Properties of Air-Blast Shot Streams

Dr. David Kirk

INTRODUCTION

Shot peening involves three factors – Shot Stream, Machine and Workpiece. These three factors interact to determine the prime-objective parameters of coverage and peening intensity. Fig.1 illustrates these interactions.

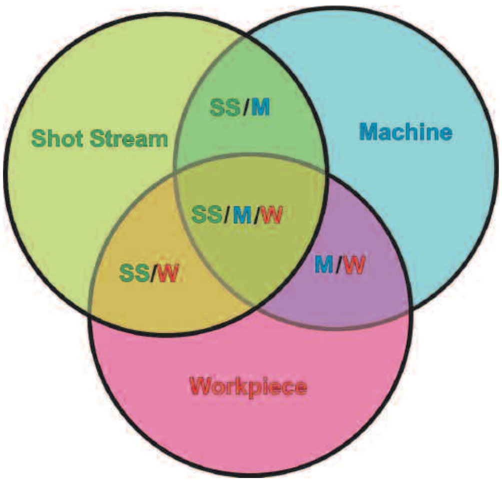

Fig.1. Interaction of Shot Peening Factors

Fig.1 represents the entirety of shot peening operations. For a particular operation the workpiece parameters (such as material, hardness, size and geometry) will be set by the customer. The prime-objective parameters of peening intensity and coverage will also be pre-determined, together with the shot type and size that are to be used. All (?) that the shot peener has to determine is the appropriate combination of shot stream and machine parameters, SS/M, that will satisfy the customer's requirements. "Parameter" in this context can be defined as "A measurable, variable, quantity that determines the outcome of an operation".

Shot streams have two components – 'inbound' and 'outbound'. The inbound shot stream component emanates from the nozzle whereas the outbound component consists of particles rebounding from a component's surface. This article is concerned with the quantification of both shot stream components. Quantification is an essential feature of modern engineering process control. A case study of inter-shot collisions is used to show how quantified properties can be employed to analyze significant peening problems.

The simplest geometrical model of an inbound air-blast shot stream is that of a truncated right circular cone. That means that the 'point' of the cone is missing, the axis is at right angles to the base and the base of the cone is a circle. The properties of an inbound shot stream are determined by the magnitudes and interactions of five primary parameters:

1. Mass Flow
2. Nozzle Diameter
3. Cone Angle
4. Shot and
5. Shot Velocity.

PRIMARY PARAMETERS

Fig.2 illustrates the general concept of a truncated right circular cone together with the five primary parameters.

Mass flow is the rate at which shot is being fed from the nozzle into the shot stream. Machine setting allows this to be quantified to some degree of accuracy. A MagnaValve setting of, for example, 6kg per minute, is equivalent to $100 g \cdot s^{-1}$.

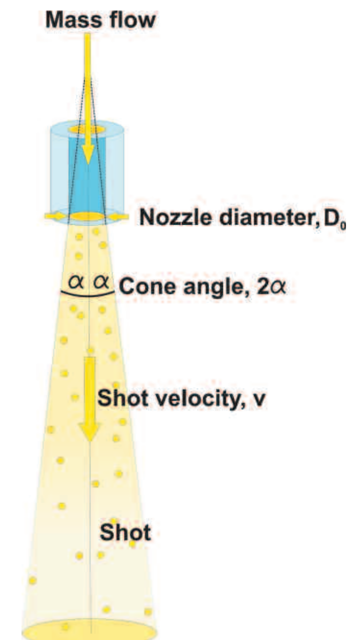

Fig.2. Primary parameters of inbound shot stream - shown as a truncated right circular cone.

Nozzle diameter, D_0, is a matter of a few millimeters, but is not constant due to progressive enlargement caused by wear.

Cone angle, 2α, is a vital parameter that defines the 'spread' of the shot stream. Its magnitude depends upon the type and length/diameter ratio of the nozzle. A long narrow cylindrical-bore nozzle will have a small cone angle-compared with that for a short wide nozzle. Convergent/divergent-bore nozzles will have cone angles regulated by the divergence angle. Commercial nozzles have a cone angle within a range of 5 – 45°.

Shot velocity, v, is a function of the air-pressure being applied. It's magnitude can be measured using either high-speed photography or inductive instruments. Alternatively the velocity can be inferred from measured indentation diameters imposed on material of known hardness. The magnitude is affected by the mass flow value.

Shot is simply the type of shot specified for a particular operation, e.g. S230. Specification ensures the chemical composition, hardness and size range of the particles.

GEOMETRICAL PROPERTIES

The truncated right circular cone model is reasonably-accurate for most shot streams. Fig.3 (page 26) indicates the important geometrical properties of this model.

The circular cross-section at any distance, S, from the nozzle has a diameter AB with a corresponding area of $\pi AB^2/4$. This area increases with both S and divergence angle, 2α. Fig.3 shows the relevant geometry of the situation.

The nozzle diameter, D_0, and the semi-angle, α, are defining shot stream parameters.

The cone has an imaginary origin at O and the circular base has a diameter D_S which varies with distance, S, from the nozzle. Equation (1) gives the relationship between circular base diameter, nozzle diameter and semi-cone angle.

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$$D_s = D_o + 2S.\tan\alpha \qquad (1)$$

We can only use equation (1) if we know the value of $\tan\alpha$. This has to be obtained by experiment e.g. by firing a stationary shot stream held at right angles to a stationary flat test plate and measuring the diameter, D_s, of the resulting indentation pattern. The nozzle diameter, D_o, and the nozzle-to-plate distance, S, are also measured. Alternatively, we could measure the average width (D_s) of the indentation 'trail' produced as the nozzle is moved at a fixed distance from a flat test plate. It follows from equation (1) that:

$$\tan\alpha = (D_s - D_o)/2S \qquad (2)$$

As an example: a given shot stream fired from a 10mm diameter nozzle produces a 50mm diameter indentation pattern when the nozzle is 200mm from a flat plate. Substituting these values into equation (2) gives that $\tan\alpha = (50 - 10)/400 = 0.10$. (The corresponding value for α is 5·7°.) Armed with a known value for tan· we can now estimate the shot stream diameter for any distance from the nozzle. We can also estimate the cone-section area variation with distance, A_s, using:

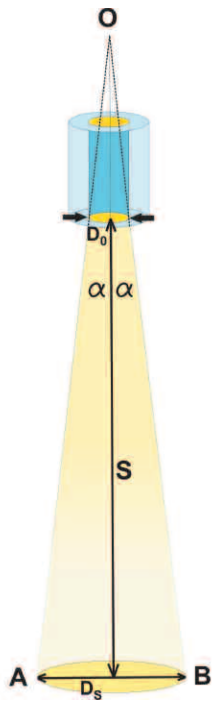

Fig.3. Geometry of an inbound conical shot stream.

$$A_s = \pi(D_o + 2S.\tan\alpha)^2/4 \qquad (3)$$

The change of stream diameter with distance from the nozzle is a **linear function** whereas that for area change is a **quadratic function**. The difference is illustrated in fig.4.

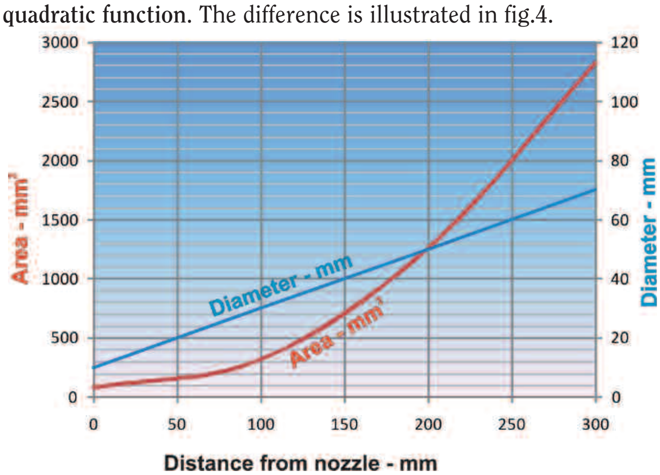

Fig.4 Variation of cone diameter and cross-sectional area with distance from a 10mm diameter, 5.7°, nozzle.

The divergence angle, 2α, can be in a range of 5° to 45° - depending on the type of nozzle being used. A smaller range, say 10° to 24° is normally employed, as illustrated in fig.5.

An elliptical shape is formed when a circular cone is intersected by a flat surface, see fig.6.

The ellipse has an area that is larger than that of the circle, diameter AB, formed at the same distance S from the nozzle. As a good approximation the major axis of the ellipse, DC, equals AB/cosθ. If, for example, θ is 45° then the area of the ellipse

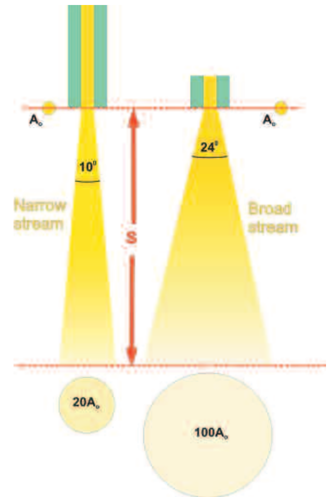

Fig.5 Narrow and broad inbound shot streams.

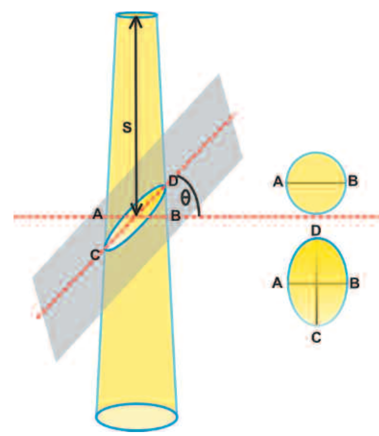

Fig.6. Ellipse formed by flat surface intersecting a circular cone at an angle θ.

($\pi \cdot a \cdot b$) is 1·4 times that of the circle, diameter AB, see insets on right of fig.6.

DYNAMIC PROPERTIES OF INBOUND STREAMS

Shot streams are made up of vast numbers of high-velocity particles. Collectively these streams of particles have dynamic parameters. The particles also have static parameters that are well-documented: size distribution, shape, material, hardness and density. Machine settings determine the rate and velocity at which shot is fed into the shot stream. These, in turn, control the dynamic shot stream parameters.

Mass Flow and Mass Flux

Mass flow, **MF**, is simply the mass of shot being fed into the shot stream per unit of time. Mass flux, **MXs**, on the other hand, is the mass of shot crossing a unit of area per unit of time. Hence:

$$MX_s = MF/A_s \qquad (4)$$

where A_s is the circular cross-sectional area at a distance, S, from the nozzle.

As an example, consider a machine setting whereby 6kg per minute of shot is constantly being fed into a 10mm diameter circular-section nozzle. Mass flow, MF, equals **$100 g \cdot s^{-1}$**. The cross-sectional area, A_s, at the nozzle is **78·5mm²** so that the nozzle mass flux is **$1{\cdot}27 g \cdot mm^{-2} \cdot s^{-1}$**. Mass flow, MF, is constant but the mass flux varies with the cross-sectional area of the shot stream. Substituting the value for A_s given by equation (3):

$$MX_s = 4MF/[\pi(D_0 + 2S.\tan\alpha)^2] \qquad (5)$$

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For instance, if MF = $100 \cdot g \cdot s^{-1}$, D_0 = 10mm, S = 200mm and α = 3·4° then MX_S = $0 \cdot 11 g \cdot mm^{-2} \cdot s^{-1}$.

Particle Flow and Particle Flux

Particle flow, PF, is the number of shot particles being fed into the shot stream per unit of time. **Particle flux, PX_S,** is the number of particles crossing a unit of area per unit of time. If we know the value of particle flux we can predict the rate at which the shot stream is making indentations on a component.

Particle flow is given by:

$$PF = MF/m \qquad (6)$$

where **m** is the average mass of an individual particle fed into the shot stream.

The simplest way of determining **m** is by weighing a known number of shot particles. That requires a high-precision set of scales - since S70, S170, S230 and S930 cast steel shot particles have average masses, **m**, of about 0·12, 0·54, 1·48 and 89.8mg respectively. If the mass flux was $100 g \cdot s^{-1}$ then the corresponding particle flux values would be 830,000, 190,000, 68,000 and 1,100s^{-1} respectively. As 'ballpark' figures, the range is from about one million to about one thousand particles per second depending on shot size (for the assumed mass flow of $100 g \cdot s^{-1}$).

Particle flux, PX_S, is given by:

$$PX_S = PF/A_S \qquad (7)$$

Consider, for example, a 36mm diameter shot stream striking a flat plate. The impact area is approximately 1000mm^2. The rate of impacting would then range from 1000 particles to 1 particle per square millimeter per second depending on steel shot size.

Particle Space Density and Particle Space Occupancy

Two significant questions are: "How many particles are there per unit volume of space in the shot stream?" and "How much space is occupied, on average, by each shot particle in the shot stream?"

Particle space density, **PSD**, is the number of shot particles per unit volume of space. PSD depends upon the mass flow, MF, particle velocity, v, cone-section area, A_S, and average mass of a particle, m. Equation (8) gives the corresponding relationship:

$$PSD = MF/(v \cdot A_S \cdot m) \qquad (8)$$

As an example: if **MF** = $40 g \cdot s^{-1}$, v = $60 m \cdot s^{-1}$, A_S =400mm^2 and **m** = 0·54mg (S170 shot) then equation (8) gives that **PSD** = 0.0031mm^{-3} (or 3.1 per cm^3).

Fig.7 is a simulated 'time-lapse picture' of the positions of the three shot particles (as estimated in the preceding example) in a one centimeter cube. The 'time-lapse' is 1/6000th of a second which is the time required for particles to travel 1 cm when at a speed of $60 m \cdot s^{-1}$. On average, three particles will have entered and three will have left the cube in that period. Particle positions are *almost* random ("almost" because particles cannot share the same space).

Particle space occupancy, **PSO**, is the volume of space occupied, on average, by each shot particle. It is simply the reciprocal of PSD so that:

$$PSO = v \cdot A_S \cdot pm/MF \qquad (9)$$

For the values in the previous example, PSO = 323mm^3. That is equivalent to one particle per 7mm-sided cube.

Particles in flight, N

The number of particles in flight, **N**, is the total number of particles in the inbound shot stream between the nozzle and a specified distance, S. This can be estimated using the equation:

$$N = MF \times S/(v \times m) \qquad (10)$$

For example, if **MF** = 40gs^{-1}, S = 300mm, **v** = 60m.s^{-1} and **m** = 0.54mg then **N** = 370.

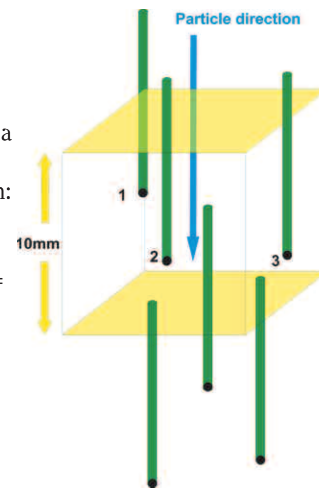

Fig.7. 'Time-lapse' representation of inbound particle positions for a PSD of 3 per cm^3.

Kinetic Energy

Every shot stream contains, at any given instant, a large number of particles moving at high velocity. Each particle has a kinetic energy, E, given by the most significant equation in the whole field of shot peening:

$$E = \tfrac{1}{2}mv^2 \qquad (11)$$

where **m** is the mass of the particle and **v** its velocity.

The velocity of shot particles is generally in the range of 10 to 100m s^{-1}. *For an individual shot particle,* we can combine a known shot velocity with its known mass to give its kinetic energy value. Fig.8 shows a 'log-log' plot of the variation of kinetic energy with velocity for different cast steel shot sizes. The range of energies involved is so enormous that there is no realistic alternative to the use of log-log plotting.

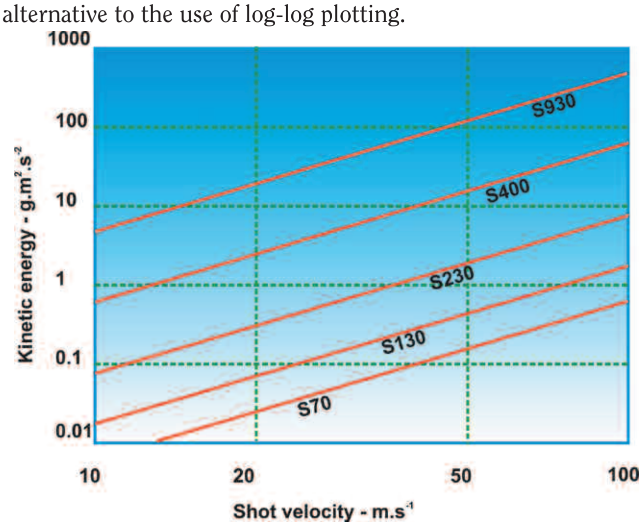

Fig.8. Variation of kinetic energy with size and velocity of cast steel shot particles.

There is a direct correlation between kinetic energy of particles and 'saturation intensity'. Coverage, on the other hand, is a combined function of kinetic energy flux and peening time.

Kinetic energy flow, KEF, is the total kinetic energy entering the shot stream per unit of time, E/t. Using equation (11) we have that:

$$KEF = \tfrac{1}{2}MF \cdot v^2 \qquad (12)$$

For a mass flow, MF, of 0.1kg·s^{-1} (6kg/min) of particles travelling at 60m·s^{-1} equation (12) gives that the kinetic energy flow is 180kg.m^2.s^{-3} – equal to 180W.

Kinetic energy flux, KFX, is the total kinetic energy of the particles crossing a unit of area per unit of time. This can be estimated by combining equations (7) and (11). *Continued on page 32*

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Hence:

$$KFX = \tfrac{1}{2}mv^2 \cdot PF/As \qquad (13)$$

OUTBOUND SHOT STREAM PROPERTIES

Shot particles rebound from the component's surface producing an 'outbound' shot stream that interacts with the inbound shot stream. The geometry of the outbound stream is largely governed by that of the component at the area of impact. It is therefore impossible to generalize about the outbound stream's properties. Fig.9 shows just one type of situation - in which a narrow shot stream rebounds from a flat-surfaced component. Very close to the component's surface the outbound shot stream has a particle space density that exceeds that of the inbound stream. For example, if we have three particles per cubic centimeter inbound at 60m·s^{-1} rebounding at 45m·s^{-1} then there must be (on average) four outbound particles in the same cubic centimeter.

CASE STUDY – INTER-SHOT COLLISIONS

A very important property of the outbound shot stream is the opportunity that it affords for particle collisions. Some of the rebounding outbound particles must collide with inbound particles. Collisions vary over a range from 'slight glancing' to 'head-on'. Head-on collisions can lead to fracture of shot particles because of the combined velocities – just as with an auto crash. The rebound velocity depends upon the inbound velocity and on the coefficient of restitution between the particle and the component surface. As a typical example, the rebound velocity is 70% of the inbound velocity. For an inbound velocity of 60m·s^{-1} a head-on collision between inbound and outbound particles would then be at about 100m·s^{-1} (220 m.p.h.). Glancing collisions divert the incoming particles so that they strike components at less favorable angles than if they had not suffered a collision. A 'serious collision' occurs at a much greater velocity than does simple particle/component impacting. It is therefore likely to be the dominant cause of shot breakage – especially for relatively-brittle shot particles.

Fig.9. Inbound shot stream generating outbound shot stream.

Important questions are: "What is the probability of a 'serious collision'?" and "What factors affect the frequency of collisions?" Reasonable estimates can be obtained using the semi-descriptive approach that follows. More precise estimates require complex analytical statistical methods.

Collision Circles

Consider just two 0·5mm diameter particles, one inbound and one outbound, that are 'set on a collision course'. The center of one particle must lie somewhere within a 1·0mm diameter 'collision circle' that coincides with the center of the other particle, as illustrated in fig.10. An inbound particle with its center at A will make a 'head-on' collision with the outbound particle. If the center is at B, on the edge of the collision circle, it will only just make glancing contact. The area of the 'collision circle' is π·d^2 where d is the diameter of the particle.

Glancing-angle collisions will, however, have no significant effect on peening efficiency. A 'serious collision' could be defined as one where the diameter of the inbound particle lies within a circle that is half of that of the collision circle. For such impacts the inbound particle is diverted to a striking angle of 30° or less. Hence we can define a 'serious collision circle', as shown in fig.10 with an inbound particle having its centre at C. The area of the 'serious collision circle' is π·d^2/4, where d is the diameter of the particle.

Collision Probability

The probability, **p**, for any type of single pair collision depends upon the particle space density and the particle diameter. *If*, for example, we have just one pair of 0·5mm diameter particles in a one centimeter cube then since **p = area of collision circle/area of cube face** we have that **p = π/100 or 3·2%**. The area of a 'serious collision' circle is only a quarter of that of the collision circle. The probability of a 'serious collision' is therefore only a quarter of that for 'any type of collision', e.g. 0·8% (for the previous case).

The probability, P_T, of an 'any type' collision occurring within a defined volume (1 cubic centimeter) for an individual inbound particle increases with the particle space density, as shown by equation (14):

$$P_T = \frac{\pi.d^2}{100} . \frac{4}{3} . \text{P.S.D.} \qquad (14)$$

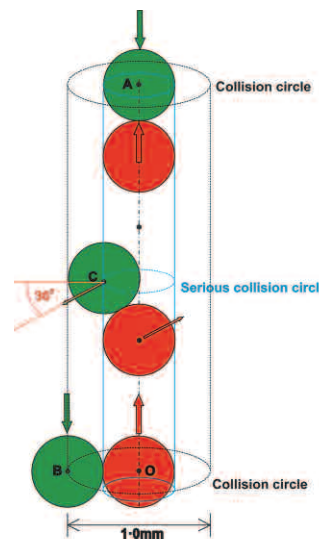

Fig.10. Collision circles for inbound and outbound particles.

If, for example, P.S.D. equals 3 then we have 4 outbound particles in our defined volume (assuming that the rebound velocity is 75% of the inbound velocity). For d = 1mm then P_T = 12·8%. The probability of *one particular* particle having a 'serious collision' is a quarter of that for an 'any type' collision – 3·2% for this example.

Collisions will occur not only in just one centimeter cube but also in other such cubes that are in the same line. The number of such cubes depends upon the geometry of the stream/workpiece interface. Flat component surfaces, as shown in fig.9, would generate the largest number and hence the greatest multiplying factor.

The collision probability for every shot particle fired at a component is directly proportional to the particle space density of the shot stream. Particle space density is, however, directly proportional to the mass flow, MF. Hence we have the important relationship that:

The collision probability for every shot particle fired at a component is directly proportional to the mass flow of the shot stream.

Fig.11 illustrates the linear relationship between collision probabilities and mass flow. It should be noted that the actual values are specific to the shot variables used in the previous example (0·5mm diameter steel shot at 60m.s^{-1} and a 400mm^2 shot stream cone cross-section).

DISCUSSION

All of the significant shot stream properties

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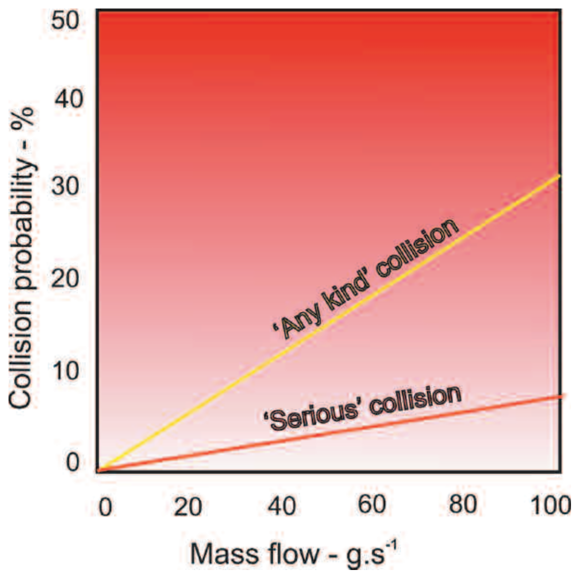

Fig.11 Effect of mass flow on collision probabilities – for specified shot stream parameters.

can be quantified to a reasonable degree of accuracy. Most of those properties require a knowledge of the shot stream's divergence angle. This angle is governed by the aspect ratio (length/diameter) and shape of the nozzle. There are hundreds of different nozzles available commercially - covering variations of shape, material and aspect ratio. Given the importance of shot nozzle divergence angle it is surprising that there is virtually no published information on the subject. Users appear to have to rely upon prior experience/guesswork to select an appropriate nozzle angle.

Control of all engineering processes is affected by parameter variability. During a given peening operation variations occur in mass flow rate, shot size, shot velocity and shot shape. The nozzle diameter, for example, increases progressively due to the severe wear regime. This, in turn, affects the shot stream's properties.

Quantified shot stream parameters can be employed to examine various aspects of shot peening. The one example given in this article, that of collision probabilities, has indicated that, with typical machine parameters, there is a significant chance of a 'serious collision' between inbound and outbound particles. Their combined velocities induce a much more critical shot fracture situation than that experienced by inbound particles contacting the component's surface. Colliding inbound particles are deflected away from the ideal perpendicular impact with the component's surface. Collision frequency and shot fracture rate can be reduced by lowering the shot feed rate (mass flow). This does, however, require longer peening times in order to achieve the same coverage. It is worth noting that 'excessive' peening not only wastes peening time and reduces component surface properties but also increases the total number of shot particle fractures.

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.