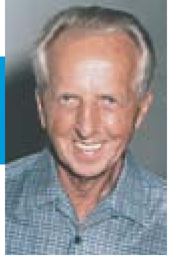

ACADEMIC STUDY

by Prof. Dr. David Kirk | Coventry University, U.K.

Shot Stream Power and Force

INTRODUCTION

Shot peening is achieved by directing a powerful shot stream at components. The stream's power depends upon the velocity, flow rate and density of the shot and carrier fluid (normally either air or water). Much of the power of the shot stream is absorbed when it strikes a component causing dents, compressive residual stress and surface work-hardening. The force exerted on components is rarely considered – but is very important. This force can easily be measured, giving an insight into the relative contributions of shot and carrier fluid.

This article presents equations that allow reasonably accurate estimates to be made of a shot stream's power and the force that it can exert. The mathematical background to these equations is necessarily included - in order to justify the practical implications that are considered. A separate section summarizes the equations as an Excel worksheet - which can be used directly to estimate power and force for any shot stream situation. The equations show that air-blast shot streams normally have several hundred watts of power whereas wheel-blast streams have several kilowatts of power. The force that a shot stream applies (to reasonably flat surfaces) varies from tens of Newtons to hundreds of Newtons. Air, on its own, will exert a higher force than will an air/shot mixture – because of the drag-effect slowing down the air's velocity. For the rest of this article, air is assumed to be the carrier fluid. Calculations can readily be modified to accommodate a different fluid.

SHOT STREAM POWER

Shot streams are a mixture of shot particles and a carrier fluid – assumed hereafter to be air - moving at a high velocity. Shot stream power, **P**, therefore has two components; shot power, **S**, and air power, **L**. Hence: **P = S + L**. Shot power is the sum of the kinetic energies of those shot particles that cross a defined plane, AB, per second – see fig.1. Air power, **L**, is the kinetic energy contained by the volume of air that crosses the corresponding area, **A**, of that defined plane per second.

Shot Power, S

Shot power is kinetic energy per second summed for all of the particles crossing a defined area. Each shot particle crossing the area contributes its individual kinetic energy, $\frac{1}{2}\mathbf{m}\mathbf{v_s}^2$. Particles are striking the surface at a very high frequency. Coupled with the relatively high moment of inertia of a component that means that particle impact can be treated as if it was continuous. The shot feed rate, **M**, sums the mass of all of the particles fed during one minute. Hence we have, when using metric units, that:

$$\mathbf{S = M^* v_s^2/120} \qquad (1)$$

where **S** is in watts, **M** is in kg/minute and $\mathbf{v_s}$ is in meters per second.

As a typical air-blast example:
if **M** = 10 kg/minute and $\mathbf{v_s}$ = 50 ms^{-1} then **S** = 208 watts.

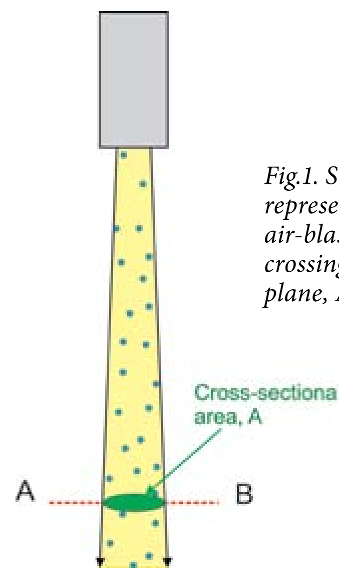

Fig.1. Schematic representation of an air-blast shot stream crossing a defined plane, AB.

Equation (1) is based on the familiar expression for individual particle kinetic energy, $\frac{1}{2}\mathbf{mv}^2$, summed for the total mass of particles fed during one second.

Use of imperial units requires a different divisor from that given in equation (1). Hence:

$$\mathbf{S = M^* v_s^2/2848} \qquad (2)$$

where **S** is still in watts but **M** is now in lb/minute and $\mathbf{v_s}$ is in ft/second.

Converting the values used for the metric example gives that M = 22 lb/minute and v_s = 164 ft/second. Substituting these values into equation (2) again gives that **S** = 208watts.

The feed rates for wheel-blast shot streams are an order of magnitude greater than those for air-blast machines. It follows that the corresponding shot power will usually be several kilowatts.

Air Power, L

Air power, **L**, is the kinetic energy contained by the volume of fluid that crosses the defined plane per second. The volume of air passing across the plane per second, **V**, depends upon its velocity, $\mathbf{v_A}$, and the area of intersection, **A** (see fig.1). Now $\mathbf{V = v_A * A}$. The mass of any object is its density, **ρ**, multiplied by its volume. Hence: Air mass flow per second is given by $\mathbf{\rho * v_A * A}$. Air power, **L**, is its kinetic energy, $\mathbf{½mv_A^2}$ summed for the mass of air crossing the plane per second. Therefore:

$$\mathbf{L = ½\, \rho * v_A^{3} * A} \tag{3}$$

where **L** is in watts, **ρ** is in $kg.m^{-3}$, $\mathbf{v_A}$ is in meters per second and **A** is in square meters.

The density, **ρ**, of air at atmospheric pressure, is 1.225 kgm^{-3}. For a stream of air passing through a standard area, A, of 0.001 m^2 (1000 mm^2) at a velocity, v_A, of 50 ms^{-1} equation (3) indicates that its power is 77 watts.

If, however, the fluid was water, with its density of 1000 kgm^{-3}, then for the same area and velocity used for the preceding example, the fluid stream power becomes 62.5 kilowatts!

Combined Shot Stream Power, P

The combined shot stream power, **P**, is the sum of shot power, **S**, and air power, L, as shown pictorially in fig.2. If we assume that shot and air velocities are almost equal we get, as a very close approximation, that:

$$\mathbf{P = M * v^2/120 + ½ * \rho * v^3 * A} \tag{4}$$

where **v** is the shared shot and air velocity.

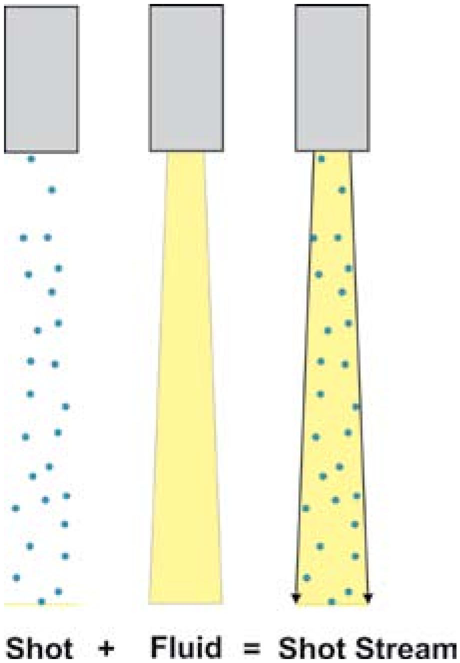

Fig.2. Constituents of a shot stream.

Shot and air velocities are equal at a 'neutral point distance' from a nozzle, i.e., when $\mathbf{v_S = v_A}$. This has also been termed the "sweet point" – which corresponds to a maximum in the peening intensity potential of a shot stream. Fig.3 represents schematically, the neutral point distance, **NP**. From the nozzle to the neutral point the air is travelling faster than the shot so that the shot particles are being accelerated. After the neutral point the shot is being decelerated.

If no shot has been added to a given air stream then its velocity must be greater at any given distance from the nozzle – as indicated in fig.3. The presence of shot particles means that the high-velocity air has to do work in order to accelerate the particles. Airflow patterns are also being disturbed as the air molecules have to find a way around the particles.

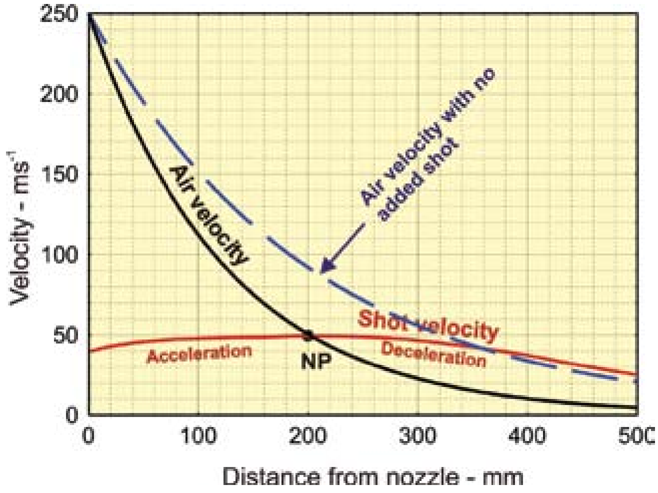

Fig.3. Neutral point, NP, when air and shot have equal velocities.

FORCE EXERTED BY SHOT STREAMS

Shot streams exert a force when they strike components. This force increases with increased power of the shot stream. Reasonable estimates of the forces involved can readily be obtained by invoking Newton's 2nd Law of Motion. This law can be written as:

The force exerted by a fluid stream is equal to the rate of change of momentum encountered on striking an object.

Momentum is mass multiplied by velocity. Rate of change of momentum is, therefore, mass times velocity divided by time. This leads to two 'textbook' equations that are relevant to shot stream force estimation:

Shot force, $\mathbf{F_s}$ = Mass x Velocity/Time or

$$\mathbf{F_s = M * v_s/60} \tag{5}$$

Where **M** is the feed rate in kg/minute and $\mathbf{v_s}$ is the shot velocity in ms^{-1}.

$$\textbf{Air force, } \mathbf{F_A = \rho * A * v_A^2} \tag{6}$$

Where **ρ** is the air density in kg/m3, and $\mathbf{v_A}$ is the air velocity in ms^{-1}.

Equation (5) shows that the force exerted, by just the shot particles, is a linear function of both feed rate and shot velocity. Equation (6) shows that the force exerted by the air alone is a linear function of the cross-sectional area, A, but increases with the square of the air velocity. Fig.4 illustrates the velocity-variation of the two force components over practicable ranges of shot feed rates and stream cross-sectional area. It is noteworthy that at high velocities the examples show that air tends to exert a much higher force than does the shot.

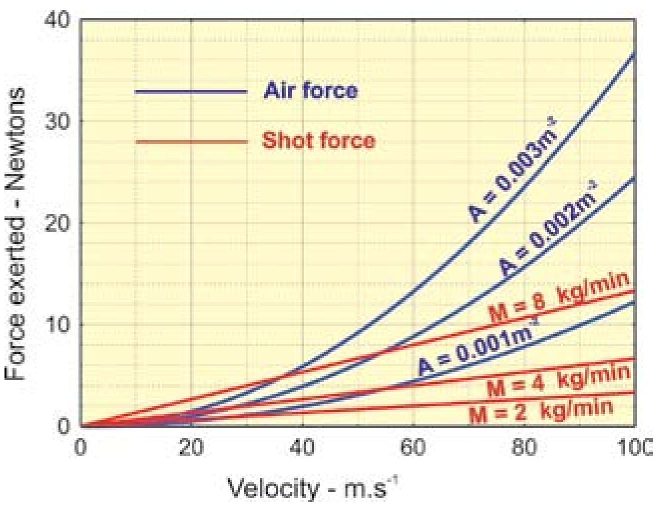

Fig.4. Force variation for separate air and shot components of a shot stream.

Shot stream force, **F**, is estimated by adding the shot and fluid force components so that:

$$\textbf{Shot stream force, } F = M^*v_S/60 + \rho^*A^*v_A^2 \qquad (7)$$

Even if we know **F**, **M**, **ρ** and **A**, equation (7) still contains two 'unknown quantities': $\mathbf{v_S}$ and $\mathbf{v_A}$. Fortunately, most shot peening is carried out at, or near to, **NP**, the 'neutral point distance' when $\mathbf{v_S}$ and $\mathbf{v_A}$ equal one another. The addition of forces for equal air and shot velocities is illustrated in fig.5. This uses an example when M = 4 kg/minute and A = 0.002 m².

For point X in fig.5, it can be seen that air contributes 6.25 N and the shot contributes 3.75 N to the total of 10 N. The common shot and air velocity at the point X is 52 m.s⁻¹.

FORCE MEASUREMENTS

Shot stream forces can easily be measured directly. Fig.6 shows a schematic representation of a direct force measurement device.

Force can be indicated by several types of instrument – from a dedicated load cell to a simple household weighing scale. The type of facility indicated in fig.6 is readily portable and can be inserted into various locations in a shot peening machine: - for example to assess a multi-nozzle arrangement.

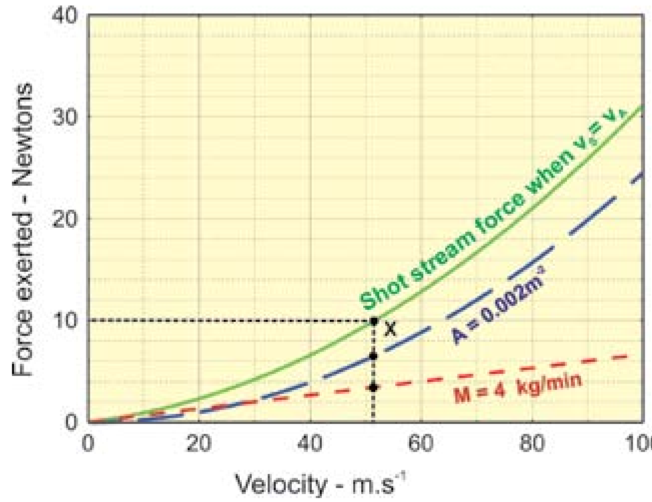

Fig.5. Shot stream force when air and shot velocities are equal to one another.

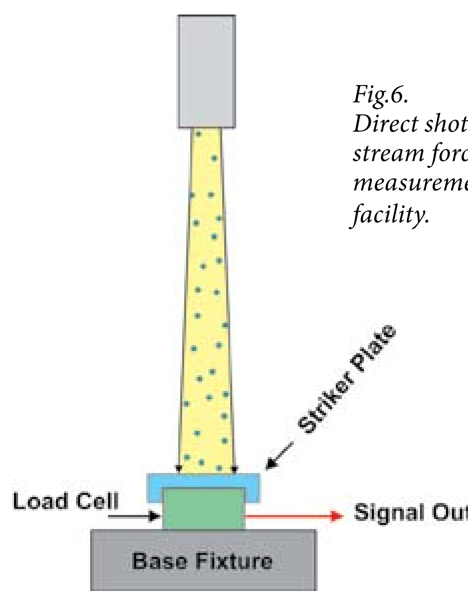

Fig.6. Direct shot stream force measurement facility.

FORCE MEASUREMENT STUDIES

Measurements have been made involving different air pressures and shot feed rates. These measurements were carried out at Electronics Inc. under the supervision of Jeff Derda. The setup involved the use of a highly controlled air-blast cabinet, S230 shot, 8 mm nozzle at 150 mm from a target steel plate on a protected digital weighing scale. Shot indentations on the steel plate indicated a circular impact region having a diameter of 49.5 mm. That translates to a target area, A, of 1924 mm². Table 1 on page 30 details the twelve measurements obtained (converted from Imperial to S.I. units). Analysis of the data in Table 1 can be carried out using graphical representations.

Table 1. Force Measurement Data Obtained by Electronics Inc.

Air pressure	Measured forces - Newtons			
	Air-only	Air + 2.2kg/min	Air + 4.5kg/min	Air + 7.0kg/min
20 psi (1.4 atm)	7.6	5.8	4.9	4.0
40 psi (2.7 atm)	14.7	12.9	11.1	10.5
60 psi (4.1 atm)	22.7	18.7	17.8	17.4

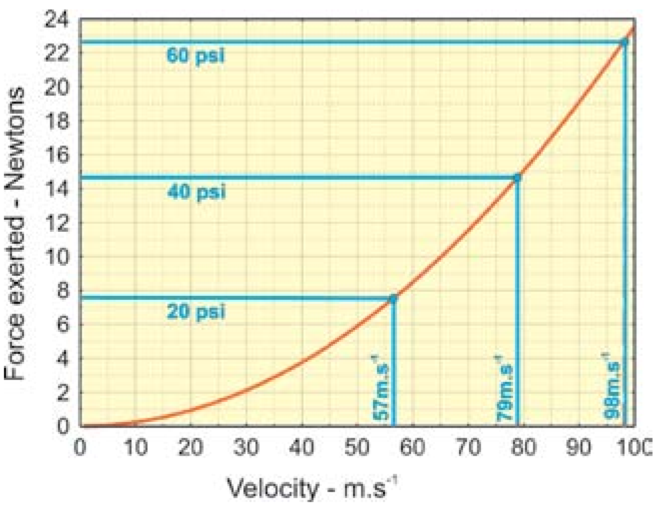

Fig.7. Force predicted with air-only stream striking a circular area of 1924 mm².

Fig.7.represents the 'Air-only' data, indicating: (1) that the force exerted increases directly with the air pressure and (2) that the inferred air-only velocities are 57, 79 and 98 $m.s^{-1}$ for 20, 40 and 60 psi pressures respectively.

Before analyzing the air-plus-shot data it is important to bear in mind that:

Shot added to an air stream must slow it down.

The amount of air velocity reduction will increase with the proportion of shot in the mixture.

Fig.8 represents the shot feed rate of 4.5 kg/min accelerated by an air pressure of 40 psi. The measured value of force being exerted by this combination was 11.1 Newtons (see Table 1). A force of 11.1 Newtons intersects the air-plus-shot line at point X in fig.5. The common velocity for the air and shot will, therefore, be 54 ms^{-1}. The air velocity for air flow on its own at 40 psi is 79 ms^{-1}. Hence it can be deduced that the shot, when fed at 4.5 kg/min, has slowed down the air velocity of the shot/air stream from 79 to 54 ms^{-1}. Such a reduction, 25 ms^{-1}, is perfectly reasonable. It should be noted that air on its own at 79 ms^{-1} exerts a force of 14.7 Newtons – significantly greater than the 11.1 Newtons for air-plus-shot at the same nozzle pressure.

Similar analysis can be applied to each of the nine air-plus-shot values. Graphical analysis is unnecessary if the required calculations are incorporated into, say, an Excel worksheet. Table 2 presents the results of a worksheet analysis of the Table 1 data.

Table 2. Analysis of Data Showing Estimated Velocities and Retardation Effect

Air pressure - psi	Parameter	Air only	Air + 2.2kg/min	Air + 4.5kg/min	Air + 7.0kg/min
20 (1.4 atm)	Force - Newtons	7.6	5.8	4.9	4.0
	Retardation – Newtons	-	1.8	2.7	3.6
	Velocity - ms^{-1}	56.8	42.4	32.4	23.3
	Retardation – ms^{-1}	-	14.4	24.4	33.5
40 (2.7 atm)	Force - Newtons	14.7	12.9	11.1	10.5
	Retardation - Newtons	-	1.8	3.6	4.2
	Velocity - ms^{-1}	79.0	66.6	54.5	46.4
	Retardation – ms^{-1}	-	12.4	24.4	32.5
60 (4.1 atm)	Force - Newtons	22.7	18.7	17.8	17.4
	Retardation - Newtons	-	4.0	4.9	5.3
	Velocity - ms^{-1}	98.1	81.6	72.4	64.7
	Retardation – ms^{-1}	-	16.5	25.7	33.5

"Retardation" is the difference between the estimated 'air only' values and the values when shot is being fed into the stream. For example: at 20 psi applied pressure the air velocity is 56.8 ms^{-1} with no added shot. This is reduced to 42.4 ms^{-1} when 2.2 kg/min of shot is added. The difference (56.8 minus 42.4) is the retardation value of 14.4 ms^{-1}. Retardation increases with shot feed rate for each of the force and air velocities. Retardation is, however, very similar for different air pressures but a constant feed rate. For example: with a feed rate of 4.5 kg/min the retardation is 24.4, 24.4 and 25.7 ms^{-1} for 20, 40 and 60 psi air pressures respectively.

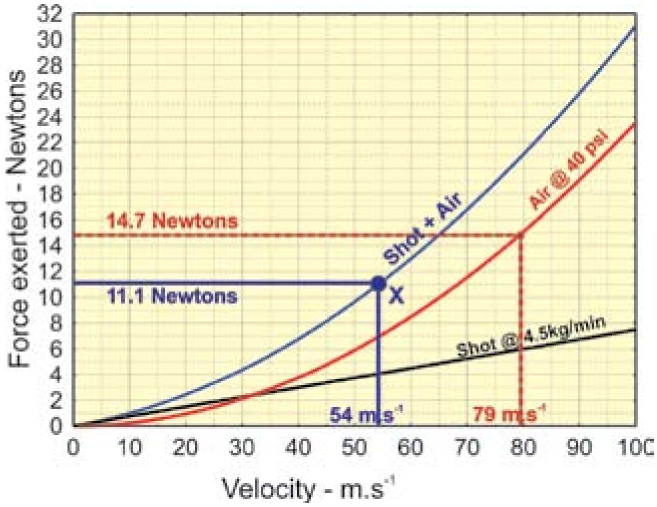

Fig.8. Force exerted with a feed rate of 4.5 kg/min and an air pressure of 40 psi.

POWER AND FORCE ESTIMATION

The equations presented for estimating power and force can easily be fed into an Excel worksheet. One example is presented as Table 3 (page 32), where the column heading letters correspond to those in an Excel table as do the row numbers.

Table 3. Excel Worksheet for Estimating Shot Stream Power and Force

A	B	C	D	E
3	Feed rate	M	5	kg/minute
4	Shot velocity	v – shot	50	m/second
5	Fluid velocity	v – fluid	50	m/second
6	Fluid density	ρ	1.225	kg/cubic meter
7	Cross-sectional area of shot stream	A	0.001	meters squared
10	Shot power	S	104	watts
11	Fluid power	L	77	watts
13	Shot stream power	P	181	watts
15	Shot force	F_S	4	Newtons
16	Air force	F_A	3	Newtons
17	Force applied on flat surface	F (F_S+F_A)	7.2	Newtons

Values of variables are entered into rows 3 to 7 of column D to yield the required estimates (given in red). Table 4 gives a number of examples, illustrating the range of power and force that can be encountered for different shot streams, obtained using the worksheet.

Table 4. Estimates of Shot Stream Power and Force Exerted on a Flat Surface

M – kg/minute	5	10	20	10	100
V_s –m.s^{-1}	100	100	100	50	50
V_L –m.s^{-1}	100	100	100	50	50
ρ	1.225	1.225	1.225	1.225	1.225
A	0.001	0.001	0.001	0.001	0.01
Power, P - watts	1029	1446	2279	208	2849
Force, F - Newtons	20.6	28.9	45.6	11.4	114

DISCUSSION

Shot stream force and power can be regarded as useful complements to established parameters: such as peening intensity, coverage and residual stress profile. They enable different aspects of the process to be controlled.

The force required to propel a shot-plus-air stream has been the subject of previous studies by Robert A. Thompson of the General Electric Company. His 1989 patent (U.S. Patent Number 4,848,123) included the incorporation of a force sensor behind the peening gun to monitor the reaction force of the shot peening gun. Hence the force required to propel the shot stream out of the nozzle was being measured. That is different from the force that a shot stream imparts onto a workpiece – which varies with distance from the nozzle. The device recommended in this article monitors shot streams directly and has the advantage of being removable from the peening cabinet.

Assessment of force due to the air flow alone can be used as a check on air supply from the nozzle. Force variation is a direct function of the air pressure being supplied to the actual nozzle. Hence it would be possible to confirm the validity of any air pressure meters - they must, of necessity, be back stream of the nozzle.

Assessment of force due to a given shot stream (air-plus-shot) will indicate (a) the potential for component distortion during the actual peening process and (b) if previous assessments using the same peening parameters are being maintained. Component distortion due to the force applied by a shot stream will be the theme for the next article in this series.

The power and force equations presented in this article are based on fundamental laws of physics. They do not have to be understood in order for them to be utilized. Excel worksheets can be devised or obtained from the author via email at shotpeener@btinternet.com.

Force measurements can be made using quite simple equipment. The force equations have enabled the effect of shot on slowing down air stream velocity to be quantified. The measurements also allow an estimate to be made of the common air and shot velocities that reign at the neutral distance ("sweet point") from the nozzle. The force equations presented in this article can be modified to accommodate different anticipated velocity differences.

Shot peening should normally be carried out with a nozzle-to-workpiece distance at, or close to, the neutral distance. That is where the shot particles have their maximum velocity and hence their maximum peening intensity potential. The neutral distance can be established by experimentation. Two techniques that have been used are (a) to produce saturation curves for various nozzle-to-workpiece distances and (b) to peen polished mild steel strips at various nozzle-to-strip distances using a low coverage regime. The average diameter of indentations is a direct measure of the shot stream intensity. Mild steel is recommended because it is relatively photogenic, facilitating indent diameter measurements.

The potential for applying large forces can readily be quantified using the equations presented in this article. Very large forces can plastically distort thin sheet metals. For example: Waterjet streams have been utilized as a shaping process for annealed, 0.3 mm thick, aluminum sheet. Steel shot had to be added to the water stream to generate large-enough forces to plastically form stainless steel sheet (Iseki et al, Key Engineering Materials, p. 575, vol. 344, 2007). The use of water underlines the significance of carrier fluid density incorporated into this article's equations.