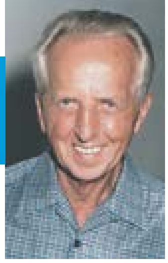

ACADEMIC STUDY

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Back to Basics

Energy Controls Shot Peening Efficiency

INTRODUCTION

Energy is arguably the most important factor in shot peening. Without energy there would be no shot peening. It follows that energy has to be controlled in order to maximize shot peening efficiency. Energy is the capacity for doing work. The law of conservation of energy states that "Energy can be converted in form, but not created or destroyed."

Air-blast shot peening relies upon potential energy stored in compressors. Compressed air provides the means for accelerating shot particles. Wheel-blast peening allows shot particles to be accelerated dynamically via rotating blades.

Energy is essentially quantitative and therefore has corresponding units depending upon whether we are considering potential or dynamic energy. This article starts with a consideration of energy units and continues with considering the role of energy in various aspects of shot peening. Minimizing the required energy input maximizes shot peening efficiency.

ENERGY UNITS

Potential Energy Unit

Potential energy is stored energy. A simple way to envisage stored energy is to visualize how an air compressor works. Fig.1 illustrates the relevant principle. A piston is forced down on air in a closed container. The compressed air then has the potential energy required to accelerate shot particles.

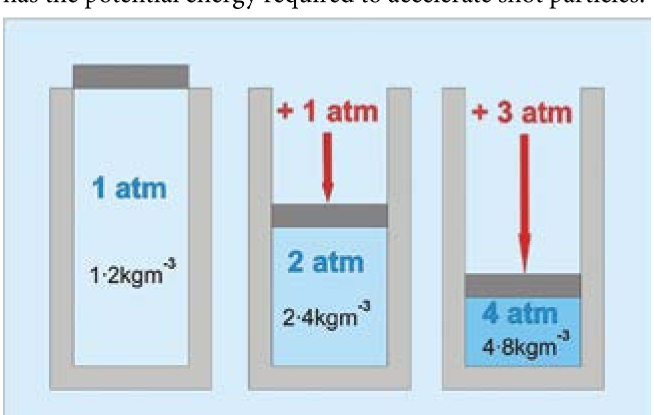

Fig.1. Air compression generating potential energy.

The units for potential energy are the same as those for work done, i.e., force multiplied by distance. Force is expressed as **Newtons**, **N**, and distance as **metres**, **m**. Hence the basic unit for potential energy is **Newton metres**, **Nm**. Consider, as an example, lifting an apple by a distance of one metre. A medium-sized apple exerts a force of one Newton (at the Earth's surface). We have therefore done 1 Nm of work in raising the apple.

Weight is a force and so is measured in Newtons (N).

On earth, the downward force of gravity on a 1 kg mass is 10 N. So, if ten apples weigh 1 kg then one such apple exerts a force of one Newton.

Kinetic Energy Unit

An accelerated shot particle has a kinetic energy, **K**, conveniently defined by:

$$K = \tfrac{1}{2}mv^2$$

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

As shot peeners, we use both potential and kinetic energies. The following case study is an example of their interplay.

Case Study: How does work done lifting an apple compare with the same work done accelerating shot particles?

Joe, approaching retirement and with thirty years of shot peening experience behind him, thought he could catch out Tom, the firm's newest recruit. "Tom, I've read that it takes about 1 Nm of work to lift an apple by 1 metre. About how many S170 shot particles could be accelerated to $50ms^{-1}$ using the same amount of expended energy?"

"I'll have to do some sums," said Tom. "Firstly, I have to work out the kinetic energy required to accelerate one S170 particle to 50 ms^{-1}. Secondly, work out how much kinetic energy is equivalent to 1 Nm. Finally, divide that by the energy requirement per particle. Here goes:

Kinetic energy, K = ½mv². S170 is listed as having an average mass of $0.33134x10^{-3}$g.

Therefore, $\mathbf{K_{S170} = \tfrac{1}{2} \times 0.33134x10^{-3}x(50ms^{-1})^2}$ which comes to $\mathbf{0.414175m^2s^{-2}g}$.

1 Nm of energy is equal to $\mathbf{1000g.m^2.s^{-2}}$. Dividing $\mathbf{1000g.m^2.s^{-2}}$ by $\mathbf{0.414175m^2s^{-2}g}$ gives us the required answer of **2,414** particles."

"I can see why the CEO hired you," said Joe, with a sigh. "Shot peening seems to have a lot more science to it now than when I started out. Perhaps it's time that I thought of retiring." "Not before you teach me the practical side of peening," said Tom, diplomatically.

POWER – RATE OF USING ENERGY

Shot peening energy requirements depend upon the rate at which we need to use energy. This rate is called "power"—the rate of transfer of energy between sources. For air-blast peening, we use an air compressor to maintain a reservoir of compressed air. Wheel-blast peening uses electric motors to maintain required speeds of revolution.

The energy input required to accelerate individual shot particles is of basic significance. Shot peeners are more concerned with the rate of energy input required to accelerate all the particles in a given shot stream. For air-blast peening, we must also input the energy needed to accelerate the air. 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.2). 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, $\frac{1}{2}mv_s^2$. 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:

$$S = M*v_s^2/120 \quad (1)$$

where **S** is in watts, **M** is in kg/minute and v_s is shot velocity in metres per second.

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

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

$$S = M*v_s^2/2848 \quad (2)$$

where **S** is still in watts but **M** is now in lb/minute and v_s is in feet per second.

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

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, v_A, and the area of intersection, **A** (see fig.2). Now $V = v_A*A$. The mass of any object is its density, **ρ**, multiplied by its volume. Hence: Air mass flow per second is given by $\rho*v_A*A$. Air power, **L**, is its kinetic energy, $\frac{1}{2}mvL^2$ summed for the mass of air crossing the plane per second. Therefore:

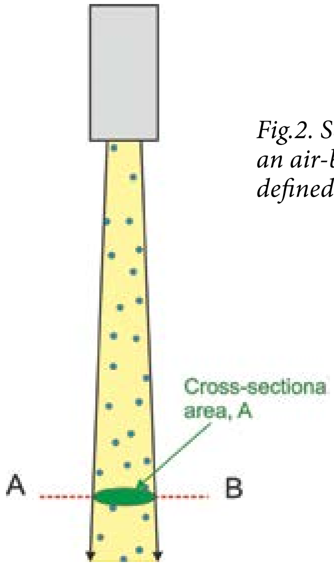

Fig.2. Schematic representation of an air-blast shot stream crossing a defined plane, AB.

$$L = \frac{1}{2}*\rho*v_A^3*A \quad (3)$$

where **L** is in watts, **ρ** is in $kg.m^{-3}$, 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:

$$P = M*v^2/120 + \frac{1}{2}*\rho*v^3*A \quad (4)$$

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

Equation (4) quantifies the power that must be put into the shot stream to generate the required shot velocity. Equation (4) can be approached either by direct calculation or using it to produce graphs. Direct calculation is illustrated by the Excel worksheet shown as Table 1. For the example shown, the fluid is travelling at the same velocity as the shot particles. The worksheet program does allow for them having different velocities.

Table 1. Excel worksheet being used to estimate Shot Stream Power Requirement.

A	B	C	D	E
1	Feed Rate	M	5	kg/minute
2	Shot Velocity	v - shot	50	m/second
3	Fluid Velocity	v - fluid	50	m/second
4	Fluid Density	ρ	1.225	kg/cubic metre
5	Cross-section of shot stream	A	0.001	metres squared
6	Shot Power	S	104	watts
7	Fluid Power	L	77	watts
8	Shot Stream Power	P	181	watts

The power needed to accelerate the shot particles in a desired shot stream is much less than the overall power requirement. No plant can be 100% efficient. Efficiency estimates are complicated by having intermittent energy inputs to compressed air storage facilities. There is, however, a fairly steady relationship between shot stream and overall power requirements. For example, doubling the feed rate doubles the power requirement. Doubling the required shot velocity quadruples the power requirement.

RELATIVE VELOCITY OF AIR AND SHOT PARTICLES

For air-blast peening, the relative velocities of air and shot particles in the shot stream are very important. The relative velocities are illustrated in fig.3. As the shot stream forms at the nozzle, the air is flowing faster than the shot particles. The shot particles continue to be accelerated until the air and shot velocities are equal— point N in fig.3. Thereafter, the air velocity is lower than that of the shot particles so that the air decelerates the shot particles. For the specific example shown in fig.3 (obtained in the author's shot peening laboratory) this occurs at some 200 mm from the nozzle with a maximum shot velocity of 50 ms^{-1}.

The point N is then the optimum peening distance from a component.

The shot velocity varies only slightly on either side of the optimum distance. The range from 100 mm to 300 mm is indicated by the green arrow in fig.3. Within that range, shot velocity varies by only 1 or 2 ms^{-1}. At 500 mm from the nozzle the shot velocity has virtually halved. Attempting to peen with a nozzle-to-component distance of 500 mm would, however, impart a much lower peening intensity than if applied at 200 mm. The useful distance range (100 to 300 mm in this example) means that we do not have to continually make fine adjustments of nozzle-to-component distance in order maintain a steady applied peening intensity.

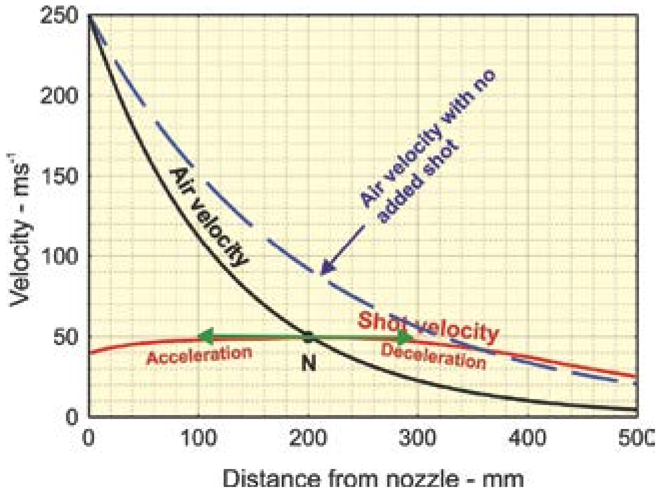

Fig.3. Relative velocities of air and shot in shot stream.

For wheel-blast peening, shot particles continuously decelerate after leaving the wheel. Shot velocity on component impact is more variable than it is with air-blast peening.

ENERGY SOURCES

Compressed air and rotating wheels are the basic energy sources for the majority of shot peening. Compressed air accelerates shot particles indirectly whereas rotating wheels accelerate shot particles directly. Figs. 4 and 5 represent the difference schematically.

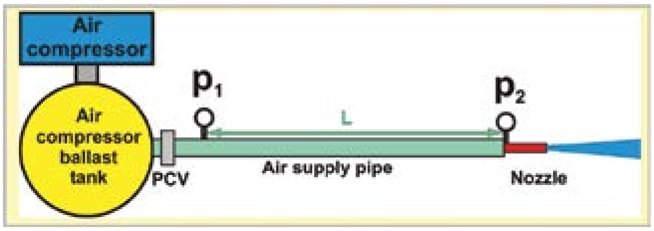

Fig.4. Compressed air supply system.

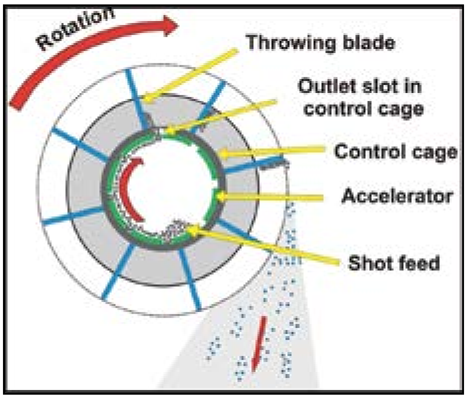

Fig.5. Wheel-blast shot acceleration.

Compressed air supply systems are liable to air velocity fluctuation. Normally the air compressor reacts to signals from the air ballast tank that the pressure has fallen below a set level. The compressor switches on and pumps up the pressure in the ballast tank until it is told to switch off. The net effect is that the outlet air pressure from the ballast tank fluctuates between the set limits. This can be monitored via a pressure gauge—**p2** in fig.4. Long-term fluctuation of air pressure is caused by factors such as the conditions of the supply pipe and nozzle.

The rotational speed of a wheel-blaster tends to be constant. Energy transfer to shot particles depends to a small extent on the position of particles within the batches released onto the blades. A second factor is that there is a variable amount of distance to a component. This means that shot particles are slowed to varying degrees by surrounding air.

ENERGY TRANSFER ON SHOT/ COMPONENT IMPACT

Energy transfer from particle to component is of basic importance. The first significant question is "What proportion of the flying particle's energy is transferred on impact?" Fig.6 represents an experimental explanation. If a ball bearing is dropped from a height of **H1** and rebounds to a height of **H2** then the loss of energy is simply **H1-H2**. Experiments have indicated that the energy loss is approximately 50% for steel components. The softer the component the greater will be the energy fraction transferred on impact.

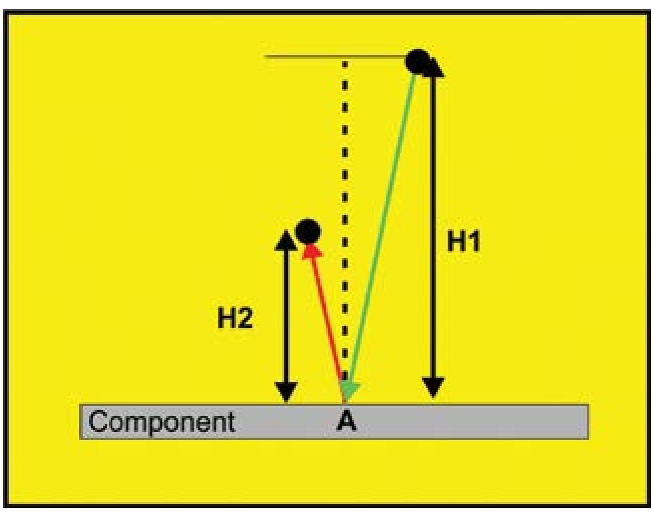

Fig.6. Energy loss as particle impacts component.

A second significant question is "What happens to the energy transferred to the component on impact?" Basically, energy is eternal. It cannot be destroyed. It can only be transferred. When a flying shot particle impacts a component's surface, energy is transferred in four ways:

Work needed to create dimple
Work-hardening underneath dimple
Residual stress profile creation and
Heat generation

These four ways are shown schematically in fig.7. Heat generation accounts for most of the total energy transfer. Perhaps surprisingly, dimple formation, residual stress profile, and work hardening account for only small fractions of the total amount of energy transferred. Their relative proportions vary according to peening parameters but they are always small when compared to that of heat.

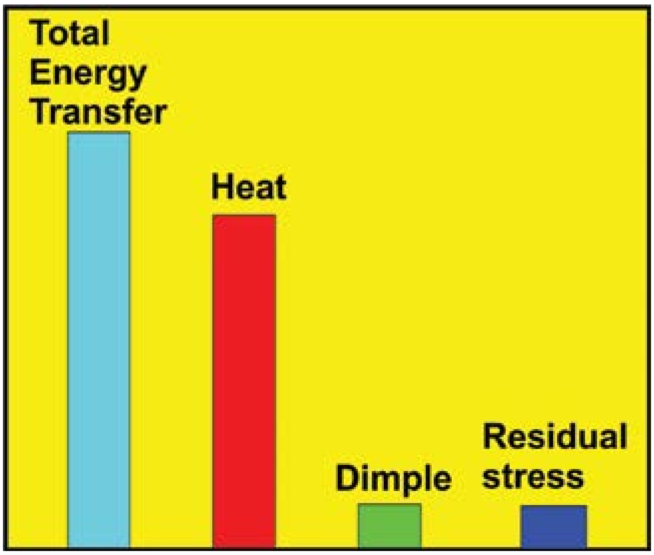

Fig.7. Components of energy transfer on particle impact.

Heat generation

Heat generation can be appreciated by considering the following analogy:

Analogy of heat generation by friction

As a simple office/home experiment, rub bare hands together slowly. No significant temperature rise occurs. Now rub them together vigorously. A detectable skin temperature rise now occurs. Finally, try to imagine rubbing bare hands together at thousands of times per second. A substantial skin temperature rise would be predicted. The moral is that the rate of sliding determines the temperature rise. When flying shot particles impact, planes of atoms move over one another at astronomical rates. This causes significant temperature rises at the component's surface. Japanese researchers even managed to induce rises of hundreds of degrees Celsius by employing highly-selective peening parameters.

Heat generation was described in a previous TSP article (Summer 2003). In that article the author described finding that surface temperature rises of up to 60˚C occurred when employing conventional air pressures and flow rates using a shot size of S170 on Almen strips (see fig.8). The shape of the surface heating curves is very close to that of a two-exponent

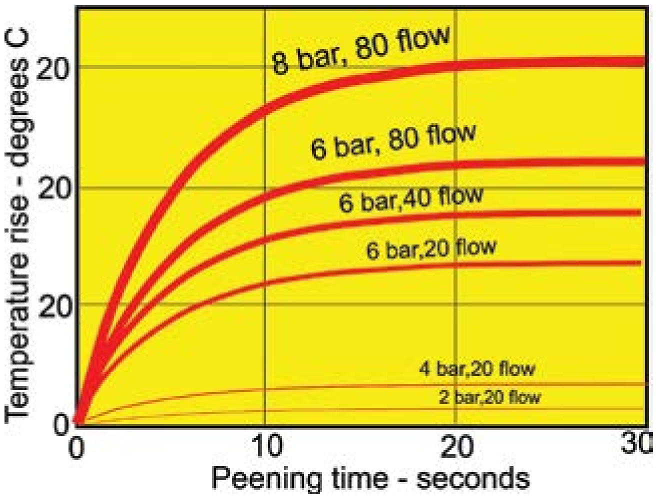

Fig.8. Surface heating by shot peening, using S170 shot.

saturation curve. Line thickness has been used to emphasize how heating increases with shot velocity and shot flow rate. A temperature rise of 20˚C would be sufficient to slightly increase Almen intensity having lowered the surface's yield strength.

Work needed to create dimple

The work needed to create a dimple is the product of component hardness and dimple size. Dimple size is its volume, **V**—approximated by the following equation.

$$V = \tfrac{1}{3}\pi h^2(3R - h)$$

Where **h** is the depth of the dimple and **R** is the shot particle's radius.

Work-hardening underneath dimple

Fig.9 is a schematic representation of the work-hardened zone underneath a peening dimple. The degree of work-hardening varies in the zone—being a maximum at the dimple's surface and falling to zero when impact stressing only just reaches the material's elastic limit. Hardening mechanisms are described in a previous TSP article (Summer, 2007).

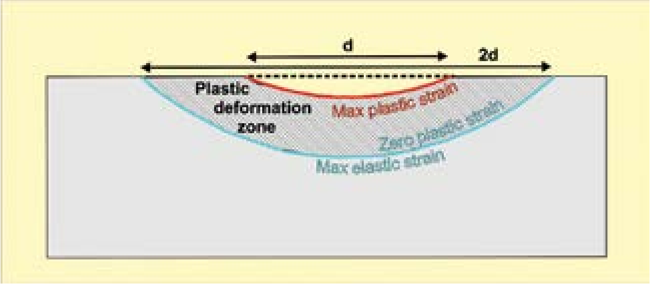

Fig.9. Zone of work-hardening caused by plastic deformation as dimple is created.

Residual stress profile creation

The residual stress profile induced by shot peening has long been recognized as promoting component life. The conventional shape is illustrated as fig.10. A beneficial zone of compression occurs at the component's surface. This must be balanced by a tensile zone. The amount of energy required to generate the residual stress profile increases with component hardness and required depth of compression zone.

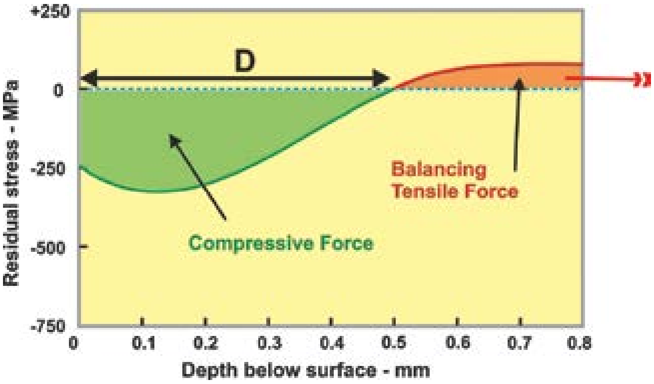

Fig.10. Conventional shape of residual stress profile created by shot peening.

Several effects are associated with the residual stress profile. Primarily, compressive stress at the surface offsets applied tensile service stresses. The compressed zone also induces bending—contributing approximately half of Almen arc heights. This bending is the essential element in peen forming. Post-peening heating must be minimized; otherwise stress-relief will occur.

SUMMARY

This article, the last in the Back-to-Basics series, has attempted to summarize the vital role played by the energy requirements of shot peening. Energy sources are generally compressed air and rotating wheels. Energy input increases as the square of the required velocity and increases linearly with shot particle mass. Increased component hardness increases the energy input needed to produce a given size of dent. Residual stress in the surface zone is beneficial to component life but also induces bending that is noticeable in very thin components. All aspects of energy input should be managed to improve process efficiency.