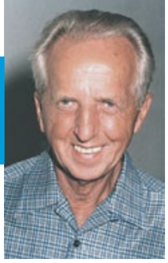


ACADEMIC STUDY
Dr. David Kirk | Coventry University

Wear and Its Reduction

INTRODUCTION

Shot peeners are beset with wear problems. Every piece of shot and all peening equipment are subject to wear to a greater or lesser extent. A universal example is the wear endured by shot particles on impact with components. As another example: the late Jack Plaster aptly said that "A centrifugal blast machine is probably the most self-destructive of all modern mechanical machines." Enormous numbers of hard particles are pressed against unlubricated rotating surfaces, hence generating fiendish wear problems. To some extent a centrifugal wheel-blast machine acts as a giant pepper mill—with shot particles playing the role of peppercorns!

This article uses impacting shot and the blast wheel to illustrate the types of wear mechanisms most commonly encountered by shot peeners. These mechanisms are called "Adhesive wear" and "Abrasive wear". For both mechanisms we have either "two body" or "three body" situations. These alternatives are illustrated in fig.1.

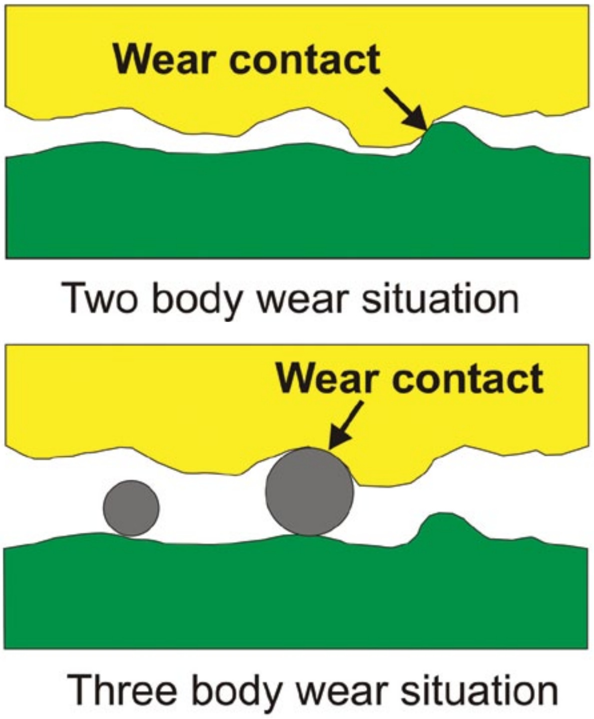


Fig.1. Two and Three Body wear situations.

The article also indicates how material selection and component design can reduce wear rates. An attempt to improve on blast wheel design is included as an illustration.

For every shot peening component the following adage is appropriate: *"If a man can make a better mouse trap, the world will make a beaten path to his door."*

Wear only occurs if two surfaces are in contact and are moving relative to one another. The resulting rate of wear is governed by both pressure and speed.

The effects of pressure and speed can be visualized by a simple example. Think of rubbing an old, rusty Almen strip using emery paper. We all know that the greater the applied pressure the higher will be the polishing rate. Less obvious is the effect of speed of rubbing. The faster the rate of rubbing the more material is removed per stroke! Think of why two sticks have to be rubbed quickly against one another if there is to be any hope of generating a flame. Classic survival techniques include pressing a pointed stick into a block and rotating it with a bow's string—hence generating both high pressures and high speeds.

ADHESIVE WEAR

As the name implies, adhesive wear occurs when two surfaces physically adhere to one another. This type of wear is often called "galling." Adhesion takes the form of micro-welds formed between the two surfaces. Two nascent metal surfaces pressed together will micro-weld to one another at points of contact. "Nascent" means newborn and implies a surface completely free from oxide protection. Relative movement of the two surfaces breaks apart the tiny points of adhesion, causing wear. Fig.2 on page 30 illustrates the formation of a single micro-weld with subsequent tearing apart.

This section uses the formation of a dent to illustrate how nascent surfaces are generated, leading to adhesive wear.

Dent Formation

All non-noble metallic components form a protective oxide layer when exposed to air. If this layer is broken, oxygen in the atmosphere will, normally, rapidly repair it. The oxide layer is, however, extremely brittle. When a shot particle hits a component the shot particle deforms elastically. This elastic deformation is sufficient to shatter the particle's oxide layer. As a dent is being produced the dent surface itself is stretched

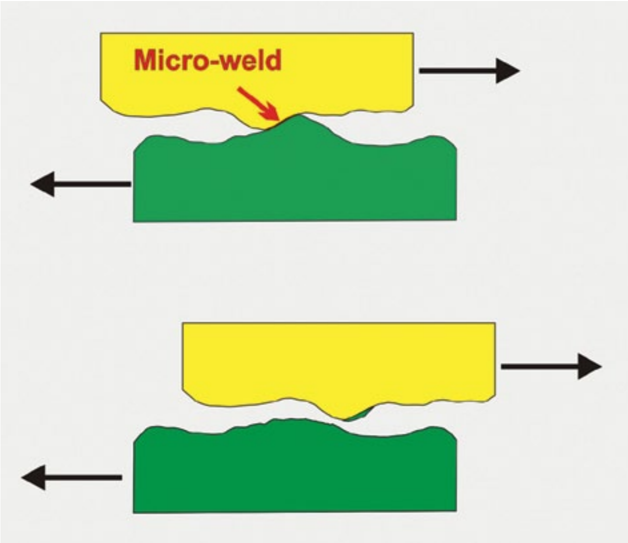


Fig.2. Micro-weld formation and subsequent tearing apart.

both plastically and elastically. This stretching fractures the component's oxide layer. For a typical dent whose diameter is ten times its depth the stretching is about 3%. This vastly exceeds the ductility of any oxide coating. Fig.3 illustrates the stretching that is involved. The arc ABC is 3% longer than the original surface length AC.

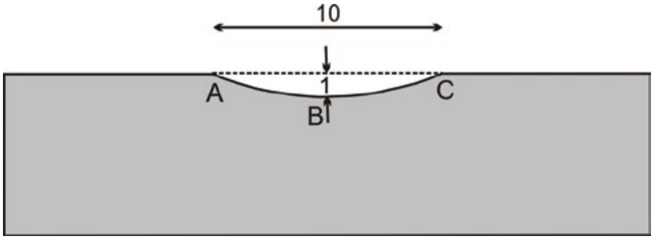


Fig.3. Typical dent geometry.

No oxygen can get to the interface between the impacting shot particle and the dent's surface. Hence we have two nascent surfaces being pressed together and also moving relative to one another. Huge numbers of microscopic auto-welds are therefore formed and then broken apart. As a consequence, adhesive wear must occur. The microscopic scale of the adhesion process promotes the observed polished appearance of dents.

Susceptibility to Adhesive Wear

A good indication of adhesive wear susceptibility is the thickness of the oxide coating on a metal's surface. Noble metals such as gold have the thinnest of oxide layers—a monolayer—but are rarely shot peened. Metals such as aluminum and chromium have very thin oxide layers—so thin as to be translucent. Aluminum alloys and stainless steels also have very thin oxide layers. It is well-established that aluminum, stainless steels and gold are very susceptible to adhesive wear. Gold foil has been used for thousands of years based on the "cold-welding" that occurs when it is hammered into place.

ABRASIVE WEAR

Abrasive wear mainly occurs when a harder material rubs against a softer material. Emery paper contains particles that are harder than metals—hence its usefulness for rust removal. That is an example of two-body wear. Metallurgists use diamond-impregnated polishing wheels to produce ultra-smooth surfaces. That is three-body wear. Both two- and three-body wear occurs in shot peening situations.

Abrasive wear characteristically occurs when an asperity on the harder surface strikes an asperity of the softer surface. This is illustrated in fig.4. As an asperity on the harder surface strikes an asperity on the softer surface something has to give! In this case it is the asperity on the softer surface which is work-hardened until it fractures.

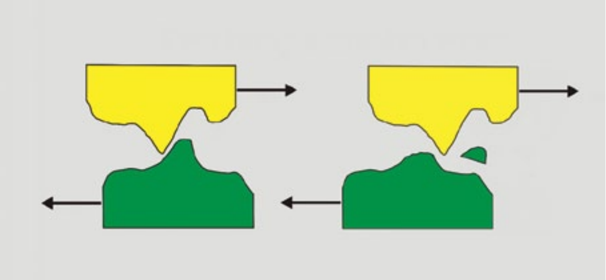


Fig.4. Two-body abrasive wear.

WEAR REDUCTION

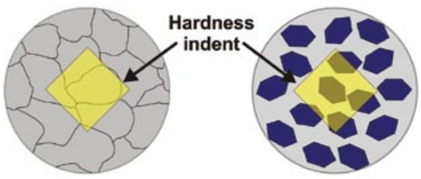
Material selection and component design are the two major factors in wear reduction.

Material Selection

Material selection has benefited from the enormous advances made in developing wear-resistant materials. The choice is now so large that it is easy to over-simplify selection. Consider, for example, using just hardness as a wear-resistance criterion. The assumption then is that the higher the hardness the greater will be the wear resistance. This assumption is only valid when comparing materials that have similar microstructures.

Fig.5, on page 32, illustrates schematically two types of wear-resistant alloys having the same measured hardness but with quite different microstructures. Each grain of the single-phase material has a similar hardness. For the two-phase material very hard particles are imbedded in a softer matrix. A macro-hardness indenter can only measure average hardness. Hence both types of material may have identical measured values of hardness. A common example of a two-phase wear-resistant material has tungsten carbide particles imbedded in cobalt. This has a much higher wear-resistance than a single-phase steel of the same measured macro-hardness. Micro-hardness indenters are, however, capable of differentiating the hardness of individual particles.

Material selection based on macro-hardness values alone is not recommended. Attention must also be paid to the type of micro-structure. If, however, two materials have similar micro-structures then it is highly probable that the harder material will be more wear-resistant.



(a) Single-phase (b) Two-phase

Fig.5. Single-phase versus two-phase structures.

Component Design

All components that are in a wear environment must be designed to withstand wear to a specified extent. Commercial considerations are of paramount importance for both supplier and user. A balance has to be obtained between cost and useful life. If, for example, it was possible to design a component that had an infinite life then suppliers would soon go out of business. On the other hand if a component had to be replaced frequently then users would be prepared to pay a premium. A universal example is that of light bulbs. The classic shot peening design problem is that of blast wheels whose performance is adversely affected by substantial wear.

Wear reduction for shot particles and blast wheels are considered in the next two sections of this article.

SHOT PARTICLE WEAR

Shot particles are, of course, central to the process of shot peening. All available types of shot wear away during use but at different rates. They can therefore be classed as an essential consumable. The most obvious effect of wear is a progressive reduction in the average diameter of the shot particles. This is illustrated schematically in fig.6.

Without any correction, wear would eventually cause the average shot diameter to fall below its specification. Correction procedures, which can be on-line or intermittent, include sieving and replenishment. The effect of intermittent correction is illustrated in fig.6.

Shot wear mechanisms are based on oxide layer breakdown and adhesive interaction with components. Oxide layer breakdown also contributes to the accumulation of dust which has to be removed. Adhesive interaction depends primarily on the relative chemical compositions of shot and component. The greater the wear rate for the shot the greater

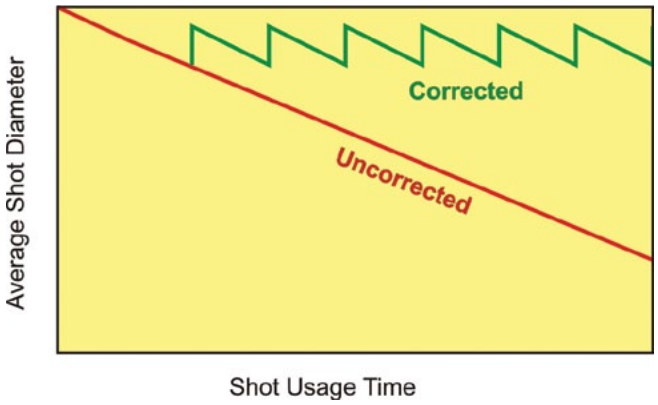


Fig.6. Effects of wear on shot diameter and intermittent correction.

is the frequency of associated corrective treatments. It follows that a low shot wear rate is greatly advantageous.

Wear resistance is just one of the several factors that influence shot selection. Several types of carbon steel shot are available including cast, cut wire and carburized. Alloy steels include stainless and high-manganese varieties. High-manganese steels are famous for their wear resistance.

Shot wear can be defined as the gradual reduction of average shot particle mass during use. This reduction of mass corresponds to a progressive reduction in shot particle volume and hence shot particle diameter. There are no standard tests or specifications that relate directly to shot wear.

One specification, J445 Metallic Shot and Grit Mechanical Testing, is commonly used in conjunction with an Ervin Tester to estimate the durability of shot samples. It has the considerable advantage of only requiring about 100 g of shot. It does not, however, measure wear rate directly.

J445 includes three different procedures that can be used to assess shot durability. The first of these involves taking a 100 g sample of shot and subjecting it to batches of peening cycles. After each batch of, for example, 500 cycles, the sample is removed and re-weighed with some mass having been ejected through a nominated control screen. Screen-retained sample mass is then plotted against the number of cycles. Cycling is ended when more than 95% of the original 100 g sample has been lost through the control screen. Fig.7 on page 32 shows the corresponding graph (Fig.1 in J445).

The area under the plotted curve, colored green in fig.6, is determined using the prescribed trapezoidal method. This area, 160,500 % cycles for fig.6, is then divided by 100% to give a value of 1605 cycles. A rectangle, ABCD, has been included in fig.7 that has exactly the same area as the trapezoidal area. Division by 100% gives the horizontal side, CB, of the rectangle—1605 cycles for this example. This number of cumulative cycles is designated as the durability parameter in J445—the larger the number the greater the durability.

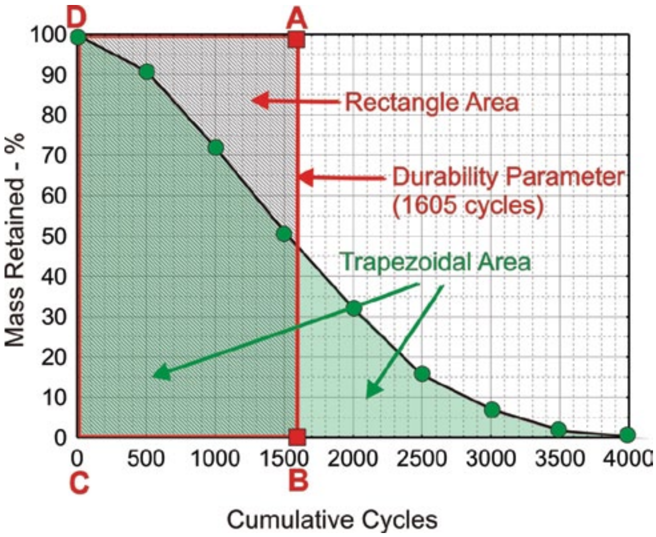


Fig.7. Modified version of J445's fig.1.

The J445 durability test can be modified to give a direct indication of shot wear rate. Fig.8 shows the same SAE data points as are included in fig.6. At a 50% mass loss it can be assumed that the screen-retained sample still has the same number of particles as it had originally. A 50% mass loss corresponds to a loss of only 20% diameter for spherical particles. Assuming that the original average diameter of the S660 particles was 0.066 inch this would therefore have been reduced by 0.0132 inch at 1500 cycles. Dividing diameter reduction by the number of cycles gives us a direct wear rate parameter. For this example the wear rate value is therefore 8.8 x 10^{-6} inch per cycle (224 x 10^{-6} mm per cycle) being 0.0132 inch divided by 1500 cycles.

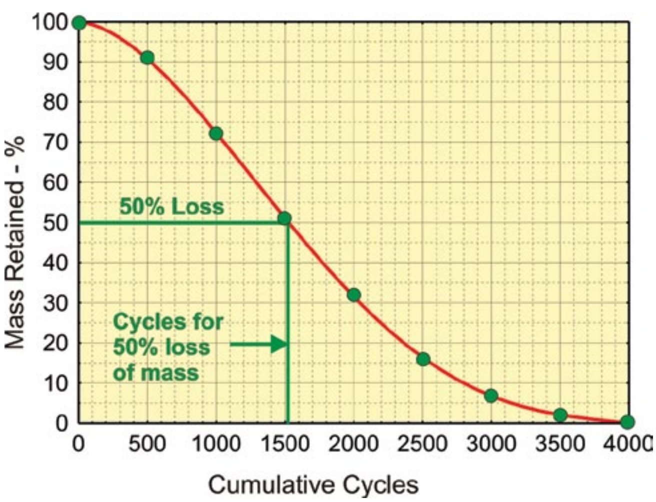


Fig.8. J445's fig.1 data used to estimate cycles for a 50% mass loss.

COMPONENT DESIGN

This section is an exercise in the thought processes that could be involved in reducing wear by modifying component design. It uses the wear-prone blast wheel as an example. Fig.9 shows the components of a conventional type of blast wheel.

With a blast-wheel we have both high pressures and high speeds. Both accelerator and throwing blades normally rotate at the same angular velocity. If, for example, the blade tips sweep a circumference of 1.0 m at 60 r.p.s. then the thrown shot will have a velocity of at least 60ms^{-1}. If, for the same example, the accelerator has a circumference of ⅓m (radius 53mm) then shot is scouring the control cage at a sliding speed of 20ms^{-1}. This shot is also being pressed into the accelerator/control cage interface with an acceleration of some 770 times that of gravity! That figure comes from dividing the square of the circumferential velocity by the radius of rotation [(20ms^{-1})^2/0.053m = 7540m.s^{-2} = 770g, where g = 9.8m.s^{-2}].

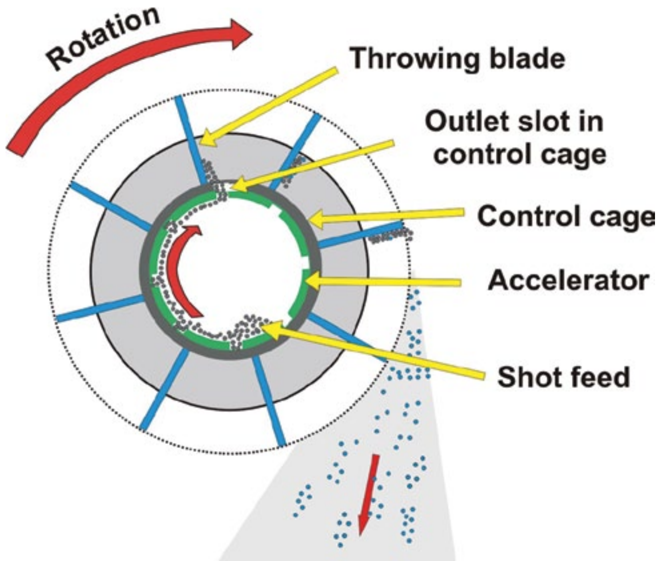


Fig.9. Schematic representation of a typical centrifugal blast wheel.

Two-body wear of a blast wheel will occur when shot particles are moving along the blades—shot as one body and the blade as the second body. Another example is when shot particles strike a component's surface to produce a dent. Three-body wear will occur, for example, when shot particles are trapped between the accelerator and the control cage as infig.9.

Wear rate increases with both force and sliding speed. One way to reduce the wear rate would be to reduce the diameter of the accelerator—hence reducing both sliding speed and centrifugal force. That approach, however, induces several problems. One is that the throwing blade length must then be a large fraction of the wheel radius. Long blades generate a relatively-large spread angle for the thrown shot stream. Another problem is that exiting the shot through the control cage opening becomes more difficult because the centrifugal force on the shot—pushing it out of the control cage—is lower and also because the outlet slot has to occupy a greater angular proportion of the control cage. The maximum number of throwing blades that can be accommodated without interfering with the shot stream also decreases with increase in blade length.

Wear reduction might, however, be effected by component design modification. Such a modification would need to reduce the sliding speed without reducing the accelerator diameter. A modification is presented here which could offer substantial advantages in terms of wear reduction, increased shot stream concentration and reduction of component number.

Possible Modification

This modification involves:

(a) Not having a separate, static, control cage. Instead every throwing blade has an outlet slot,

(b) Having one fewer slot in the accelerator than there are blade outlet slots (and hence blades) and

(c) Rotating the accelerator at a specified faster rate than the throwing wheel. This rate synchronizes the accelerator and outlet slots - so that they always coincide at only one point on the circumference.

Fig.10 illustrates the mechanical arrangement for the suggested modification.

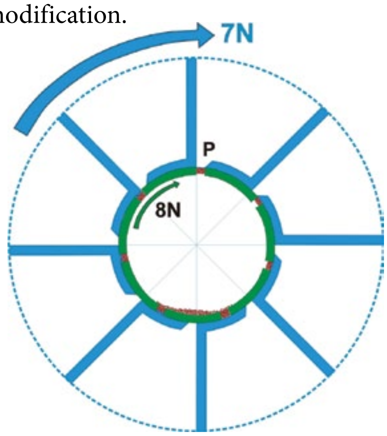


Fig.10. Modified system for eight-bladed wheel.

The accelerator's angular rotation rate has to be faster than that of the throwing blade wheel by the ratio of the number of throwing blades to the number of accelerator slots. In fig.10 there are eight throwing blades and seven accelerator slots. Hence the accelerator rotation rate has to be 8/7 times that of the throwing blade wheel. The reason for the matched, but different, rotation speeds is that an accelerator slot and a blade slot must only coincide at the same, fixed, angular position – such as P in fig.10. Coincidence is achieved when the product of angular rotation speed and number of slots is the same for both accelerator and blade wheel.

There are several advantages that can be attributed to the suggested system. The most important advantage is that the relative surface speeds between the moving parts are greatly reduced for given diameters of accelerator and blade wheel. For example, a relative surface speed of 35 $m.s^{-1}$ for an eight-bladed wheel would be reduced to 5 $m.s^{-1}$. This would lead to reduced shot breakage and wear, together with reduced accelerator cage and blade wheel wear. A second advantage is the number of basic components is reduced from three to two—from accelerator, control cage and blade wheel to simply accelerator and blade wheel. That means that there are now only two major sources of wear and breakage. With the reduced overall wear it is possible to increase the wheel blade and accelerator diameters so as to accommodate a greater number of blades on a given wheel. That, in turn, leads to a more concentrated thrown shot stream.

Mechanics of Control Cage Shot Transfer

Conventional blast wheels have two stages of shot transfer: (i) shot has to emerge from a slot and cross over the static slot and (ii) be collected by a moving blade. With the suggested system, shot transfers directly onto a moving blade. The differences in the respective movements are illustrated in figs.11 and 12 on page 38. Shot transfer from the slot involves a combination of "hammer throwing" and "burst pipe" mechanics. Neither of these is very effective in moving shot at 900 to the tangential direction of the accelerator.

The exit slot for a conventional wheel has to be several times the width of the cage slot. That is to allow time for the surface layers of the shot in the accelerator slot to be transferred to the exit slot. Once in the exit slot the shot is travelling across a "no man's land" until it crosses into the path of the moving blade. The forward face of the exit slot may be sharply angled to bounce shot into the path of the blade. Once shot is collected by the blade it is propelled outwards by centrifugal force until it reaches the blade tip.

With the suggested modification, shot is transferred directly to the root of a moving blade as soon as the accelerator slot starts to coincide with an exit slot. It is important to note that the relative speed of the slots is much less than that for a conventional wheel. For an "8/7" modified wheel, the relative motion is seven times slower than that for a conventional wheel. That means that the exit slot does not need to be much wider than the accelerator slot – there is seven times as much time for exiting of shot per degree of wheel rotation. Shot transfer, being direct to the blade, is much more orderly than that with a conventional wheel.

DISCUSSION

Wear between unlubricated moving parts can never be eliminated. At best it can be reduced by attention to both materials and component design. Numerous studies have

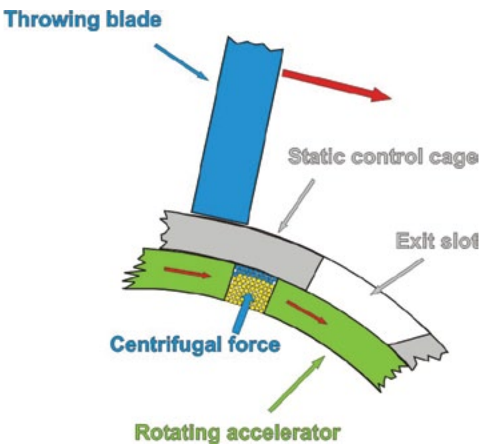


Fig.11. Conventional Exit Slot arrangement.

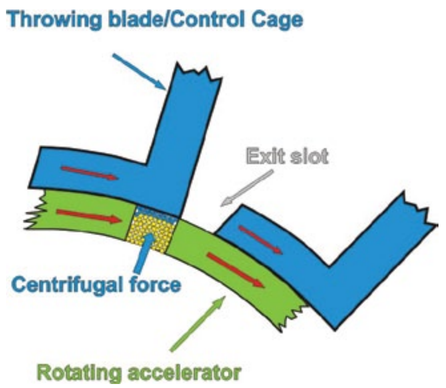


Fig.12. Modified Wheel Exit Slot arrangement.

indicated that there is an almost linear relationship between contact speed and wear rate for a given contact stress and contacting materials. Consideration of changes in any piece of peening equipment is improved by having at least a basic understanding of wear mechanisms.

Quantification of shot wear rate is difficult in the absence of a directly-related specification. Modification of the J445 shot durability specification can, however, yield wear rates directly. Shot selection for optimum wear rate is complicated by the additional factors that have to be considered. Hardness is not the sole factor affecting wear rate. As always, the maxim "caveat emptor" (let the buyer beware) prevails.

The suggested modification of blast wheel design is purely an academic exercise designed to illustrate the types of thought processes and calculations that might be encountered in product re-design. Additional examples of relevant calculations are available from the author on request at Prof.David.Kirk@btinternet.com.

Improvement of wear performance is a constant factor for equipment manufacturers. A balance has to be struck between cost and longevity. Simply buying the cheapest shot, for example, is poor economics. At the other extreme, a manufacturer selling shot that lasted forever would soon go out of business.