Dr. David Kirk | Coventry University

Shot Stream Generation

INTRODUCTION

Air-blast shot streams consist of a mixture of fast-flowing air and entrained shot particles carried along by the flow of air. Generating an air-blast shot stream embraces two main problems: firstly producing a fast-flowing stream of air of appropriate velocity and secondly introducing the shot particles into this fast-flowing stream (see schematic fig.1).

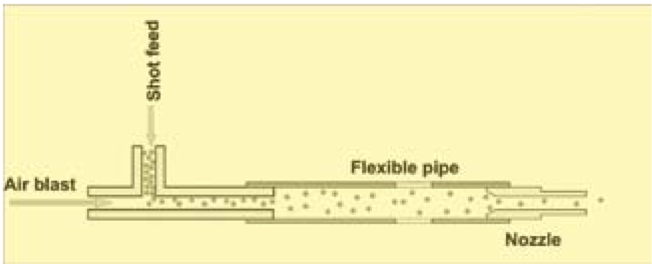

Fig.1. Direct-feed air-blast shot stream generation.

With wheel-blast shot streams, shot particles travel along rotating metal blades until they are flung off at their ends. Air travels with the particles and has a similar velocity at the blade tips. Fig.2 illustrates the essential features of a wheel-blast shot stream.

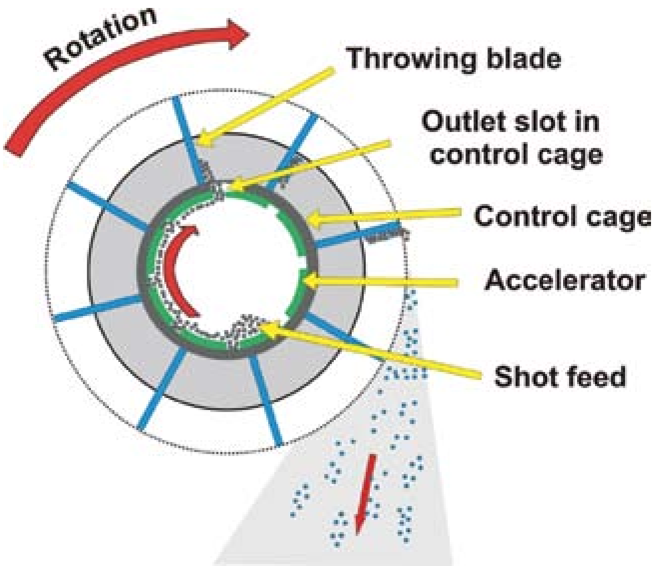

Fig.2. Essential features of a wheel-blast shot stream.

Generating a conventional wheel-blast shot stream embraces several problems: feeding shot into the center of the wheel, accelerating the shot until it reaches the outlet of the control cage and controlling the wheel velocity.

The theory and mechanics of generating air and wheel-blast shot velocities have been described in previous *Shot Peener* magazine articles, refs.1 and 2. Relevant concepts are included in this article. One major addition is a consideration of what happens to air flow after it leaves the nozzle.

Air- and wheel-blast machines generally operate with widely different shot flow rates. Each has its own advantages and disadvantages. Apart from the introduction of flapper peening, there appears to have been no significant developments in shot stream generation in the last half century. This article concentrates on the variables of the two major processes and discusses possible new developments. Important equations are included but it is emphasized that no mathematical expertise is required to employ them.

AIR-BLAST SHOT STREAM GENERATION

Air, being compressible, allows us to control the velocity of the shot particles that are entrained in the air stream emerging from the nozzle. The most important variable is the pressure of the air in the nozzle. Increasing the air pressure in the nozzle increases its density, as illustrated in fig.3.

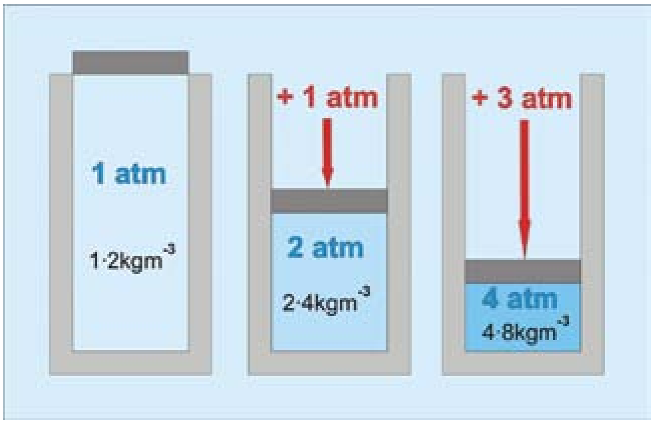

Fig.3. Increase of air density with applied pressure.

Nozzle Air Velocity

An important principle is that:

The maximum velocity of air in any form of pipe is the speed of sound in air.

The change of nozzle air velocity with nozzle air pressure is illustrated in fig.4. If the air pressure in the nozzle is one atmosphere (the same as outside the nozzle) then there can be no significant movement of air. As we gradually increase the air pressure in the nozzle it flows with increasing velocity. When the nozzle air pressure reaches two atmospheres the velocity suddenly reaches a limit—the speed of sound in air. Any further increase of nozzle air pressure will not increase the air velocity in the nozzle! What does happen is that the air travelling at this limited velocity becomes denser as the pressure increases.

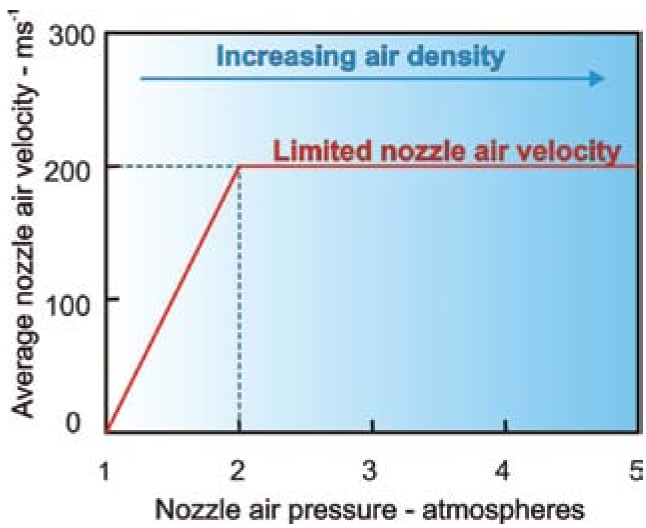

Fig.4. Effect of nozzle air density on nozzle air velocity.

It should be noted that the limited nozzle air velocity is on the centerline of the nozzle and velocity is a minimum (virtually zero) at the wall of the nozzle, as shown schematically in fig.5. Air velocity prediction is straightforward for the commonly used straight nozzles. Venturi-shaped nozzles are more complicated.

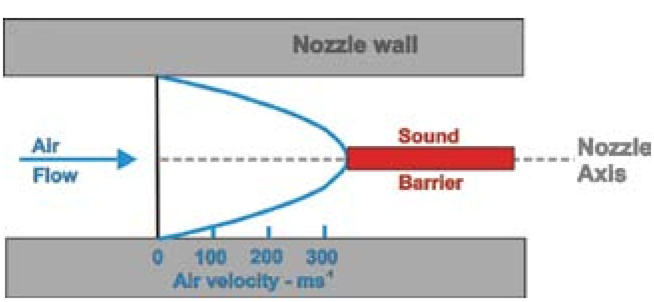

Fig.5. Distribution of air velocity in nozzle.

Along the centerline of the nozzle, air flow is limited to the speed of sound. Air flow away from the centerline is, however, retarded by friction at the nozzle wall. Hence, between the nozzle wall and the centerline there is a variation of velocity. The average air velocity within the nozzle is some two-thirds of the speed of sound. As pointed out in a previous article (ref.1) this has been found to be fixed at about 210 ms^{-1} for most commercial nozzles.

Nozzle Shot Velocity

As we introduce solid shot particles into a fast-flowing air stream the particles are forced to accelerate. The mechanics of this acceleration have been described previously (ref.1). Before introducing the relevant equations for this acceleration, consider the following simple qualitative analogy.

Trapped in a Pipe

Imagine being trapped in a large-diameter underground pipe. If there was no air flowing down the pipe we would feel no force from the air. On the other hand, if the air was flowing at, say, 10 meters per second, we would definitely feel a force but it would not sweep us off our feet. If water was flowing along the pipe at the same velocity we would certainly feel a much larger force—enough to knock us off our feet. That is because water has a much greater density than air. The greater the density the greater the force exerted. If the air pressure was increased without increasing its velocity, we would feel a larger force because the air has become denser. Doubling the air pressure would, however, also mean that the air velocity at the center of an open-ended pipe would have to be at the speed of sound. That high-velocity air would fling us along the pipe at an increasing velocity.

The velocity of shot emerging from a straight nozzle can be estimated using equation (1) from ref.1:

$$\mathbf{v_S = (1{\cdot}5.C_D.\rho_A.s/\pi.d.\rho_S)^{0.5}\,(v_a - v_s)} \qquad (1)$$

where $\mathbf{v_s}$ = average shot velocity, $\mathbf{C_D}$ is the "drag coefficient" (a dimensionless number that depends upon the shape of the object and for a smooth sphere $\mathbf{C_D}$ = 0.5), $\mathbf{\rho_A}$ = density of air in the nozzle, **s** = distance that the shot particle travels as it is being accelerated, **d** = average shot diameter, $\mathbf{\rho_S}$ = density of the shot and $\mathbf{v_a}$ = average air velocity in the nozzle.

Equation (8) may look a bit off-putting but we do not need to be a mathematician to employ it. The simplest approach is to set up an Excel spreadsheet that includes a formula that is a re-arranged form of equation (8). Table 1 shows how the estimated shot velocity (cell C11) is evaluated using the following (in Excel format):

=C9*((1.5*C3*C5*C4*C8)/(C6*C7))^0.5(1+((1.5*C3*C5*C4*C8)/(C6*C7))^0.5)

With an Excel spreadsheet, it is a simple task to enter specific values for the variables. Changing a variable gives an instant insight of its significance. (The author is very willing to email a copy of the spreadsheet. Please send the request to dr.d.kirk@btinternet.com.) For the example shown in Table 1, the density for steel shot has been entered.

Table 1. Specimen estimation of nozzle-induced average shot velocity using Excel.

1	B	C	D
2	**Parameter**	**Value**	**Units**
3	Cd	0.5	none
4	Normal Air Density	1.2	kgm^{-3}
5	Air Pressure	9	atm
6	Shot Density	7860	kgm^{-3}
7	Shot Diameter	0.25	mm
8	Nozzle Length	50	mm
9	Average Air Velocity	200	ms^{-1}
10			
11	**Shot Velocity**	**48.6**	$\mathbf{ms^{-1}}$

Post-Nozzle Air Flow

Air is a compressible fluid. When compressed air emerges from a nozzle it must almost immediately expand to atmospheric pressure. Fig.6 illustrates, schematically the sideways air velocity, $\mathbf{V_S}$, as well as the forwards air velocity, $\mathbf{V_F}$, which are present as a consequence of this expansion. The figure corresponds to a nozzle pressure of 4 atm. which, on expansion, doubles the diameter of the air stream.

The basic problem when investigating air flow is that it is invisible. In other industries, air flow is commonly studied by introducing smoke into the air stream. One important region is very close to the nozzle exit. The model shown in fig.7 is of a cylinder of plastic foam that has been partly inserted into a transparent tube. The foam, being compressible, simulates the expansion of compressed air as it exits the tube (the shape at A being equivalent to the dotted lines shown in fig.6). Lines, C, tangential to the foam, have been added to the photograph in order to indicate the conical direction of air flow.

The conical shape of the air stream is maintained until it exceeds the distance used for shot peening—thereafter the air billows out.

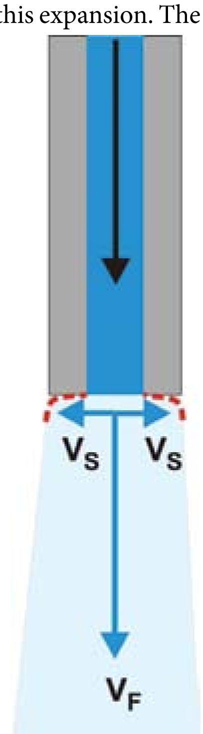

Fig.6. Schematic representation of air flow leaving a nozzle.

Post-Nozzle Shot Flow

The flow of shot leaving nozzles has already been studied directly using high-speed cameras and indirectly by examining dents on plates inserted into the shot stream. One important question is: "Why does the shot stream have a conical shape when projected from a cylindrical nozzle?" The answer lies in the effect of the sideways air velocity, $\mathbf{V_S}$, shown in fig.6. $\mathbf{V_S}$ increases with distance from the centerline of the nozzle. Sideways motion of the air stream pushes entrained shot slightly sideways, generating the conical shape.

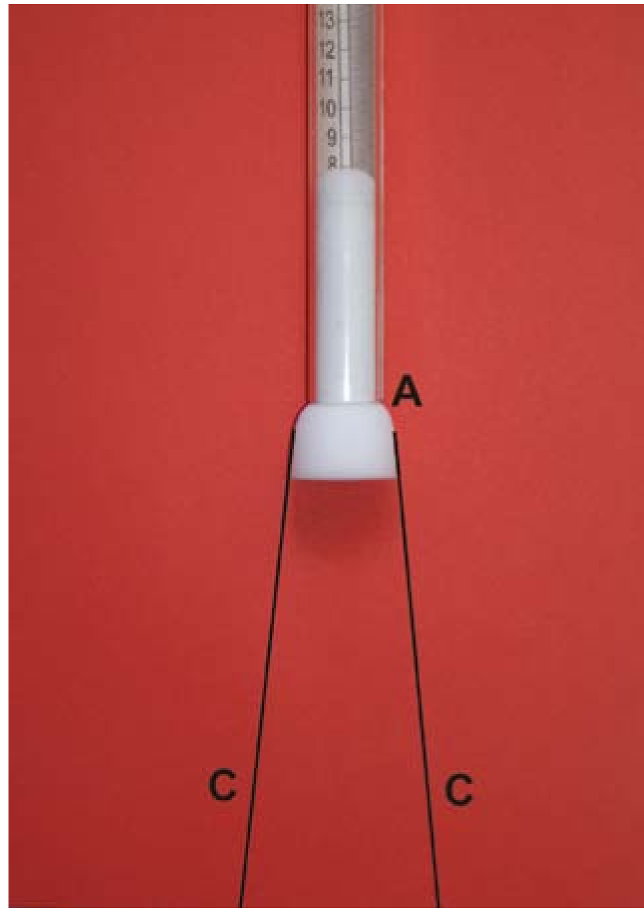

Fig.7. Model of expansion of a compressible substance on leaving a tube.

When shot emerges from the nozzle, it is travelling slower than the air stream. This causes the shot speed to further increase until the air is flowing at the same speed as the shot. As a consequence we have a "sweet spot" of maximum shot velocity. Previous studies have shown that the peening intensity value is a maximum at this sweet spot distance from the nozzle (commonly about 250 mm). After this distance the air velocity becomes less than that of the shot and slows down the shot.

WHEEL-BLAST SHOT STREAM GENERATION

Wheel-blast shot stream generation has been analyzed in a previous TSP paper, ref.2. Particles are pushed along fast-rotating blades by centrifugal force. When each particle leaves the tip of the blades it has a combination of radial velocity, **V_R**, and tangential velocity, **V_T**, as shown in fig.8. The combination of these two velocities gives the actual shot velocity, **V_S**.

It has been shown (ref.2) that the velocity of shot as it leaves the blade tip, **V_S**, is a simple function of wheel speed, **N**, blade length, **L**, and wheel radius, **R**. These factors are shown in fig.9. The corresponding equation for estimating **V_S** is:

$$V_S = 2*\pi*N(R^2 + 2*R*L - L^2)^{0.5} \qquad (2)$$

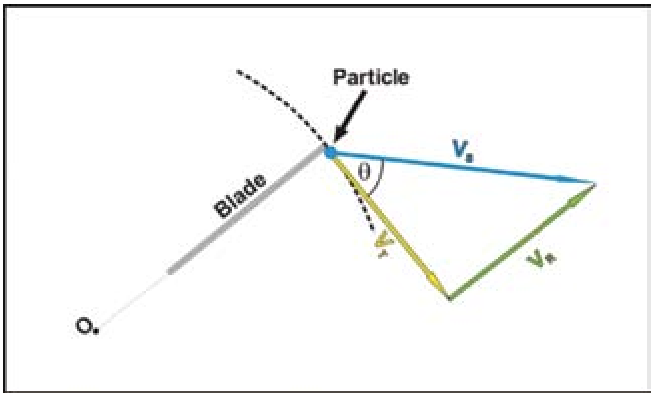

Fig.8. Shot velocity as a combination of radial and tangential velocities.

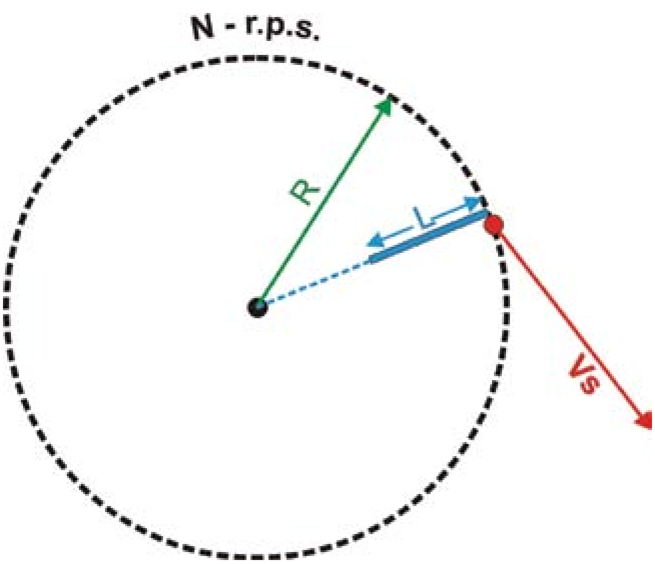

Fig.9. Wheel-blast variables contributing to thrown shot velocity.

Equation (2) can be used in several ways:

Example 1 Calculating thrown shot speed, V_S.

Assume that the wheel is rotating at 50 r.p.s. so that N = $50s^{-1}$, R = 0.2 m and L = 0.1 m. Substituting these values into equation (2) gives that:

$$V_S = 2*\pi*50(0.2^2 + 2*0.2*0.1 - 0.1^2)^{0.5} \text{ so that } V_S = 83ms^{-1}$$

Example 2 Calculating effect of different blade lengths

If, for example, the blade length in the previous example was only 0.05m we have that:

$$V_S = 2*\pi*50(0.2^2 + 2*0.2*0.05 - 0.05^2)^{0.5} \text{ so that } V_S = 75ms^{-1}$$

The difference between the shot velocities for these two examples may seem small but we have to remember that the kinetic energy of a shot particle is proportional to the square of its velocity. Particles traveling at $83ms^{-1}$ have 22.5% greater kinetic energy than if they were travelling at $75ms^{-1}$. The speed of sound limits the maximum radial velocity of the wheel's blades.

ALTERNATIVE SHOT STREAM GENERATION

Conventional shot stream generation appears to be mainly restricted to two methods—air-blast and wheel-blast. Both methods accelerate shot particles in manners that can be likened to a jet-ski and a paddle steamer respectively. "Thinking outside the box" seems to be an appropriate way of exploring alternative methods. Two possible alternatives are outlined in this section.

Direct Air Compression

Air compression normally involves an indirect procedure. Air is compressed into a ballast tank from which it is fed via hoses to shot peening cabinets. One thought is that a small individual compressor could be directly attached to each peening nozzle. Fig.10 is a schematic representation of such an arrangement.

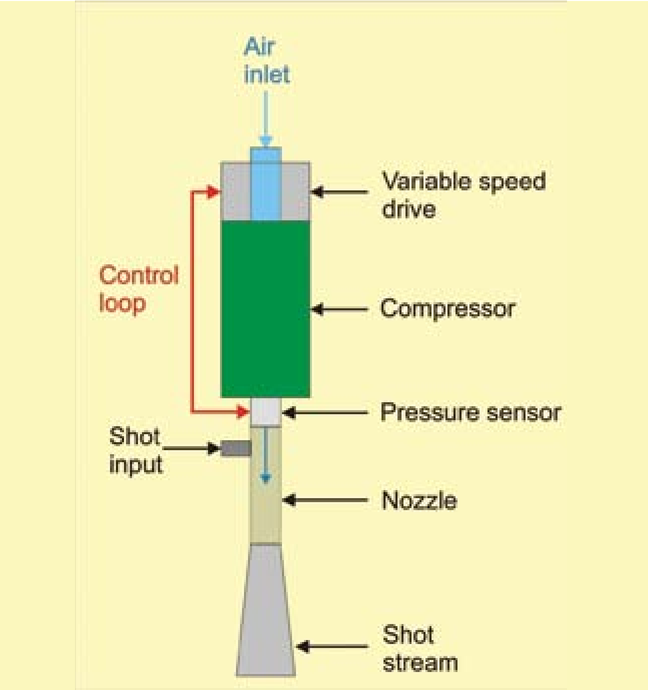

Fig.10. Direct drive air compression system.

A direct drive system would obviate the need for conventional flexible hoses. The variable speed drive would operate in conjunction with a pressure sensor to provide closed-loop control.

Screw Shot Propulsion

The "paddle steamer" analogy of wheel-blast propulsion sparks a thought that the more efficient screw propulsion principle could be invoked. Screw propulsion is widely used to move both liquids and solids at ordinary speeds and air at high speeds. Literature searches by the author have failed, however, to reveal any high-speed applications for solids. That does not mean that they are not possible. Fig.11 represents, schematically, a combination of compressed air and "Archimedean" propulsion. The screw could be either integral with an outer cylinder or spinning inside a static cylinder. The combination could provide a system intermediate between high-precision low-volume air blast and low-precision wheel-blast generation.

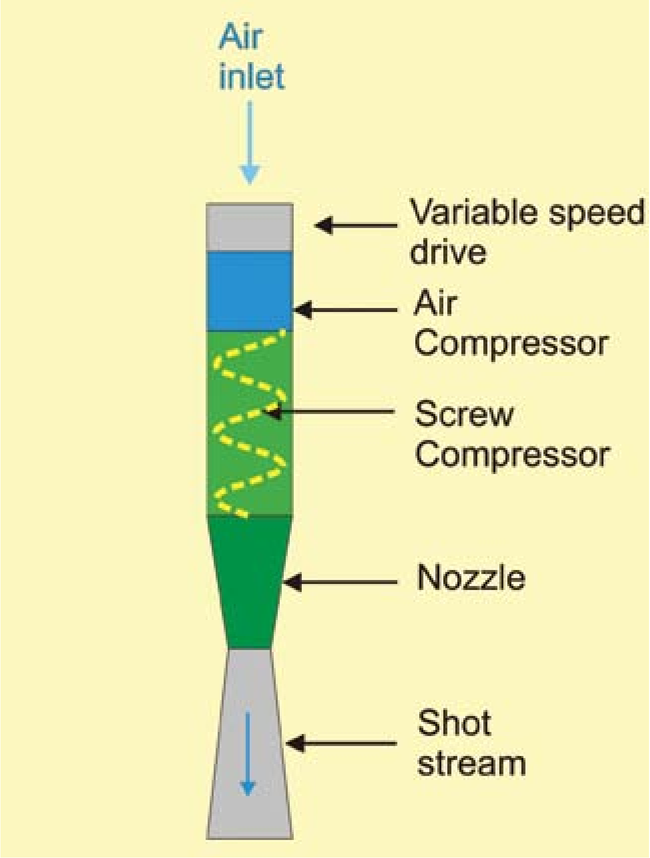

Fig.11. Schematic representation of combined air/screw shot stream generation.

DISCUSSION

Shot peening is wholly dependent on quantities. Individual parameters, such as coverage and peening intensity, are readily appreciated. Peening control depends, however, on the combined effects of several parameters. These combined effects can be expressed either as graphs or as equations or both. In this article the effects of individual parameters on shot stream generation have been highlighted. The beauty of programs such as Excel is that no mathematical skills are needed to examine the effects of changes in parameter values. We simply substitute different values, press "Enter" and observe the change in, say, shot velocity.

Progress in peening technology requires changes, minor or major, in the techniques that we employ. Perhaps the greatest barrier to progress is the all too familiar attitude of "We have always done it this way and it works. Why should we change?" Profitable changes will only occur if we make the effort to be innovative. The two examples given in this article are intended to be indicative of areas where changes could be effected.

References

1. Generation of Air-Blast Shot Velocity, *The Shot Peener*, vol.21, No.1, pp 24-30, 2007.
2. Generation of Wheel-Blast Shot Velocity, *The Shot Peener* vol.21, No.2, pp 24-30, 2007.