ACADEMIC STUDY

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Water-Jet Peening and Water-Jet Shot Peening

INTRODUCTION

Water-jet peening and water-jet shot peening have the common feature of employing a jet of water. There are, however, important differences between the two processes. Water-jet peening has to impose a direct pressure high enough to generate surface plastic deformation. Water-jet shot peening, on the other hand, uses entrained high-velocity shot particles to generate the required surface plastic deformation. Figs.1 and 2 illustrate the essential differences between the corresponding impacting streams.

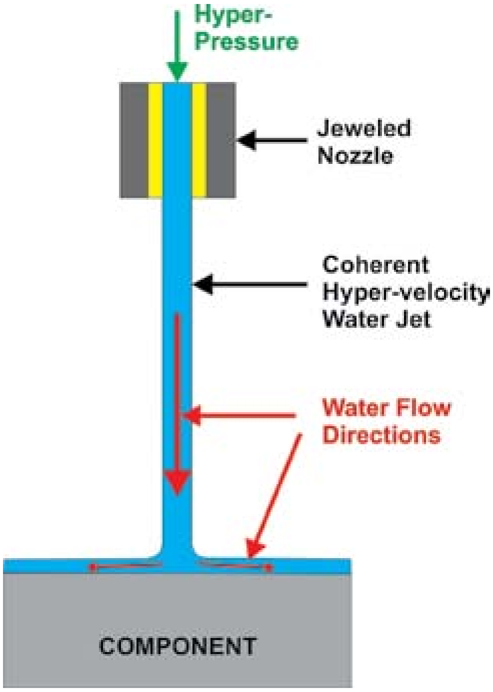

Figure 1. Schematic representation of Water-jet Peening

With water-jet peening, the nozzle shown is jeweled in order to provide adequate wear resistance. Every attempt is made to preserve 'coherence' of the jet stream, i.e., to prevent divergence.

With water-jet shot peening, shot is added to a much lower-velocity stream. Shot particles are accelerated by the water-jet, impact the surface and rebound.

The two processes are treated separately in this article but use common methods for estimating factors such as pressure, force and power.

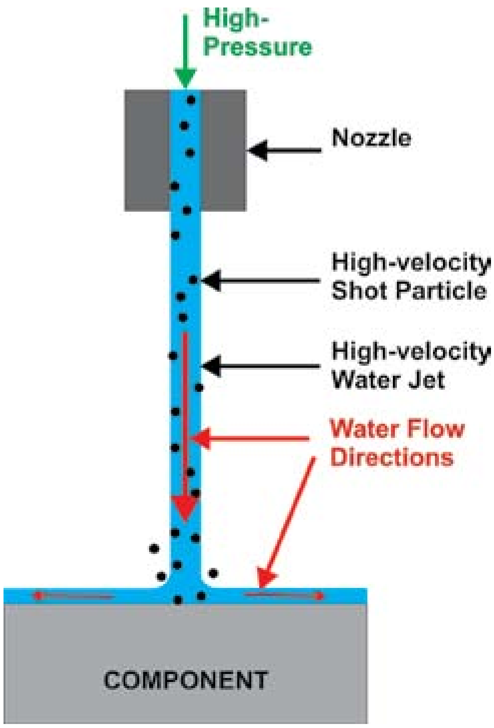

Figure 2. Schematic representation of Water-jet Shot Peening

WATER-JET PEENING

The essential requirement with water-jet peening is that the jet must exert a pressure greater than the compressive yield strength of the component material. Enormous pressure has to be applied to the water as it enters the nozzle. If the water stream diverges then its velocity drops. Water, being a liquid, is incompressible. That means that it behaves differently from an air jet.

Velocity of Water Jet

The velocity of a water jet, **V**, can be estimated using the following formula:

$$\mathbf{V = 44.721{*}P^{0.5}} \tag{1}$$

Continued on Page 26

Where **V** is water-jet velocity in m/s and **P** is the pressure applied behind the nozzle, in MPa.

As an example: If the applied pressure was 500MPa then substitution into equation (1) gives that **V** = 1000 m/s.

Equation (1) when using Imperial units becomes:

$$\mathbf{V = 377.56 * P^{0.5}} \tag{2}$$

Where V is water-jet velocity in ft/s and **P** is the pressure applied behind the nozzle, in kpsi.

Equations (1) and (2) are simplified forms of the classic fluid mechanics equation that $v = 0.98(2*P/\rho)^{0.5}$ where ρ is the density of water (1000 kg/m^3 for equation (1) and P is in Pascals).

Equation (1) has been plotted in fig.3 for a range of applied pressures. A logarithmic scale has been used for pressure because of the huge range that is involved. Water-jet velocities can be arbitrarily divided into "Low", "High" and "Hyper". It is hyper velocity that is applicable to water-jet peening.

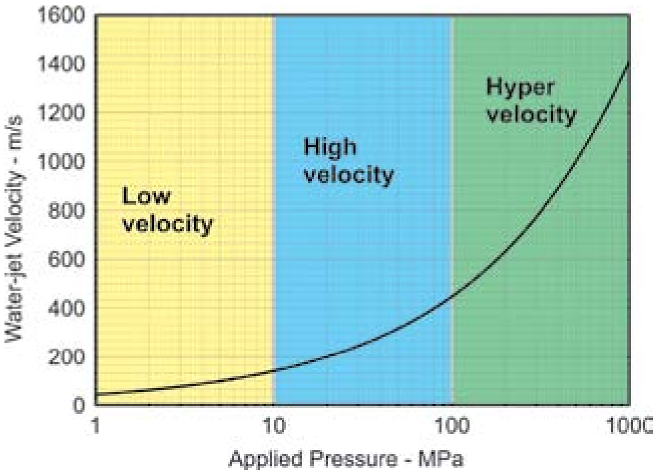

Figure 3. Effect of Applied Pressure on Water-jet velocity

Pressure Applied on a Component by a Water-jet

The pressure made on contact with a component, $\mathbf{P_W}$, is the key factor in water-jet peening. This pressure can easily be estimated knowing the density of water and the jet's velocity on impact. The following equation is central to water-jet peening:

$$\mathbf{P_W = \rho_W * v_W^2} \tag{3}$$

Where $\mathbf{P_W}$, in Pa, is the pressure exerted by a water-jet impacting at 90˚, $\boldsymbol{\rho_W}$ is the water density, in kg/m^3, and $\mathbf{v_W}$ is the velocity, in m/s, of the water-jet on impact.

In words: **the water-jet impact pressure is the density of water multiplied by the square of the jet's velocity.**

Water-jet peening relies on being able to exert a pressure greater than the component's yield strength in compression. According to metalworking theory, the yield strength in compression is 1.155 times the yield strength in tension. For water-jet peening the density of water is fixed at 1000 kg/m^3. Equation (3) therefore simplifies to become:

$$\mathbf{P_W = 1000 * v_W^2} \tag{4}$$

Air, at atmospheric pressure, has a density of 1.225kgm^{-3}. That means that a water-jet will exert about 800 times the pressure that would be exerted by an air jet that had the same velocity. The key to understanding water-jet pressure is that it is proportional to the square of the jet's velocity. Fig.4 plots the impact pressure of a water-jet against the jet's velocity. Material yield strength is plotted on the same scale.

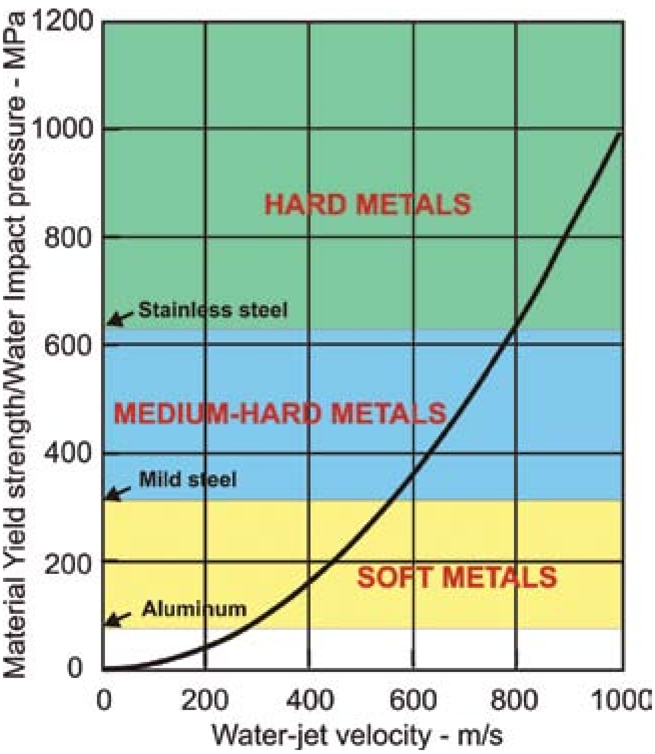

Figure 4. Effect of water-jet velocity on Impacting Pressure and Material Yield Strength

The water-jet velocity must generate enough impacting pressure to exceed the material's yield strength. In fig.4 materials have been divided, arbitrarily, into three groups. The softest material normally peened is aluminum which would require a minimum of about 300 m/s of water-jet velocity. At the top of the "Soft Metals" range mild steel would require nearly 600 m/s. Stainless steel, at the top of the "Medium-hard" group, would require a water-jet velocity of at least 800 m/s. Harder materials (than stainless steel) would require even greater water-jet velocities.

A curiosity of fluid mechanics is that the impacting pressure of a coherent water-jet is approximately twice the pressure applied behind the nozzle.

The foregoing account assumes that the water-jet neither diverges nor converges after it leaves the nozzle. Unlike air, water has 'surface tension'. Surface tension forces tend to maintain and minimize the surface area of water – either as drops or as a stream. Hence a water-jet stream tries to maintain its shape. Jet design and jet materials play an important part in ensuring that the water-jet stream does not diverge significantly. Imagine, however, that a water-jet stream doubled its diameter between nozzle and impact on a component. This would reduce the impact pressure by a factor of four (the cross-sectional area having been increased by a factor of four).

Water-jet Power

A high-velocity water-jet stream represents an enormous amount of power. This can be estimated using an equation presented in an earlier article in this series (Summer 2013):

$$\mathbf{JP = ½\ \rho * v^2 * A} \qquad (5)$$

Where **JP** is Jet-stream power, **ρ** is water density, **v** is water-jet velocity and **A** is the cross-sectional area of the water-jet as it leaves the nozzle.

As an example: a water-jet travelling at 1000 m/s and having a cross-section of 10 mm^2 represents a power of 5,000 kilowatts.

Water-jet Energy

Water-jets have a kinetic energy, ½mv^2, where m is mass and v is velocity. The energy can readily be estimated before it impacts a solid object.

Example: Consider the situation illustrated in fig.5. A 10 cms length of jet that has a cross-sectional area of 0.1 cm^2 will have a volume of precisely 1 cc. Water has a density of 1 g/cc so that this length of jet will have a mass of 1 g. If the jet velocity is 1000 m/s then the kinetic energy of the length being considered will be ½*1*1000,000 $g.m^2/s^2$ or 500 $kg.m^2/s^2$. Now 1 $kg.m^2/s^2$ = 1 J (Joule) and 1 calorie = 4.186 J. Therefore, 500 $kg.m^2/s^2$ = 500 J = 120 calories.

Water-jet Energy Absorption

When a water-jet impacts a component there must be a change in the distribution of its energy. Forward momentum is lost completely and the direction of the jet changes by 90˚ - on hitting a flat plate, see fig.1. Some energy remains in the water flowing sideways, i.e. parallel to the component's surface.

If it assumed that most of the kinetic energy becomes thermal energy then the contacting water-jet can become hot – even boil. There are reports in the literature of water-jets creating clouds of steam.

Example: Assume that in the previous example the water temperature before impact was 10˚C and that 10 of the 120 calories were retained as sideways momentum. 90 calories would be needed to heat the water from 10˚C to its boiling point of 100˚C. That leaves 20 calories that could be used in steam generation.

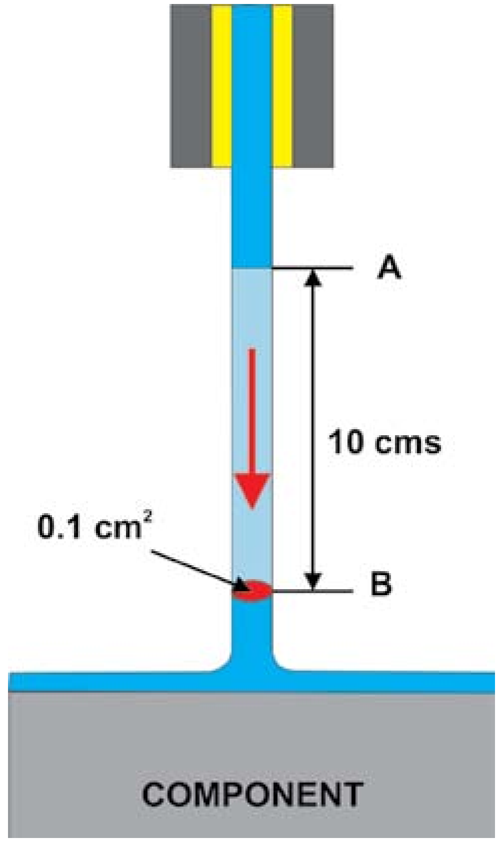

Figure 5. Imaginary length of a water-jet

There are theoretical grounds for believing that the conversion of kinetic water-jet energy to thermal energy is not uniform. The rate of momentum change will be largest on the axis of the jet stream. It can, therefore, be supposed that a much greater proportion of the kinetic energy is turned into heat on that axis. Fig.6 is a schematic representation of the possible energy transfer mechanisms.

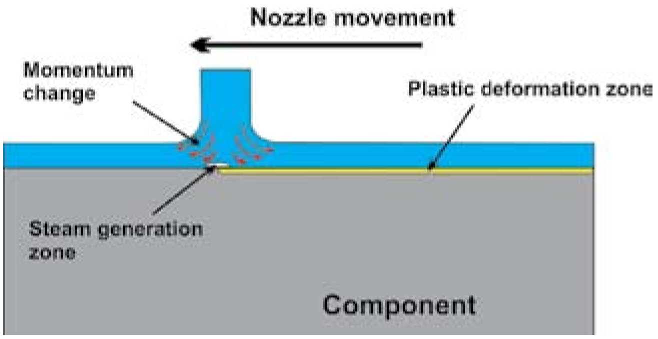

Figure 6. Schematic representation of energy transfer mechanisms during water-jet peening

A minute amount of energy will be consumed in blasting-away fractured surface oxide.

WATER-JET SHOT PEENING

The basic features of water-jet shot peening were illustrated in fig.2. Essentially, high-velocity water is used to accelerate shot particles to a high enough velocity for them to cause surface plastic deformation. Water, being so much denser than air, readily accelerates the shot particles.

Velocity of Water-jet

The required velocity of the water-jet is now much lower than that needed for water-jet peening. It is the entrained shot particles that generate surface plastic deformation – forming familiar dents in the surface. If the water-jet component does not diverge then its velocity is constant. That is because water is incompressible – unlike air, where compression by 10 atmospheres reduces a given volume by a factor of ten and increases its density tenfold.

Velocity of Entrained Shot Particles

A previous article in this series (Winter 2007) presented the relevant theory and equations for calculating the shot velocity that is induced by fluid acceleration. The only significant difference (between water-jet shot peening and air-blast shot peening) is the density of the accelerating fluid. Water has a density of 1000 kgs/m^3 which is very much higher than that of compressed air. At 10 atmospheres compression, air has a density of 12 kgs/m^3.

The velocity, V_S, achieved by the entrained shot particles depends on several factors:

(1) **Velocity of water-jet, V_J.**

(2) **Drag coefficient, C_D.** This is a dimensionless quantity equal to 0.5 for a sphere.

(3) **Cross-sectional area of shot particle, A.**

(4) **Density of water, ρ_W.**

(5) **Density of shot particle, ρ_S.**

(6) **Distance over which the particle is being accelerated, s**, and

(7) **Relative velocity of water-jet and shot particle, (V_J – V_S).**

As mentioned previously, the relevant equation for estimating the shot velocity has already been derived and presented. Table 1 shows how an Excel spreadsheet can be employed to carry out the relevant calculations. In the example shown, it is assumed that a water-jet pressure of 12 MPa is applied with steel shot acceleration taking place over a length of 100 mm. The water-jet velocity is estimated using equation (1) of this article. "Boost efficiency" is the ratio of shot velocity to water-jet velocity – expressed as a percentage. For this example the shot is travelling at over 90% of the water velocity.

In Table 1 a term "X-Factor" is used. This is the term that contains the factors listed previously. Hence, the X-Factor is given by:

$$\mathbf{X = (1.5*B2*B3*B4*B7/(B5 + B6))^{\wedge 0.5}} \qquad (6)$$

The significance of **X** is that the ratio of shot velocity to water-jet velocity, V_S/V_J, is given by:

$$V_S/V_J = X/(1 + X) \qquad (7)$$

For the example given, **X** is 10.7 so that V_S/V_J = 10.7/11.7 which equals 0.915. Expressed as a percentage that is 91.5% and is equal to the 'boost efficiency'. It should be noted that the larger the "X-Factor" the larger is the boost efficiency of the water-jet stream. Boost efficiency is plotted in fig.7 against the "X-Factor", **X**.

Table 1. Excel Spreadsheet Estimation of Shot Velocity induced by a Fluid Stream.

A	B	C	D
1	**Parameter**	**Value**	**Units**
2	Cd	0.5	-
3	Water Pressure	12.0	MPa
4	Water Density	1000	kgm^{-3}
5	Shot Density	7860	kgm^{-3}
6	Shot Diameter	1	mm
7	Length	100	mm
8	Water Velocity	155	ms^{-1}
9	**Shot Velocity**	**141.7**	**ms^{-1}**
11	**Boost Efficiency**	**91.5**	**%**
12	**X-Factor**	**10.7**	**-**

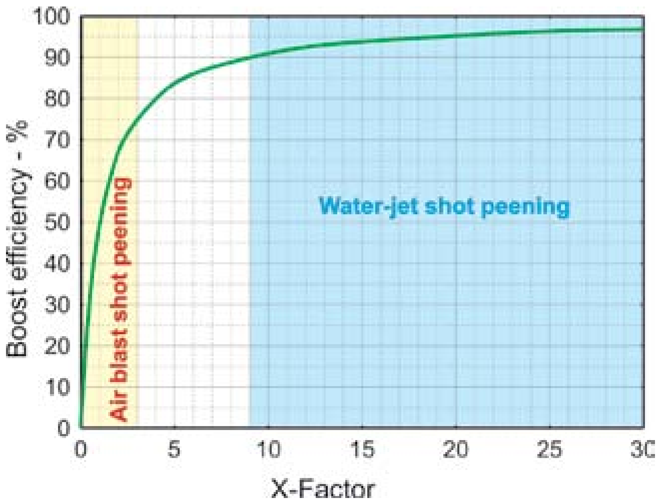

Figure 7. Effect of X-Factor on Boost Efficiency of Air-blast and Water-jet Shot Peening

The shape of the curve in fig.7 is that of a "rational function". This is also the shape of the France-specified peening intensity curve. The figure illustrates the key differences between water-jet shot peening and air-blast shot peening. With air-blast shot peening the X-Factor is, necessarily, small so that the boost efficiency is correspondingly small. The maximum air velocity at the nozzle is also restricted by the speed of sound in air (about 340 m/s). With water-jets the limiting speed of sound is some 4.3 times greater (at about 1500 m/s).

Entrained Shot Speed Variability

With water-jet shot peening, the boost efficiency is almost constant – being above 90%. The X-Factor for air-blast shot peening is, by contrast, on a steep slope. This might lead to a conclusion that the entrained shot speed will be much more variable with air-blast shot peening than it is with water-jet shot peening. That would be correct if (and it is a big if) the cross-sectional area of the water-jet stream remained constant.

If, for example, the cross-sectional area of a water-jet doubled (due to divergence) then the velocity of the jet must be halved. With such a reduction in water velocity this would rapidly slow down the entrained shot particles. This rapidity of velocity reduction is the reverse of a water-jet stream's ability to accelerate slower moving shot particles. Air, being much less efficient than water as an accelerator/decelerator, will have a much lower effect on shot speed variability after leaving the nozzle.

DISCUSSION

The analysis presented in this article is complementary to two previous TSP articles that were devoted to air-blast and wheel-blast shot peening velocities. With the aid of Excel spreadsheets it is possible to estimate, quantitatively, the relative effects of factors such as applied pressure, power requirements, velocity boost efficiency and shot characteristics. For example it is easily shown that air-blast shot peening struggles to achieve high velocities with large-diameter shot. By contrast, water-jet shot peening can easily induce high shot velocities for large-diameter shot. Power and energy requirements are of major concern, particularly with water-jet peening.

Pure water-jet peening requires hyper-velocity jet streams in order to be able to induce the surface plastic deformation needed generate surface compressive residual stress. No shot is involved, so that dimpling of the component's surface is avoided. The greater the yield strength of the component's material the more difficult it will be to induce plastic deformation.

Water-jet shot peening has the advantage of being able to generate very high shot velocities even with large shot particles. This could be advantageous for peen-forming operations. As with pure water-jet peening there is the problem of recycling.

The equations that have been presented depend on basic principles of fluid mechanics. Some simplifying assumptions have, however, been made. It follows that calculations based on the equations will not be 100% accurate. It is believed, however, that their accuracy is good enough to allow both quantitative analysis of different variables and comparison of different processes. The Excel spreadsheets for the several peening processes are available from the author via shotpeener@btinternet.com—they do not contain macros.