheel. That would also mean a substantial reduction in shot velocity and hence kinetic energy, $\frac{1}{2}mv^2$, for the corresponding fraction of the thrown shot particles.

It has been shown that the cohort of particles leaving an accelerator slot is only a few layers thick. The angular range over which particles leave the tip of a given blade depends largely on the time difference between the arrival at the blade base of the first and last particles of the cohort. That time difference is proportional to the length of the control cage exit slot. Before reaching the control cage exit the particles are being rotated against the control cage at high speed and with enormous force– leading to severe wear problems for shot, accelerator and cage.

The fact that centrifugal acceleration increases towards the blade tip means that particles are increasing their separation distance as they travel along the blade. That increases the validity of calculations based on the movement of individual particles.

Table 1

Fraction of wheel revolution during single particle transfer along blade.

Blade aspect ratio, L/R - %	Revolution fraction, T/N
10	0.055
20	0.081
30	0.104
40	0.126
50	0.148
60	0.172
70	0.199
80	0.229
90	0.267
100	0.318 (=1/π)