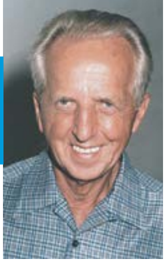

ACADEMIC STUDY
Dr. David Kirk | Coventry University

Back to Basics
Shot Peening Calculations

INTRODUCTION

The ability to quantify its variables has allowed shot peening to evolve into a smart technological process. Calculations are now an unavoidable part of shot peening. Every calculation has two components. The first is an equation and the second is data to substitute into the equation. As a trivial example, consider calculating payment for work done based on a fixed hourly rate. The equation is simply payment equals hourly rate multiplied by the time worked. At $30 per hour, working for 10 hours would earn a payment of $300. This simple example also highlights a very important feature of calculations. The units must balance! Every calculation involves a secondary equation. For this example hourly rate is $30 divided by one hour so multiplying by hours cancels out the hour unit to leave, correctly, payment as only in dollars.

This article collects together many of the large number of equations used in previous Shot Peener articles. The aim being to have them all available in one place. Some of the equations are simple, but some are complicated and were developed by the author. The properties of shot before it strikes a component are dealt with in Part 1 and the effects after striking a component are dealt with in Part 2.

PART 1

SHOT DIMENSIONS

The basic shot dimension is, of course, its diameter, **D**, as described in standard specifications. This allows us to calculate other dimensions. Hence:

$$\textbf{Particle surface area} = \pi D^2 \qquad (1)$$

$$\textbf{Particle volume} = \pi D^3/6 \qquad (2)$$

Particle mass is volume multiplied by density, **ρ**, where density is mass (in kg) per cubic metre, so:

$$\textbf{Particle mass} = \rho\pi D^3/6 \qquad (3)$$

The number of particles per kilogram is 1 kilogram divided by the mass of each particle in kg—note unit cancellation. This yields:

$$\textbf{Particles per kilogram} = 6/\rho\pi D^3 \qquad (4)$$

To illustrate these four basic dimensions, assume that a particular steel particle has a diameter, D, of 1 mm.

Rounding off π to have a value of 3, (1) tells us that this particle's area is 3 mm^2 and (2) tells us that its volume is 0.5 mm^3.

We have to be careful with the units for equation (4). The density of steel is about 7800 kgm^{-3}. 1 mm is equal to 10^{-3} m. Substituting into equation (4) gives, for 1 mm diameter steel particles (about S390): particles per kilogram = $2/7800*10^{-9}$. Using a calculator gives 256,400. Smaller shot, e.g., S110, has more than eleven million particles per kilogram! Knowing the flow rate in kg per minute, particles per kg, and shot stream diameter allows us to estimate the rate of indenting.

SHOT DIMENSION VARIABILITY

Batches of a given grade of shot exhibit a range of diameters. This variability needs to be quantified if we are to keep control of shot quality. Nominal shot sizes are fixed quantities whereas actual samples contain a range of sizes. Cut wire shot has a much smaller range of diameters than has cast shot. The range depends on production variability and associated screening procedures. Batches of shot exhibit variability that approximates to what is called a "Normal Distribution". A typical normal distribution curve is shown as fig.1. The sharper the curve the smaller is the variability. One quantitative measure of sharpness is the curve's width at half of its height (WHH). In order to get a reasonable curve for a sample of shot, we need a very large number of measurements. This is only practicable if we use a technique such as image analysis on a monolayer of shot particles. Diameter estimates are then grouped into "bins"—each bin containing a range of shot diameters. Computer analysis tools for these bin distributions are readily available, e.g., in Microsoft's Excel.

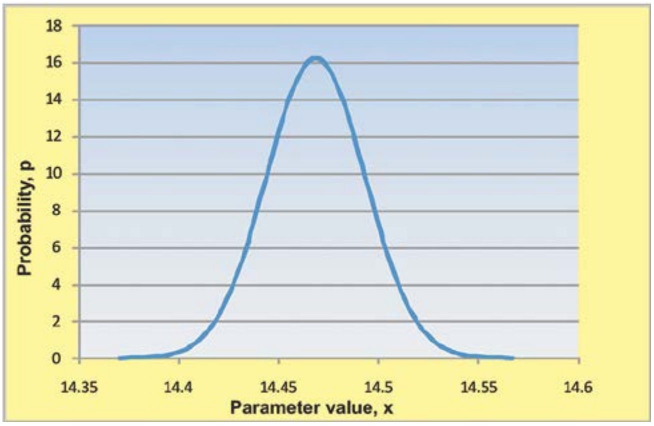

Fig.1. Normal Distribution curve.

Normal distribution curves are particularly relevant to cut wire shot variability. Wire of a fixed diameter is cut up to form cylinders that are then turned into near-spherical shapes using a process called "conditioning". Well-controlled conditioning leads to a narrower curve than does poorly controlled conditioning.

SHOT VELOCITY

The velocity of shot particles is of prime importance for shot peeners. It is the one factor that we can vary directly. Other factors, such as nozzle length, shot and shot feed mechanism tend to be fixed. Because of its prime importance, equations have been developed that show how velocity can be controlled. Different equations apply to air-blast and wheel-blast techniques.

1 - AIR-BLAST SHOT VELOCITY

For a given air-blast peening system, the major velocity control parameter is air pressure. The effectiveness of air-pressure changes depends, to some extent, on the shot feed system being employed—suction, gravity or direct. Compressed air provides the propulsion mechanism that accelerates the shot particles. Compression increases the density of the air. This is illustrated by fig.2. The effect of increasing air pressure can be visualised by the following analogy. Consider walking along into a headwind (density 1 kgm^{-3}) of 10 km/hour. No problem. Now imagine trying to walk into a wall of water (density 1000 kgm^{-3}) moving at 10 km/hour. One would be swept off one's feet. With one's back turned, the propulsive force increases with increasing density.

Air-blast shot velocity is so important that a whole article was devoted to the subject (TSP, Winter, 2007). An equation was presented that allowed us to predict the effects of variables such as shot size and density, imposed air pressure and nozzle length. It is important to remember that applied air pressure at the nozzle should be used rather than that at the air compressor. Pressure drops along the hose because of factors such as hose length, diameter and condition. The easiest way to use the predictive equation is to construct an Excel template, as given in Table 1. Required shot velocity, **v**, in C11, is calculated using the following Excel format formula:

=C9*((1.5*C3*C5*C4*C8)/(π*C6*C7))^0.5/(1+((1.5*C3*C5*C4*C8)/(π*C6*C7))^0.5) (5)

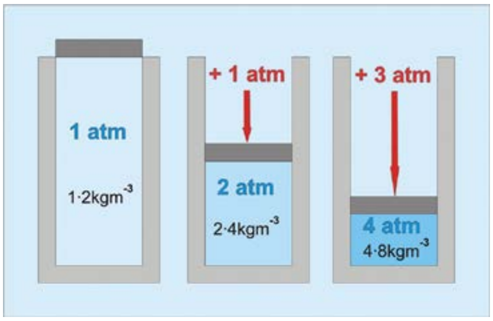

Fig.2. Effect of applied pressure on air density.

Table 1 shows an example of employing equation (5) using Excel. Note that the air velocity is fixed at 200 ms^{-1} for all practical shot peening air pressures. That is because what is called "choked flow" occurs—fixing the air velocity to a maximum value.

Table 1. Specimen calculation using equation (5)

1	B	C	D
2	**Parameter**	**Value**	**Units**
3	Cd	0.5	
4	Air density	1.2	kgm^{-3}
5	Air pressure	9	atm
6	Shot density	7860	kgm^{-3}
7	Shot diameter	0.25	mm
8	Length	50	mm
9	Air velocity	200	$m.s^{-1}$
10			
11	**Shot velocity**	**62.4**	$\mathbf{m.s^{-1}}$

Fig.3 features the most important factor in air-blast shot peening control. Practical applied air pressures are always at least 2 atmospheres. That means that the average nozzle air velocity is constant at some 200 metres per second. Therefore the only thing being influenced is the density of the air in the nozzle. If both nozzle air velocity and air density varied at the same time we would have to juggle with the duality.

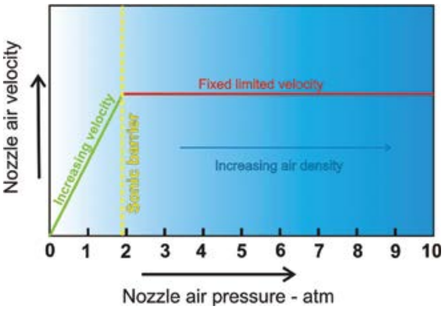

Fig.3. Effect of applied air pressure on nozzle air velocity.

Excel can also be employed to produce graphs of predicted shot velocity such as those in fig.4.

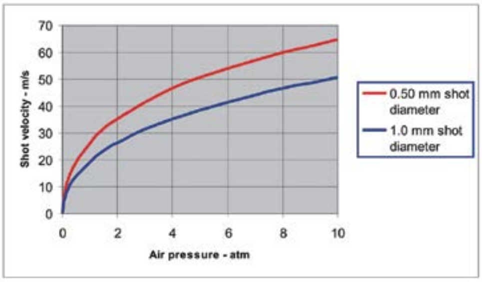

Fig.4. Predicted variation of shot velocity with size and applied air pressure.

As accelerated shot emerges from the nozzle it is always travelling much slower than the air around it. This means that the shot continues to accelerate until it reaches a maximum at about 200 mm from the nozzle. Thereafter the shot is travelling faster than the surrounding air so it slows down. It is therefore the most efficient use of energy to employ the shot stream at its "sweet distance" from a component's surface.

2 - WHEEL-BLAST SHOT VELOCITY

A good understanding of wheel-blast velocity is best based on a knowledge of how the velocity is generated. Fig.5 is a schematic representation of the principal components of a traditional wheel.

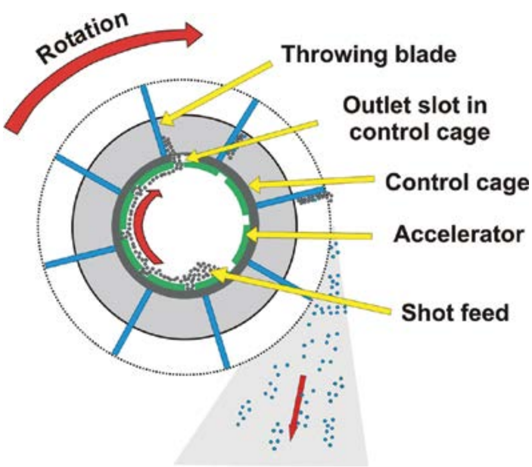

Fig.5. Wheel-blast components.

The late Jack Plaster likened a wheel-blast machine to a giant pepper mill. Expanding that analogy think of peppercorns (shot particles) being feed by gravity into a series of slots in an Accelerator. The Accelerator is rotating at high speed so imposes centrifugal force pressing the shot against a static Control Cage, rubbing them along until they can escape through the Outlet Slot and onto a Throwing Blade.

As a shot particle is thrown off the end of a blade it is given two velocity components: **1. Tangential Velocity Component, V_T** and **2. Radial Velocity Component, V_R.** The two components constitute vectors at right angles to one another so that the combined velocity of the shot particle, **V_S**, is readily obtained using Pythagoras's theorem. Pythagoras's theorem is the one that states: "The square of the hypotenuse is equal to the sum of the squares of the two right-angled sides." So if the two sides had lengths of 3 and 4, the square of the hypotenuse would equal 9 + 16 = 25, yielding that the hypotenuse's length is 5. Fig.6 illustrates the principle involved when applied to wheel-blast shot velocity.

1. Tangential Velocity Component, V_T

In one 360˚ revolution the tip of the blade will have travelled a distance **π**.2R, the circumference of the circle. We multiply that circumference by **N**, the number of revolutions per second (r.p.s.) to give the required value of **V_T** as:

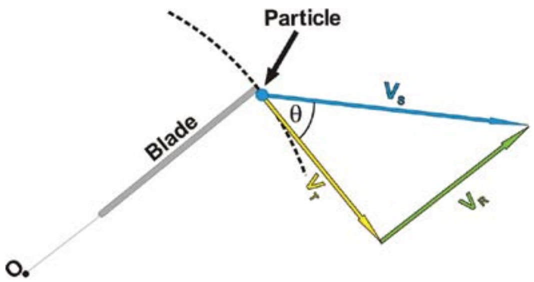

Fig.6. Wheel-blast shot velocity, V_S, based on its two components.

$$V_T = 2\pi.R.N \qquad (6)$$

As an example, if circumference of blade tip rotation equals 1 m and N = 50 r.p.s., then $V_T = 50\ m.s^{-1}$.

2. Radial Velocity Component, V_R

Centrifugal force pushes cohorts of shot off the end of the rotating blades. The velocity, V_R, imposed on each shot particle is given by:

$$V_R = 2\pi N(2.R.L\text{-}L^2)^{0.5} \qquad (7)$$

Where **L** is the length of the throwing blade (see fig.5).

Combined Wheel-blast Shot Velocity, V_S

The combined wheel-blast shot velocity is obtained by taking the square root of **$V_T^2 + V_R^2$**. Hence: **V_S**

$V_S^2 = (2\pi.R.N)^2 + (2\pi N)^2.(2.R.L\text{-}L^2)$ which simplifies to give

$V_S^2 = (2\pi N)^2(R^2+2.R.L\ \text{-}L^2)$ so that

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

For a given blast wheel, **R** and **L** are fixed, known quantities leaving just **N** as our velocity control parameter. For example assume that **R** and **L** are known to be 0.25 m and 0.15 m respectively. Equation (8) then simplifies to: **V_S = 2.13.N**. At 40 r.p.s., that wheel would accelerate shot to 85.2 metres per second.

The angle, θ, at which shot is thrown of the blade's tip is found by knowing that:

$$\tan\theta = V_R/V_T \qquad (9)$$

If **$V_R = V_T$** then **tan θ =1** so that **θ = 45˚**.

PART 2

This part considers quantifiable effects of shot striking a component. These are Dent Size, Coverage and Peening Intensity.

DENT SIZE

Shot peening produces dents in the surface of components. The profusion of dents is the most obvious indication that peening has been carried out. Important features are the average dent size and the extent of denting—coverage. Dent size is directly related to peening intensity and therefore the depth of the work-hardened, compressively stressed surface layer.

An empirical equation has been derived that connects the main variables that affect dent size:

$$\mathbf{d = 1.278.D.P^{0.25}.\rho^{0.25}.v^{0.5}/ B^{0.25}} \qquad \mathbf{(10)}$$

where **d**= indent diameter, **D** = indenting sphere diameter, **P** = proportion of kinetic energy lost on impact, **ρ** = density of indenting sphere, **v** = sphere velocity and **B** = Brinell hardness of component.

In words, equation (10) implies that dent diameter is directly proportional to shot diameter, proportional to the square root of the shot velocity but only proportional to the fourth root of the proportion of kinetic energy absorbed on impact and shot density. Dent diameter reduces with the fourth power of the component's Brinell hardness. Hence, for example, doubling dent diameter requires a fourfold increase of shot velocity and an eightfold increase in shot density.

COVERAGE

(1) Coverage versus Peening Time

The equation for coverage versus peening time is:

$$\mathbf{C = 100(1 - exp((-\pi D^2/4).R.t))} \qquad \mathbf{(11)}$$

Where **C** is the percentage coverage, **D** is the average diameter of each dent, **R** is the rate of impacting (number of dents imparted per unit area of surface per unit of peening time) and **t** is the peening time.

(2) Coverage Rate

Coverage rate is very important for shot peeners because it determines how long a component needs to be peened in order to impart the customer's specified amount of coverage. The coverage rate, **K**, is given by:

$$\mathbf{K = (\pi D^2/4). R} \qquad \mathbf{(12)}$$

For which the π**D²/4** term is the projected area of each dent. If we can assign a value to **K**, we can predict the coverage that will be achieved in any given peening time, **t**. Equation **(11)** simplifies to:

$$\mathbf{C = 100(1 - exp(-K.t))} \qquad \mathbf{(13)}$$

The coverage rate, **K**, is simply the product of the dents' average area multiplied by the rate at which these dents are being produced.

MULTIPLE DENTING

As coverage increases so does multiple denting of the component. At high levels of coverage there is a danger that parts of the component's surface will have its ductility exhausted—leading to crack formation. This topic was dealt with in the previous article in this series. The theoretical basis of multiple denting precision was presented at ICSP6.

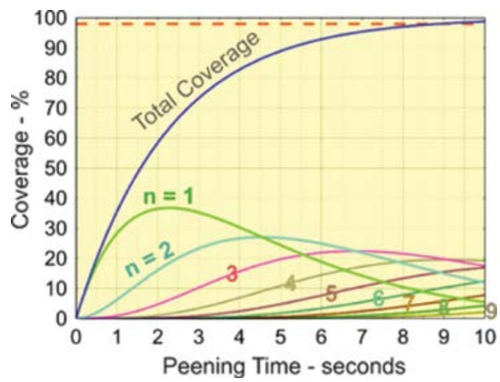

Fig.7. Contribution to total coverage of single and multiple denting.

Fig.7 allows the degree of multiple denting to be calculated graphically. For example, at 89% total coverage doubly-dented areas contribute 27% to the total, single-dented areas 25%, triple denting 20%, quadruple denting 11%, leaving 6% having greater than quadruple denting.

PEENING INTENSITY

Calculation of peening intensity is familiar to all shot peeners. The ready availability of computer-based programs allows unambiguous calculations to be made. There are, however, certain guiding principles that need to be taken on board. These concern both data collection and data analysis.

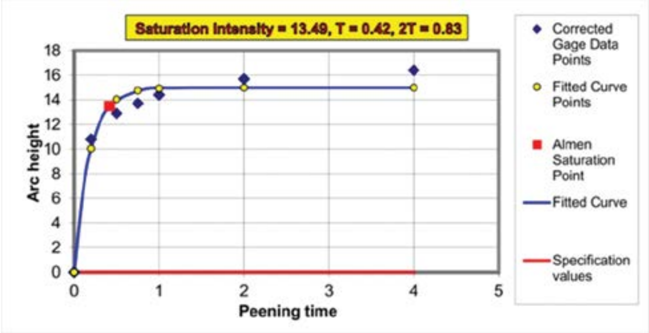

Fig.8. Peening intensity calculation using a two-parameter equation.

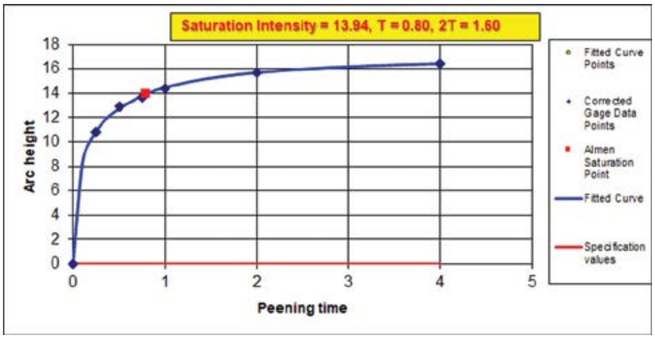

Fig.9. Peening intensity calculation using a three-parameter equation.

The Solver Suite equations used for figs. 8 and 9 were, respectively:

$$h = a*(1 - EXP(-b*t)) \tag{14}$$

$$h = a*(1 - EXP(-b*t^C)) \tag{15}$$

where **a**, **b** and **c** are parameters.

Additional calculations are present when using Solver suite programs. Fig.10 is an illustrative example. **SUM** indicates the goodness of fit— smaller values equate to better fit. The **Residuals** column shows how the data deviates from the selected equation and by how much.

SATURATION CURVE SOLVER, PROGRAM SCS1
EXP2P STANDARD vers.09

Strip No.	Time	Arc Height	Pre-bow	Corrected Height	Calc. Y	Residuals	Res. Sqrd	Parameters	Values
								a	8.65
	0	0	0	0	0	0	0	b	0.53
1	1	4	0.2	3.8	3.53419	-0.265813	0.070657	Start value for a=	9
2	2	6.3	0.5	5.8	5.62433	-0.175672	0.030861		
3	4	7.5	0.2	7.3	7.5915	0.2915015	0.084973	Sat. Intensity =	7.35
4	6	8	0.1	7.9	8.27954	0.3795433	0.144053	T =	3.61
5	8	8.3	0.1	8.2	8.52019	0.320194	0.102524		
6	13	8.8	0.3	8.5	8.64027	0.1402742	0.019677		
7	18	8.9	0.1	8.8	8.64896	-0.151038	0.022813		
8	22	9.2	0.2	9	8.64956	-0.350444	0.122811	If WARNING or ERROR appear	
9	26	9.4	0.4	9	8.64963	-0.350371	0.12276	above, read note below graph.	
			Lower Spec.=			SUM =	0.72113	RMS-R=	0.2831
			Upper Spec.=						

STEP 1 Enter data values within blue frame after deleting previous values.
Arc heights to be in thousandths of an inch or micrometers.
STEP 2 Enter largest CORRECTED arc height as a start value for "a" in J4 (required value appears in J6).
STEP 3 Select box containing Sum of Residuals squared, H16, click Data (on Excel toolbar),
select SOLVER, click on SOLVE, press OK.
STEP 4 Enter required Lower and Upper specification values in
red frame above - if you wish to, otherwise delete previous values.

Fig.10. Example of a Solver program's calculations. A four-parameter equation is available but its use is only recommended for research purposes.

DISCUSSION

An attempt has been made to cover the main types of calculation that are now encountered by shot peeners. The focus has been to base calculations on a combination of data and selection of an appropriate equation. Normally, we can predict the type of equation that will be appropriate. Having fitted the equation to the data we can then examine its significance. If the equation is not a good fit to the data, we have to consider why and consider alternative equations.

Previous calculations should always be stored for comparison purposes. For example, we may find that there is a general drift downwards in calculated peening intensity, even if precisely the same peening parameters have been applied. This can then be related to possible causes such as reduction of shot size.

Finally, it is worth repeating the opening sentence: "The ability to quantify its variables has allowed shot peening to evolve into a smart technological process." ●