ACADEMIC STUDY

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Back to Basics
Shot Peening in a Nutshell

INTRODUCTION

This article aims to cover just the basic features of shot peening. Other articles can be referred to for extended accounts. Shot peening is, essentially, a surface work-hardening process. Impacting, high-velocity particles plastically deform the component's surface. This plastic deformation induces changes in the component's properties. The most desirable of these changes is normally the increase in the fatigue strength of the component. Fatigue strength increase is caused by two factors: work-hardening and the compressively stressed surface layer. Shot peening can also be employed to correct small, unwanted component distortion. Shot-peened surfaces necessarily have tiny dents that may or may not be advantageous.

Control of shot peening centers on coverage and intensity. Coverage being the percentage of the surface that is dented and intensity being proportional to the thickness of the plastically deformed surface layer. The plastically deformed surface layer is equivalent to what can be regarded as a "magic skin".

FATIGUE STRENGTH

Fatigue strength is the level of applied alternating stress that a component can endure before fracturing after a given number of stress cycles. This strength decreases when, as is normal, there is a constant applied stress. Fig.1 illustrates the origin of these two types of stress for a leaf spring on a railway wagon. As the wagon is pulled along the leaf spring suffers cyclic stressing. At the same time the leaf spring suffers a constant applied stress due to the weight of the wagon.

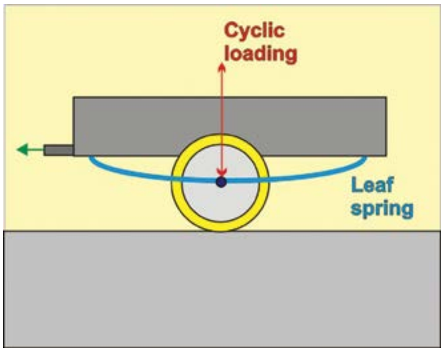

Fig.1. Leaf spring subjected to both constant and alternating stress.

FATIGUE STRENGTH INCREASE INDUCED BY SHOT PEENING

Fig.2 portrays the separate contributions to fatigue strength of work-hardening and compressive residual stress. Without any shot peening the fatigue strength has a maximum value, F.S. A, if there is no constant applied stress. This level of strength falls with increase in constant applied stress level. Fatigue strength is zero if the applied stress level is high enough, of itself, to cause fracture on single loading. Shot peening increases the fatigue strength because of the two stated contributions of work-hardening and compressive surface residual stress. For far too long the increase in fatigue strength induced by shot peening was attributed solely to compressive surface residual stress.

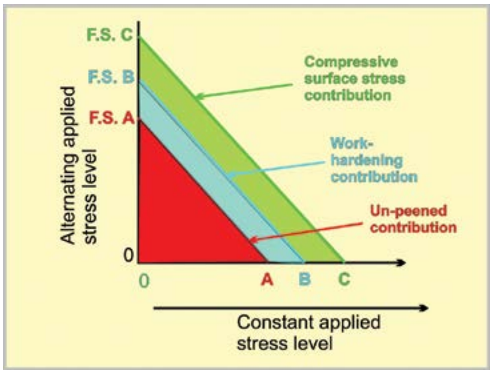

Fig.2. Increased fatigue strength due to both work-hardening and compressive stress.

FATIGUE CURVES

Fatigue curves are used to show how allowable alternating stress levels vary with the number of applied stress cycles. There are two basic shapes of fatigue curves. One, mainly for body-centered-cubic (b.c.c.) metals, such as carbon/low-alloy steels, has virtually straight lines. The other, mainly for face-centered-cubic (f.c.c.) metals, has a continuous curve. Fig.3 summarizes the two shapes. An important feature of b.c.c. curves is that they have a "fatigue limit". Below the fatigue limit level of applied cyclic stress fatigue failure never occurs.

THE "MAGIC SKIN"

The term "magic skin" has been coined because it expresses the almost unbelievable improvement in fatigue strength that

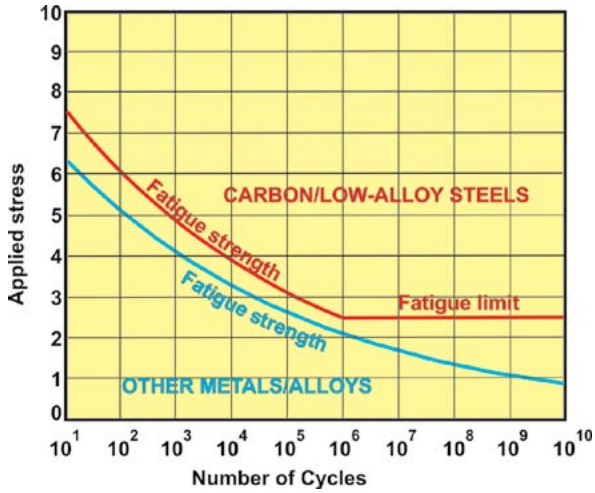

Fig.3. Two shapes of fatigue curves.

is induced by shot peening. Hammering away at the surface of a metallic component might be expected to reduce fatigue strength. In practice the reverse is true. Three important parameters of the "magic skin" can be identified—thickness, hardening and compressive residual stress.

THICKNESS OF COMPRESSED SURFACE LAYER

The thickness of the plastically-deformed surface layer depends on the familiar parameter—"Peening Intensity". Fig.4 shows that the thickness of the compressed surface layer varies almost linearly with Almen arc height. Peening intensity is monitored from the arc height induced in a set of strips—more on that later. For the thinnest compressed layers the thinnest Almen strip, N, is employed. For the thickest compressed layers the thickest Almen strip, C, is employed. Specifications such as J443 indicate the required strip thickness.

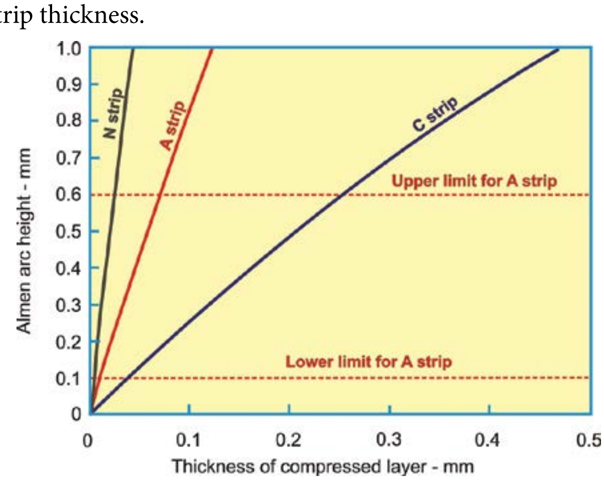

Fig.4. Effect of induced Almen arc height on thickness of compressed layer.

It has to be stressed that the quantitative relationship between arc height and layer thickness depends on the component's material. Fig.4 only applies for Almen strip material. For component material the layer thickness will depend upon its elastic modulus and hardness.

PEENING INTENSITY

Peening intensity and its measurement are such basic aspects of shot peening that they are familiar to shot peeners, being governed by specifications such as J443. Essentially, a set of Almen strips is peened for different lengths of time (or passes) and the induced arc heights are measured to produce a data set. An appropriate mathematical equation is fitted to the data set. The curve of this equation has a point height for which doubling the peening time increases that point height by precisely 10%. This procedure is illustrated by fig.5. For a four-point data set a two-parameter fitting equation is an appropriate choice. Satisfying the 10% rule is illustrated by fig.6 where an arc height h2 is precisely 10% greater than h1 when the effective peening time is doubled (from t to 2t). h1 is then the deduced peening intensity.

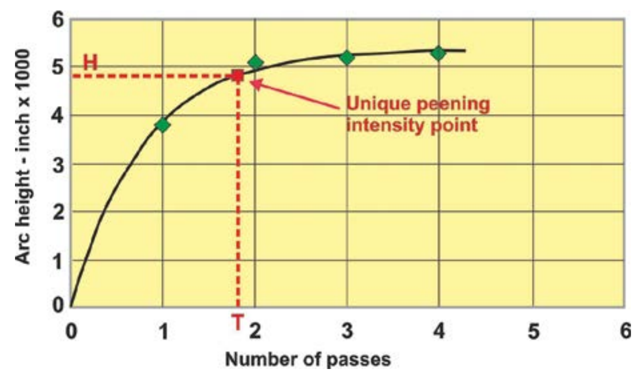

Fig.5. Four-point data set fitted and analyzed using Solver EXP2P.

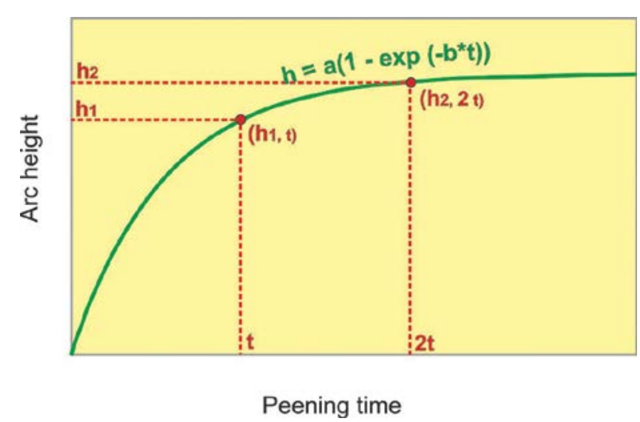

Fig.6. Application of 10% rule to determine peening intensity as being h1.

Peening intensity is so important in shot peening that numerous articles have been devoted to it. There is, however, a great difference between good and bad practice when estimating peening intensity. This is illustrated by the following hypothetical case study.

Company Discussion about Peening Intensity Measurement

Joe and Brian sat down for a discussion about the Company's procedure for estimating peening intensity. Joe had thirty years of peening experience whereas Brian, fresh from university, had only a few weeks of experience. This experience did, however, include recently attending a Shot Peening Workshop. Joe started off by saying that Brian still had a lot to learn about peening intensity measurement. "Fire away with questions." Brian was very keen so he reeled off a series of questions:

1. "Why do we always use just four strips to estimate peening intensity?" "Because it is the cheapest way in terms of test time and strip cost."
2. "Do we always measure the pre-bow of each strip?" "No, that would also take time and anyway ignoring pre-bows reduces the peening work we have to do to meet customer intensity specifications."
3. "Do we always check the indicated deflection of the Almen gage test block?" "No, again that takes up valuable time and it never seems to vary very much anyway."
4. "How long does it take to measure the arc heights for a set of four peened Almen strips?" "I can do it in well under sixty seconds—watch me."
5. "How often do we have the Almen gauge overhauled?" "Can't remember."
6. "Why aren't there any markings on our Almen strips to identify them?" "Because I buy from the cheapest supplier that I can find."
7. "What if one peened strip in a set has an excessive arc height putting the peening intensity estimate just above customer specification?" "I use a trick of the trade—putting the strip in boiling water for a few minutes. Stress-relief lowers the deflection."

At this point Brian stopped asking questions, being disgusted by the answers. When interviewed later by the company CEO, he explained that he thought that the current peening intensity test procedure constituted bad practice. If he was to be put in charge when Joe retired good practice would have to be substituted. The CEO agreed, saying: "Some customers have been lost recently, having lost confidence in our declared peening intensity values. I'll write to all of our customers telling them about our introduction of a state-of-the-art intensity measurement procedure. Hopefully we will not lose any more customers. We might even get some back."

COVERAGE

Coverage is defined in SAE J2277 as "The percentage of a surface that has been impacted at least once by the peening media." As peening progresses, coverage increases as a reverse exponential towards 100%. This is illustrated by fig.7 that also pictures the multiple impacting that must occur in any specific area. Coverages of over 98% are very difficult to measure. Hence 98% is termed "full coverage". For the example shown, 98% is achieved with some 8.5 seconds of peening. That coincides with triple impacting (n=3) being the commonest for any given spot on the component. Some areas will have been indented many more times.

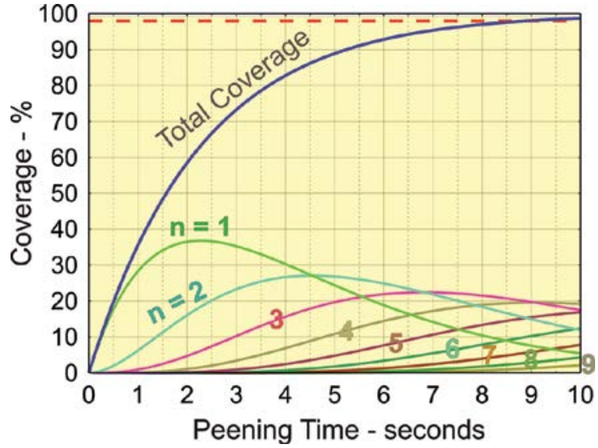

Fig.7. Contributions of multiple denting to total coverage.

It is important to appreciate that component fatigue life varies with the percentage coverage that has been applied. Optimum coverage occurs at less than 100% and depends upon component factors such as design, material and stress cycling regime. Fig.8 shows just one example, for which optimum coverage is 87%. Note that property improvement varies little on either side of the optimum coverage.

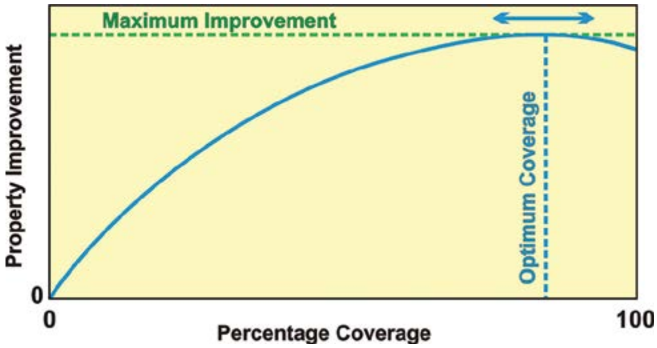

Fig.8. Example of a property optimization curve.

Measurement of coverage is a subject in itself. A simple, subjective method is to visually compare areas with those of reference images. Manual lineal analysis is much more accurate and far less subjective. Computer-based lineal analysis is quick, but requires investment in equipment.

WORK-HARDENING

Shot peening is a surface work-hardening process. Work-hardening is one of the two factors that improve the fatigue strength of components; the other being the compressive residual surface stress. Surface work-hardening induces a huge increase in yield strength—several times that which would be predicted by a tensile test. That is because peening deformation has a large compressive component. Work-hardening is almost entirely due to a massive increase in crystal defects called "dislocations". This increase has two characteristics:

(1) **During deformation, dislocations move with the speed of sound** and

(2) **During deformation, dislocations multiply at an astronomical rate.**

As an example, annealed steel containing 10^6 dislocations per square centimeter may contain 10^{12} under a peening dent. That is a million fold increase induced in, say, a thousandth of a second! The influence of dislocations on hardness is described in a previous Shot Peener article ("Work-hardening during Shot Peening," Summer 2017).

Dislocations allow movement to occur with metal crystals. Fig.10 shows the analogy of how a ruck in a very heavy carpet can be used to allow easy movement a bit at a time.

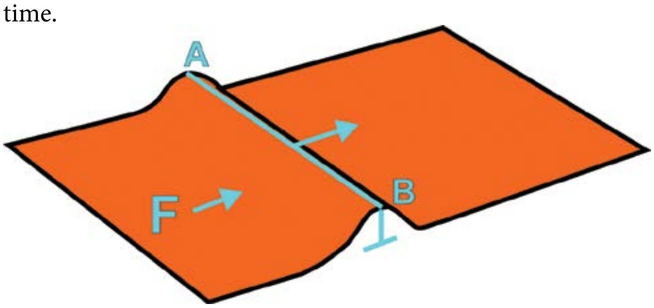

Fig.9. Ruck-in-carpet analogy of a dislocation line.

A force, F, applied in the direction shown, moves the ruck to the end of the carpet.

The overall effect of a massive increase in the dislocations can be illustrated by another analogy: Imagine early-morning traffic in a gridded city. With only a low density of traffic, progress is easy. If, however, the traffic density increased tenfold every few seconds flow would rapidly slow down. Vehicles would start to pile up and some would try to use "rat runs"— analogous to the cross-slip of moving dislocations.

The role of dislocations in allowing crystal movement is countered in many aero fan blades. These blades are grown as single crystals so as to be dislocation-free. The absence of dislocations increases the blades' resistance to creep (elongation under stressing at high temperatures).

RESIDUAL STRESS SYSTEM

Surface residual stress is the second contributor to improved fatigue strength—the other being work-hardening. A residual stress system requires that there is a corresponding residual force system. This vital concept is illustrated by the simple spring model shown as fig.10. Ten identical springs are stretched using a force of 2N on each spring. The total force of 20N is balanced by two springs compressed by 10N each. Note that the compressed springs, shown in green, occupy a smaller area than do the ten compressed springs.

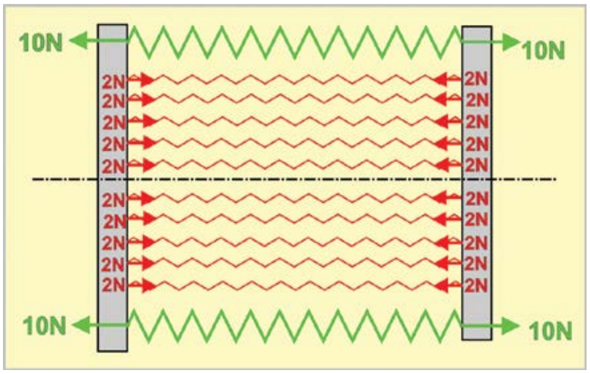

Fig.10. Spring model of a stable residual force system.

Stress is force divided by the area over which it acts. The compressive residual stress level in a shot-peened surface is much higher than that below the work-hardened depth. Fig.11 illustrates this feature.

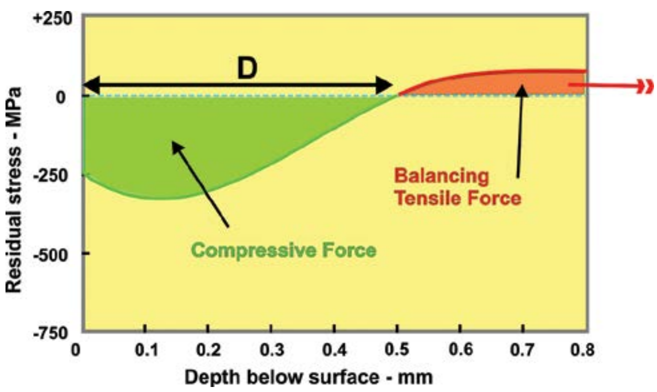

Fig.11. Typical residual stress system near a peened surface, needed to balance residual forces.

SHOT ACCELERATION

Shot has to be accelerated to controllable velocities. The two main techniques are air-blast and wheel-blast. These allow shot to be accelerated to the velocities needed to work-harden component surfaces. General accounts of air-blast and wheel-blast shot acceleration appear in Part 2 of this mini-series. The following introduces the corresponding shot velocity equations.

Air-blast shot acceleration

The velocity of air-blast accelerated shot, vs, is given as equation (8) on page 28 of the Winter 2007 *The Shot Peener* article.

$$v_S = (1\cdot 5.C_D.\rho_A.s/d.\rho_S)^{0.5}\,(v_a - v_s) \qquad (8)$$

where C_D is the "drag coefficient" (a dimensionless number that depends upon the shape of the object when, for a smooth sphere, $C_D \approx 0.5$), ρ_A is the density of the **compressed** air (1.2 kgm^{-3} times the compression ratio), **s** is the nozzle length, ρ_S is shot density, v_a is the velocity of the air stream and v_s is the velocity of the shot particle.

The most important feature of equation (8) is that there is only one variable quantity for a given shot peening setup. Shot density, nozzle length and velocity of the air stream in the nozzle are all virtually constant. That leaves us with just the density of the compressed air in the nozzle as a variable controlled by adjusting the air compressor.

An analogy for the supremacy of air density is presented as follows. Imagine having one's back to a wind blowing at 10 kilometers per hour. This wouldn't blow one off one's feet. Compare that with standing with one's back to a river of water also flowing at 10 kilometers per hour. Water, being much denser than air, would accelerate one in the direction of flow.

Equation (8) can be employed using a simple Excel program where shot velocity is given by the following formula entry for v_s :

=B8*((1.5*B2*B4*B3*B7)/(B5*B6))^0.5/(1+((1.5*B2*B4*B3*B7)/(B5*B6))^0.5)

ROW	A	B	C
	Parameter	Value	Units
2	Cd	0.5	
3	Air density	1.2	kgm^{-3}
4	Air pressure	9	atm
5	Shot density	7860	kgm^{-3}
6	Shot diameter	0.5	mm
7	Length	100	mm
8	Air velocity	200	m s^{-1}
9	**Shot velocity, vs**	**62.4**	**m s^{-1}**

The program can be extended to produce graphs, such as Fig.12.

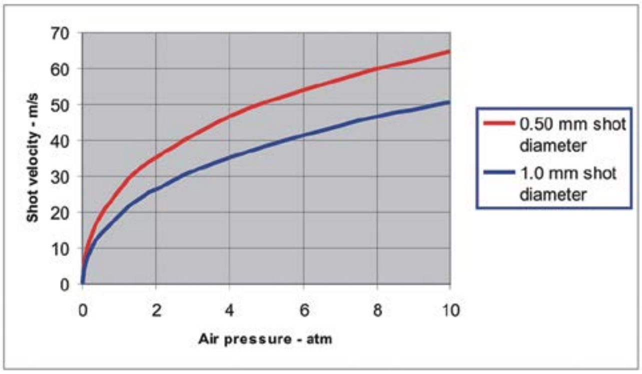

Fig.12. Variation of induced shot velocity with applied air pressure.

Wheel-blast shot acceleration

Wheel-blast shot acceleration is much more energy-efficient than air-blast shot acceleration which accounts for its continued appeal. A variety of wheel types have evolved but the mechanics involved are generally similar. Normally, blades attached to a rotating wheel throw shot at components. Shot velocity is achieved in two stages: accelerator drum and throwing blades. Particles are fed into peripheral slots formed between the accelerator and a stationary control cage. Centrifugal force keeps the particles pressed into the slots as the accelerator drum rotates. At this stage the shot particles have the rotational velocity of the drum. When a slot reaches the outlet slot in the control cage some shot particles escape onto a throwing blade for the second stage of acceleration, see fig.13.

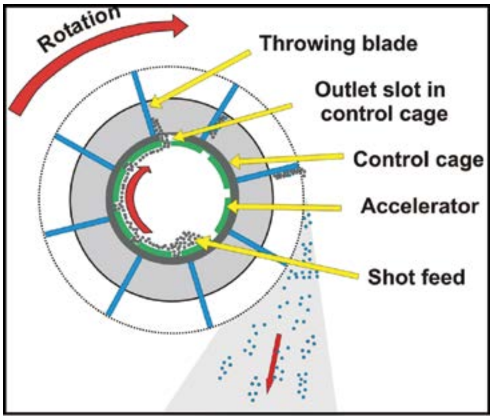

Fig.13. Wheel-blast system with "open" throwing blades.

Individual particles leaving the tips of the throwing blades have two velocity components, V_T and V_R. These are vectors which combine to give the particle velocity, V_S, as illustrated in fig.14. V_R is the radial velocity induced by the centrifugal acceleration and V_T is the tangential velocity (which is equal to the rotational velocity of the blade tip).

The values of V_T and V_R determine both the velocity and movement direction, θ, of the thrown shot particles. Tangential velocity, V_T, is quite easy to estimate, whereas the radial velocity, V_R, requires the application of physical principles (and some simplifying assumptions).

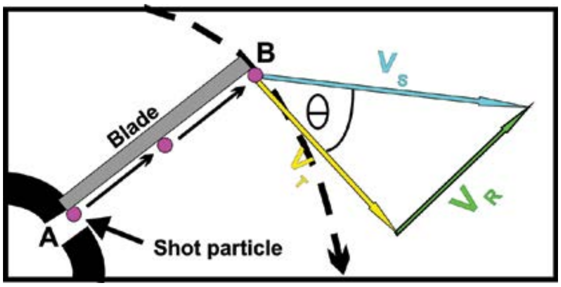

Fig.14. Vector-combined velocity, v_s, for particle leaving blade tip.

The magnitude of v_s is given by the following equation:

$$V_S = 2.\pi.N(R^2 + 2.R.L - L^2)^{0.5}$$

Where **N** is the r.p.s., **R** is the radius of the circle swept by the blade tip and **L** is the length of the blade. The direction of **Vs** is obtained knowing that $\tan\theta = v_R/v_T$.

The ratio of blade length, L, to wheel radius, R, can be termed the "blade/radius aspect ratio". Commercial accelerator-fed machines have wheels with aspect ratios within a range of 30 to 70%. The ratio for a particular machine/wheel affects both the shot's exit velocity, V_S, and the exit angle, θ. Fig.15 illustrates the effects of aspect ratio on shot velocity components and exit angle. The curves were derived by plotting equation (8) against aspect ratio. Within an aspect ratio range of 30 to 70%, the thrown shot velocity is predicted to vary from about 123 to 138% of the tangential velocity. The corresponding exit angle range is from 36 to 44˚.

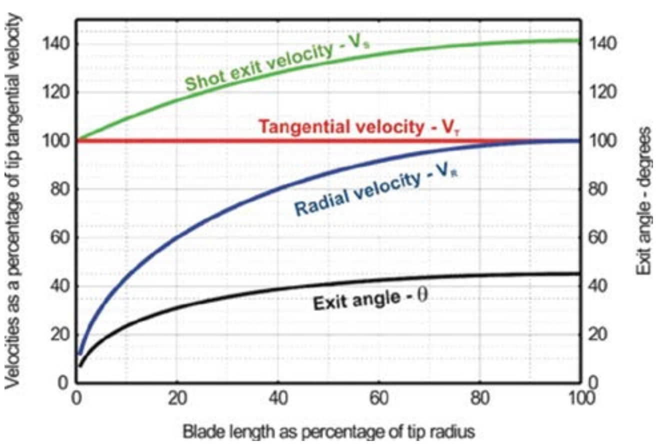

Fig.15. Effects of blade/radius ratio on induced velocities and exit angle.

DISCUSSION

This article has presented the bare bones of several articles previously published in *The Shot Peener*. Quantification can be applied to most controllable peening variables. A basic understanding of those variables is essential for effective control. Several equations have been included that model the variables. Predicted values are, however, not to be regarded as being exact but rather as indications of how parameters can be varied.

Finally, it must be realized that a very important supplementary factor is data storage. An organized data bank is so very useful for reducing the level of guesswork needed to achieve required levels of peening intensity and coverage.