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Shot peening

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Keywords

Peening, Shot blasting, Stress

Abstract

Peening is a very useful process for extending the service life of a large number of metallic components. Its benefits can only be maximised through an understanding of the principles that are involved in shot peening. Presents a comprehensive account of these principles, covering basic mechanics, peening media, residual stress distributions, coverage and equipment. The essential residual stress requirement is to induce a surface layer of compressively-stressed material. Proper control of peening parameters is needed in order to optimise the residual stress profile for specific components. Presents and discusses the several factors that influence the residual stress profile.

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Introduction

As with all branches of technology there is a large body of facts and knowledge associated with shot peening. The aim of this account is to promote understanding of the most important principles of shot peening. Six topic areas are covered:

(1) Shot peening basics.
(2) Types of shot peening media.
(3) Residual stress distribution.
(4) Coverage and saturation.
(5) Shot peening equipment and its control.
(6) New advances in shot peening.

A further reading list is appended.

A very useful analogy to shot peening is paint spraying. Useful insofar as paint spraying is a generally-understood process for which similar basic principles apply. Roughly spherical particles are projected to a surface with the object of achieving a uniform, specified, coverage (employing "masking" to prevent unwanted coverage). The particles are accelerated by compressed air as they leave a gun. A spray cone is produced whose intensity (particles crossing a unit area per unit time) decreases as the square of the distance from the gun to the workpiece. The greater the volume of paint emerging from the gun per unit time, the greater is the rate of paint application. For production purposes we can use several guns simultaneously for large components. Either the workpiece is moved relative to static paint guns or vice versa. Repeatability of paint coverage on a given component requires process control parameters to be maintained.

Shot peening basics

Residual stresses

Shot peening is a process that induces a protective layer of compressive residual stress at the surface of engineering components. The object of that compressed layer is to offset applied tensile stresses thus improving service performance (fatigue, corrosion-fatigue etc.). The compressively-stressed layer is due to the tensile surface plastic deformations caused by the bombarding shot particles. Virtually all residual stress profiles originate from

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non-uniform plastic deformation. The "Law of Residual Stresses" states that:

> The sign (+ or –) of the residual stress is opposite to the sign (+ or –) of the non-uniform plastic deformation that caused the stress.

Note: + corresponds to tensile stress and deformation whereas – corresponds to compressive stress or deformation.

The Heyn spring model is illustrated in Figure 1 and shows a balanced residual stress system. A tensile force, F, in a centrally-placed stretched spring is balanced by the same total force in two outer compressed springs. Balance of both *forces* and *bending moments* is a necessary feature of any system in equilibrium.

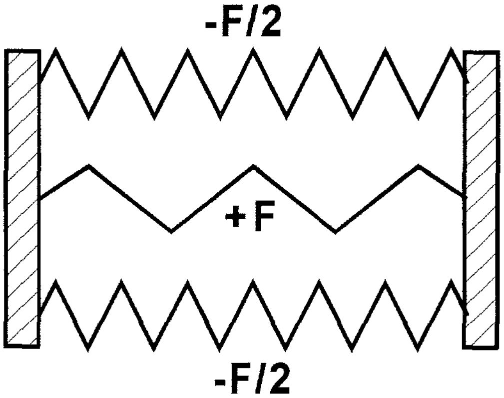
In a real component, the forces correspond to a given type of residual stress (tensile or compressive) multiplied by the area over which it acts. Hence a low level of stress acting over a large area will exert the same force as a large stress acting over a small area. With shot peening we are normally dealing with high levels of compressive surface stress acting over a small area balanced by "internal" low levels of tensile stress acting over a large area. The surface stress level will be approximately half of the yield strength of the as-peened (work-hardened) material acting over a depth similar to the diameter of the shot being used.

Shot velocity and its significance

Of the several important shot parameters (size, shape, mass, density, hardness, velocity, etc.) the most significant is the velocity. This is because of the vitally-important equation telling us that the kinetic energy, E, of a moving particle is given by:

$$E = 1/2mv^2$$

Figure 1 Heyn spring model of a balanced residual stress system



where m is the mass of the particle and v is the velocity of the particle.

In order to accelerate a shot particle we must do work on it. With "air-blasting", the particle is accelerated by an air stream where the pressure on one side of the particle is greater than on the other (see Figure 2). This pressure difference multiplied by the effective area gives the accelerating force. Air flowing faster than the particle will always accelerate it. An alternative to air acceleration is the use of centrifugal force imparted mechanically using a rotating bladed wheel.

Shot impacting metal surface

When a high velocity shot particle impacts a metal surface it does work. The particle has a kinetic energy which is in units of Force × Distance (Nm). Consider what is happening as the high-energy particle indents the surface. When the particle first contacts the surface, the stress (force/area of contact) is infinitely high. That is because the initial contact area is infinitely small. Hence deformation of the component must occur regardless of whether the shot material is softer or harder than that of the component. The area of contact then rises rapidly and therefore the stress reduces rapidly. When the stress becomes less than the yield strength of the material plastic deformation stops and the particle comes to rest as shown as position B in Figure 3. The depth of the indentation is shown as "d". The shot particle has lost its initial kinetic energy. Elastic forces on the particle at B then accelerate it in the opposite direction so that the particle "rebounds".

Work has been done by the impacting particle. This work is the product – force × distance (or the area of a force/distance diagram – see Figure 4).

The next question is: "Where has the material of the indentation gone?" In effect it

Figure 2 Spherical particle being accelerated by faster-moving air stream

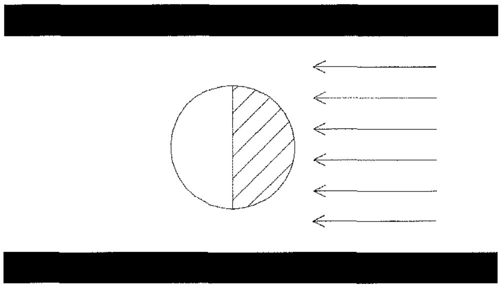


Figure 3 High-velocity shot particle striking component at point A, at rest at B

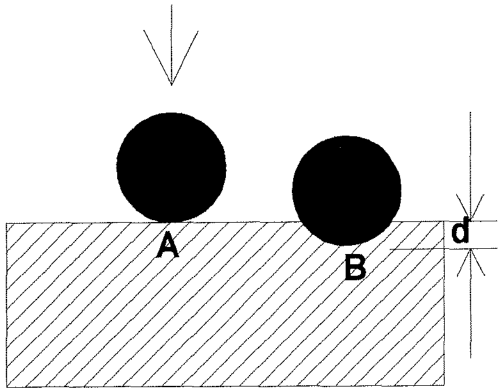
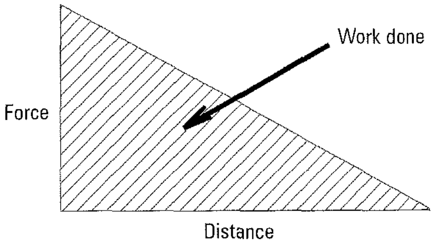


Figure 4 Simple force/distance diagram



has moved sideways (i.e. parallel to the component surface). That corresponds to the tensile surface plastic deformation that gives rise to the compressive residual surface stress that is the major aim when shot peening.

Work and power

Power is the rate of doing work. Hence for high production rates we need high-powered equipment. Centrifugal machines are more energy-efficient than air-blast machines but are less controllable so that the latter are employed for so-called "precision shot peening". For air-blast machines we must use the facility as economically as possible.

Types of shot peening media

We must distinguish media used for peening from that used for blast cleaning. The main difference is one of shape. Blasting media have to be irregular so that sharp-edged particles can cut away brittle surface deposits. Peening media, on the other hand, have to be relatively smooth-edged. The ideal shape would be a sphere, which dictates some of the types of media that are employed.

Materials

In an ideal world, batches of shot would comprise perfectly-spherical particles, all of exactly the same diameter, having infinitely-high hardness and having perfect wear, corrosion and fracture resistance. In the real world, we have to select from available materials and with parameters that can be achieved at an acceptable cost. Our choice is largely restricted to four different materials: cast iron, steel (cast or as cut wire), glass and ceramic.

With the exception of cut-wire steel shot the different materials are cast to roughly spherical particles. The ease with which spheres can be produced from these materials is the main reason why they are used. Cast iron has a much lower melting point than steel so that it is much cheaper to melt and cast. Cast iron has a carbon content in the region of 4 per cent whereas the steel used for shot has a carbon content of about 0.8 per cent. Cast iron is, however, much less wear-resistant than steel. Mild steel with its carbon content of about 0.1 per cent would be uneconomical for shot as it is so soft that it would deform too easily. Molten iron or steel is poured into a jet of water which "atomises" the liquid into roughly spherical particles of liquid which then solidify rapidly. The spherical shape of the liquid particles is due to adopting a shape that minimises the surface area/volume ratio. This reduces the total surface tension energy of the particles. Glass and ceramic beads are also produced by "atomisation" processes. Cut steel wire is produced by chopping up short lengths of continuously-fed steel wire using "flying shears". The cylinders produced must then have their sharp edges removed by a "conditioning" process.

Shape specification

A typical shape specification states that:

> The shot or beads shall be free from sharp edges and inspected for deformed shapes or broken shapes when examined. A given sample size shall contain no more than the number of unacceptable deformed shapes as shown in Figure 5 and as defined in Table I below.

That Table, in essence, requires that not more than 10 per cent of a specified sample size shall be of unacceptable shape. There is no specification for roundness – it would be too restrictive commercially.

A very high proportion of shot direct from a manufacturer would be of acceptable shape as a consequence of the method of manufacture.

Figure 5 "Mil spec" shapes taken from Mil-S-13165C

1 Acceptable shapes

2 Unacceptable "deformed" shapes

3 Unacceptable "broken" shapes

The problem in practice lies with the fact that a small proportion of shot will be deformed and/or fractured during peening operations. If we continually recycle the shot then there will be an increasing proportion of unacceptable shot developed in the shot "charge". Good practice therefore dictates that at least a proportion of used shot is treated to remove unacceptable shot particles. This unacceptable shot can then be removed and replaced with new shot.

Size specification

There are whole series of size specifications based on sieve sizes. Figure 6 shows a representation of the specification requirements for S170 (USA) shot (see also Table I).

Hence all shot must pass through the largest sieve, not more than 2 per cent must be caught on the next largest sieve, not more than 50 per cent on the 0.0197" sieve. At least 90 per cent must have been accumulated by the 0.0165" sieve. That 90 per cent is therefore the sum of the shot caught on the 0.0234, 0.0197 and 0.0165" sieves. At least 98 per cent must have been accumulated by the 0.0139" sieve (the remaining 2 per cent could be dust!). We should note that different

Figure 6 S170 specification for allowed percentages on different sieve sizes

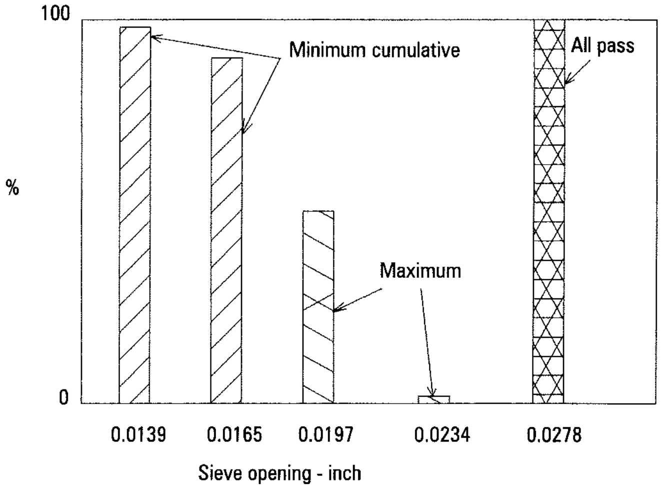


Table I Cast shot numbers and screening tolerances

Peening shot	All pass US sieve number and opening - inch		Maximum 2% US sieve number and opening - inch		Maximum 5% US sieve number and opening - inch		Cumulative min. 90% on US sieve number and opening - inch		Cumulative min. 98% on US sieve number and opening - inch	
930	5	0.157	6	0.132	7	0.110	8	0.094	10	0.079
780	6	0.132	7	0.110	8	0.094	10	0.079	12	0.066
660	7	0.110	8	0.094	10	0.079	12	0.066	14	0.056
550	8	0.094	10	0.079	12	0.066	14	0.056	16	0.047
460	10	0.079	12	0.066	14	0.056	16	0.047	18	0.039
390	12	0.066	14	0.056	16	0.047	18	0.039	20	0.033
330	14	0.056	16	0.047	18	0.039	20	0.033	25	0.028
280	16	0.047	18	0.039	20	0.033	25	0.028	30	0.023
230	18	0.039	20	0.033	25	0.028	30	0.023	35	0.020
190	20	0.033	25	0.028	30	0.023	35	0.020	40	0.017
170	25	0.028	30	0.023	35	0.020	40	0.017	45	0.014
130	30	0.023	35	0.020	40	0.017	45	0.014	50	0.012
110	35	0.020	40	0.017	45	0.014	50	0.012	80	0.007
70	40	0.017	45	0.014	50	0.012	80	0.007	120	0.005

countries may allocate different numbers to the same shot size!

Choice of shot

The customer may specify the choice of shot material in which case there is no problem! Most peening, however, is carried out with cast steel shot that has been "tempered" after casting in order to improve its toughness. This is because it is the most cost-effective material and is suitable for peening most steel components. It is "low alloy/plain carbon" steel since alloying increases the cost of the raw material. The carbon content of about 0.8 per cent ensures maximum hardness for a quenched plain carbon steel combined with adequate toughness. Carbon contents above 0.8 per cent will mean that the steel will contain primary cementite (Fe_3C) particles which embrittle the particles. Post-quench tempering reduces the hardness slightly but increases the toughness considerably. Toughness is a measure of the work that is required to fracture a material. Remember that the shot particle has a lot of work to do when it strikes the material. If its kinetic energy is greater than the work required to fracture it then it will break! Breakage rates increase with increase of shot velocity and with increased component hardness. Contamination of highly-alloyed steel or non-ferrous components with embedded shot is a serious problem if we use standard cast steel shot. Austenitic stainless steel components containing embedded ferritic steel particles will rust rapidly! Ceramic or glass beads are then a reasonable choice for peening. Their breakage rates are much higher than for steel shot and we must use a separate peening machining. Reduced air pressure peening with steel shot followed by "dressing" with ceramic shot peening is a "combined" solution.

There are, of course, several factors affecting choice of shot size. Again the customer may specify a shot size in which case again "no problem". The main problem for the shot peener is that it is very expensive to change from one size of shot to another in the same machine. Changing the size of, say, cast steel shot in a given machine requires emptying of the peening system as completely as possible. In-line screening is essential for any machine using different shot sizes.

Residual stress distribution

Basic features

The situation for a rectangular component, shot peened on two major faces, is shown schematically in Figure 7. This distribution can be appreciated by referring back to the Heyn spring model, Figure 1. The compressively-stressed surface layers exert forces equivalent to two compressed springs. An equal balancing force is given by the core material – equivalent to a stretched spring. The stress in the core is much lower because it is acting over a much larger area.

Consider next the situation represented in Figure 8.

Using the Heyn spring model analogy this is equivalent to having only two springs – one stretched and the other compressed (see Figure 9).

With this situation the component will bend in order to achieve equilibrium of clockwise and anti-clockwise moments. Such bending is the basis of peen-forming and of peen-shape-correction. Bending will cause the residual stress distribution to change until equilibrium of bending moments is achieved.

Figure 7 Schematic representation of residual stress distribution for shot-peened component

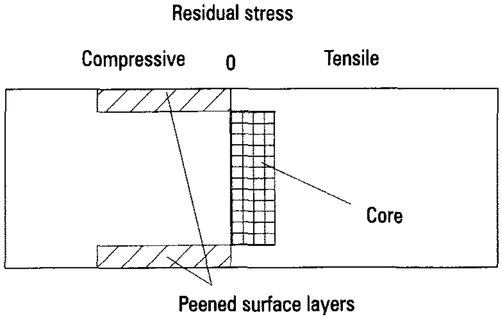


Figure 8 Schematic representation of residual stress distribution in component peened on one major face only

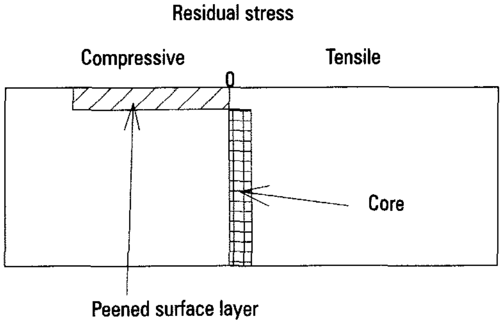
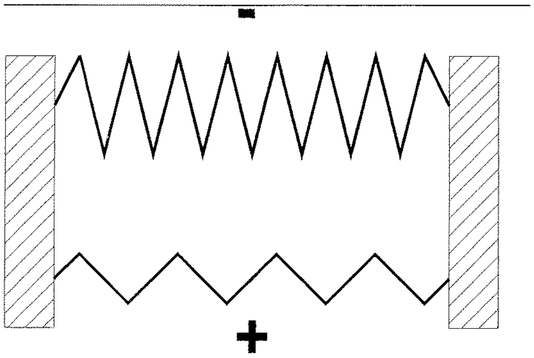


Figure 9 Unbalanced residual stress distribution represented by Heyn spring model



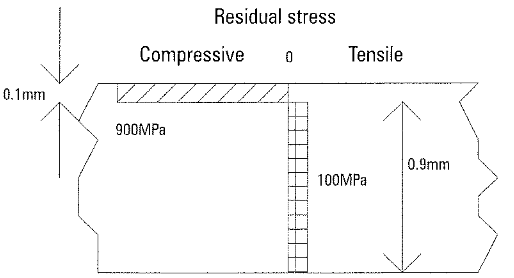
Bending moments induced by non-uniform shot peening

The classic example of bending moments induced by non-uniform peening is the peening of Almen strips. A clamped rectangular strip is peened on one major face. The clamping is then removed and the bending moment induced by peening then causes the strip to bend. The degree of bending is directly related to the "Almen Height". Consider the situation shown in Figure 10.

For the purposes of simplified calculation we assume that the strip is 1.0mm thick and that peening has induced a compressive residual stress of 900MPa in a layer 0.1mm thick. There must be a balancing tensile stress of 100MPa acting over the remaining depth of 0.9mm. The problem (of calculating bending moment) is simplified if we regard the tensile stress as acting over the entire thickness and add a "compensating" 100MPa to the compressive stress in the 0.1mm layer. The net effect then is simply one of a 1,000MPa stressed layer 0.1mm deep acting at a distance of 0.45mm from the "neutral axis" of the strip. The corresponding bending moment, M, is then given by:

$$M = 1{,}000\text{MPa} \times 0.45\text{mm} \times w \times 0.1\text{mm} \quad (1)$$

Figure 10 Idealised residual stress distribution in as-clamped Almen strip



where w = the strip width.

We can use the value of M to calculate the induced radius of bending, R, since:

$$M = E.I/R \quad (2)$$

where E = elastic modulus and I = second moment of area given by:

$$I = wt^3/12 \text{ for a rectangular section} \quad (3)$$

where w = strip width and t = strip thickness.

Assuming that E = 200GPa for steel and substituting known values into equation (2) we have that:

$$R = 200\text{GPa}.w.(1\text{mm})^3/(12.\ 1{,}000\text{MPa} \times 0.45\text{mm} \times w \times 0.1\text{mm}) \quad (4)$$

or

$$R = 200\text{mm}/(12 \times 0.45 \times 0.1) \text{ giving}$$
$$R = 370\text{mm} \quad (5)$$

We can use the value obtained for R to calculate:

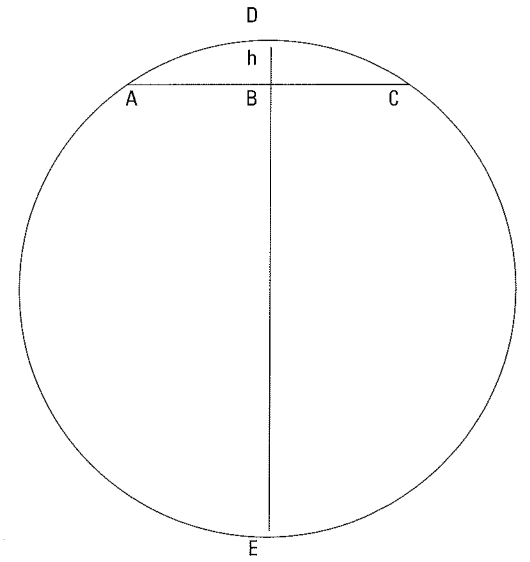
(1) the approximate deflection of the Almen strip; and
(2) the "new" residual stress distribution in the strip after it has been released from the hold-down screws.

For deflection estimates we have to convert a radius of bending into a deflection for a given length of strip. We can use the "intersecting chord theorem" illustrated in Figure 11.

The theorem tells us that if one chord is a diameter then (a) another chord at 90° to it must be bisected and (b) that:

$$AB.BC = DB.BE \quad (6)$$

Figure 11 Chords AC and DE intersecting at 90° in a circle of radius R



but AB = BC = half the strip length, DB = h (required deflection) and BE = (2R – h).

Now for an Almen strip the supported strip length is 1.25" or 32mm so that AB = 16mm and substituting into (6) gives us:

$$(16\text{mm})^2 = h\,(740\text{mm} - h) \qquad (7)$$

where h is in mm. h is very much less than 740 so that (7) can be simplified to:

$(16\text{mm})^2 = h \times 740\text{mm}$ giving:

$h = 0.35\text{mm}$.

The value of 0.35mm does not take account of the deflection caused by the transverse stress acting at 90° to the longitudinal axis stress. This will add 50 per cent to the deflection giving a total of 0.53mm.

The "new" residual stress distribution in the strip is a combination of residual stress and bending stress profiles. For a simple estimate of bending stress we can use the standard engineering formula for surface stress, o′s, in an elastically-bent beam:

o′s = E.t/(2R)

which with substitution of E = 200GPa, t = 1mm and R = 370mm gives that:

o′s = 270MPa.

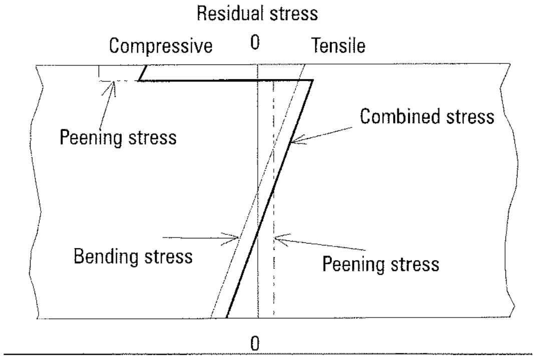
A more accurate estimate is given by adding the contribution for bending in the perpendicular plane. That surface stress would be 135MPa and its contribution to stress at 90° is that value multiplied by Poisson's ratio (say 0.28) giving an additional 38MPa for an adjusted estimate for o′s given by:

o′s = 308MPa

Adding the elastic bending distribution to the original distribution gives the new residual stress distribution, i.e. after removal of the clamping. That uses the fact that stresses can be added together (superimposed). Figure 12 shows the application of the superposition principle.

It follows from the foregoing that peen forming produces a combined residual stress profile that has compressive stress on both surfaces. That is important for service performance. In predicting the probable residual stress distribution in a component we must take into account any bending that has been induced. Components with a large section thickness will have a negligible "bending contribution", as will components that have been peened over the complete surface.

Figure 12 Superposition of peening stresses and bending stresses



Residual stress distributions in shot peened components

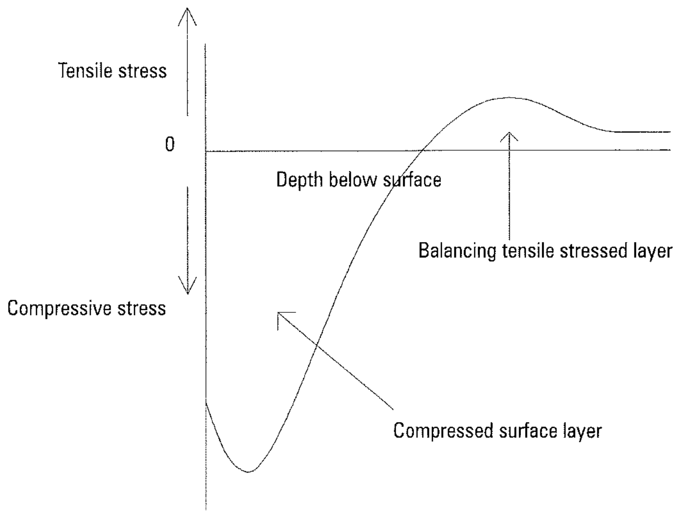
The distribution of residual stress below the surface of a shot-peened component is based on a classic profile as illustrated in Figure 13.

The level of extreme surface stress is related to the yield point of the work-hardened surface layer. As a rough guide it is half of that yield strength. If the material work hardens to three times its original (possibly annealed) yield strength we expect a residual stress that is higher than the original yield strength! It tends to be independent of shot size or shot peening intensity (defined later).

The maximum compressive residual stress occurs below the extreme surface and is roughly two-thirds of the yield point of the work-hardened surface layer.

The depth of compressed surface layer is directly related to the shot size that has been used. Larger shot means deeper layers with the maximum compressive stress moving correspondingly deeper. The relationship

Figure 13 Classic residual stress profile for shot-peened component



between shot size and depth of compressed layer depends upon several factors – including shot hardness, shot velocity, material hardness and work-hardening characteristics of the material. As a very rough guide the depth of the compressed layer is of the same magnitude as the shot diameter.

The magnitude of the balancing tensile stress depends upon the ratio of the depth of compressed layer and component thickness. In an extreme case where we might peen a thin cylindrical component such that the cross-sectional area of the peened layer is equal to that of the unpeened core (see Figure 14).

The average tensile stress must then be similar to the average stress in the shot-peened layer! Figure 15 shows this type of residual stress distribution. We can then be trying to exceed the yield strength of the core material (remember it has not been work-hardened). The situation then is very dangerous since if the core plastically extends we then induce compressive stress in the core that must be balanced by tensile stress in the peened surface

Figure 14 Cylinder with equal cross-sectional areas of peened and unpeened material

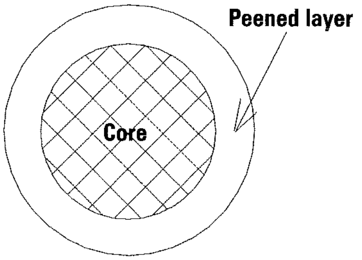
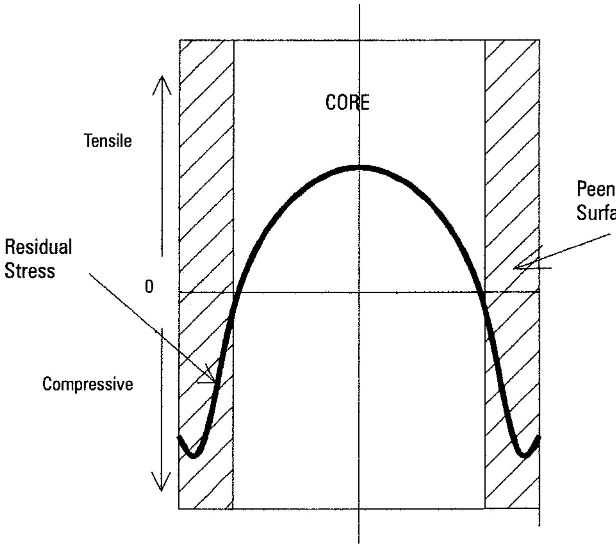


Figure 15 Residual stress distribution in a thin cylindrical component



Prior residual stress distribution will affect the distribution left after shot peening. Consider a typical residual stress distribution in a carburised, quenched and tempered component as shown in Figure 16.

Peening has increased the level of beneficial extreme surface compressive residual stress and that just below the surface. The extra compressive force has to be balanced by extra tensile force. This is reflected in a reduction of the level of compressive stress further below the surface. Overall we have improved service performance unless maximum service stressing is well below the surface.

Phase transformations can occur during shot peening which will affect the residual stress distribution. One common example is that "retained austenite" in a carburised surface can be transformed to martensite by cold-working. This crystallographic transformation, of itself, induces compressive residual stress. Hence we find even higher levels of surface compressive residual stress than we would normally expect. Another, fortunately less common, example is that some grades of austenitic stainless steel (e.g. 304) will partially transform to martensite due to the cold-working effect. This gives higher surface hardness and higher surface compressive residual stress than if we gave the same peening treatment to 316 austenitic stainless steel. Unfortunately the two-phase crystallographic structure has much reduced corrosion resistance!

Figure 16 Residual stress distributions in as-carburised and peened carburised component

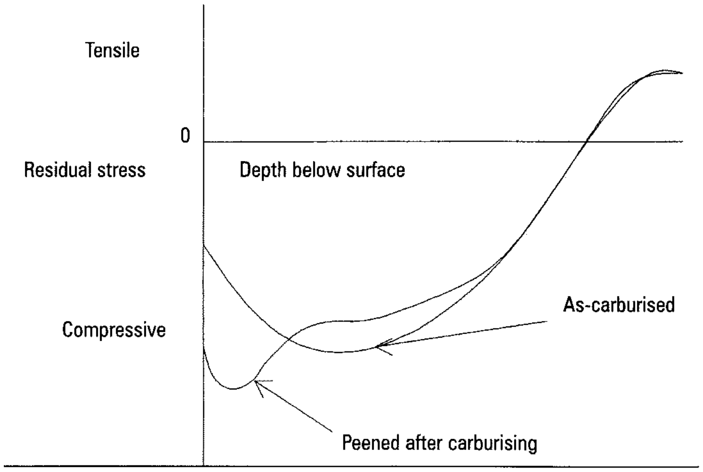
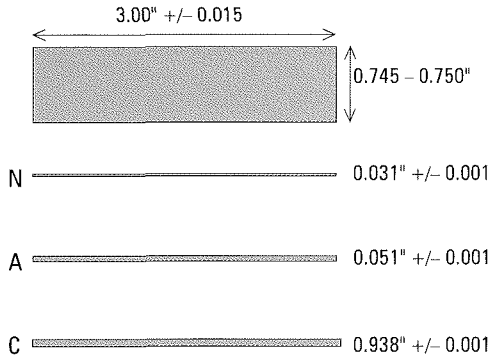


Figure 19 Almen strip dimensions



The chosen thickness of Almen strip is fixed to a test block of specified dimensions as shown in Figure 20. The fixture is 3" by 1.5" by 0.75" thick with 0.192-0.194" reamed holes in a symmetrical rectangle spaced 1 and 9/16" by 0.940-0.945". After fixing, the strip is exposed to the shot stream for the time required to achieve a specified Almen intensity. When peening is complete, the strip is removed from the fixture and placed on an Almen gauge. There is a variety of more or less sophisticated Almen gauges that can be purchased or manufactured. The essential feature for each gauge is that the peened strip is supported on a rectangular array of four 3/16" hardened steel balls. This array is set at 1.248-1.252" by 0.623-0.627". A standard flat specimen is used to zero the monitoring gauge and then the peened strip is placed on the four supporting balls. The deflection (from flat) of the peened strip is the Almen height.

A saturation curve is produced by exposing a series of nominally-identical strips to the same intensity of shot stream but for different peening times. The measured Almen heights are then plotted to produce the required curve (see Figure 21).

Figure 20 Holding fixture for Almen test strips

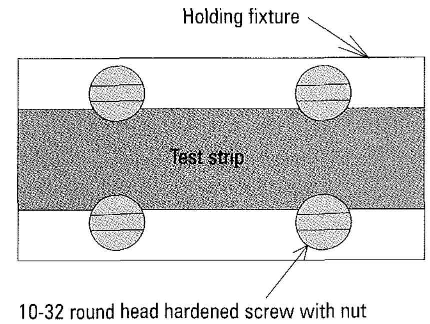
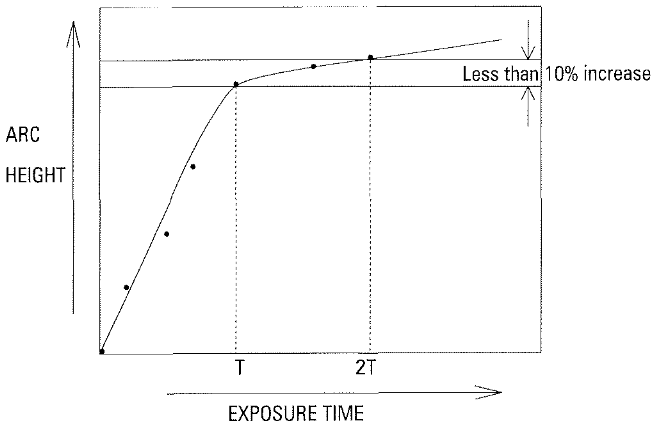


Figure 21 Almen saturation curve

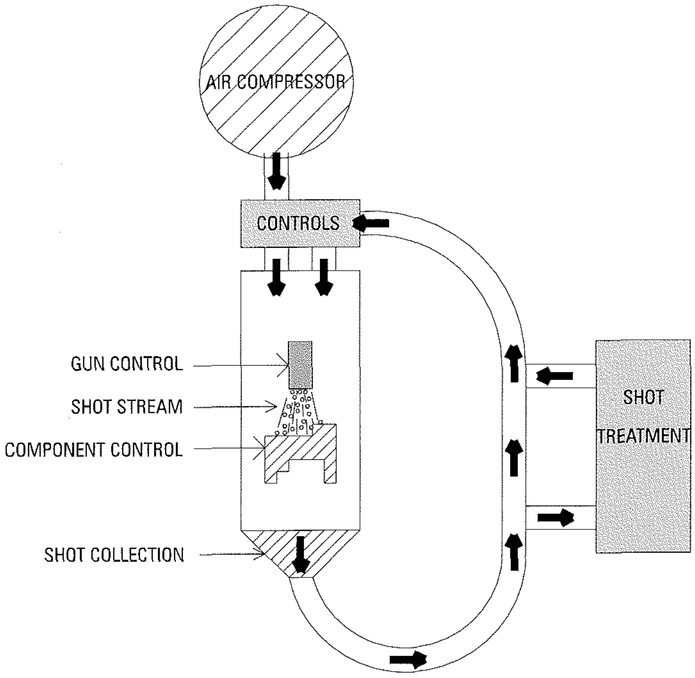


Saturation is defined (in the military specification) as the time to produce a height that is increased by not more than 10 per cent if the peening time is doubled (see Figure 21). T is the minimum time that meets the specification. Longer times than T would meet the specification as stated. Commercially we need the minimum time to achieve a specified Almen height (generally known as "Almen Intensity"). That is why saturation curves are important for the shot peening organisation.

Shot peening equipment and its control

A schematic representation of air-blast peening equipment is shown in Figure 22.

Figure 22 Schematic representation of air-blast shot peening equipment



Coverage and saturation

Development of coverage

The cumulative effect of shot peening impacts is to increase the *coverage* of the surface. The shot particles arrive *randomly* at the surface producing a series of indentations as shown in Figure 17.

As peening progresses, more and more area is covered. In the early stages virtually all of the indentations will be individual. Later on there will be more and more overlap of indentations. In the later stages virtually all of the indentations will be overlapping previous indentations. There is a basic problem of "When have we completely peened the surface?" In fact it is impossible to say when we have completely covered the surface with indentations. Statistically we can only be certain of complete coverage when we have peened for an infinite time! We have to resort, for control purposes, to an indirect measure of coverage. This will be dealt with later.

Each impact of a shot particle work hardens a localised region of the component's surface. An overlapping impact means that a region has been subjected to more than one deformation. Eventually a material will have suffered so much plastic deformation that it will try to crack. Figure 18 shows how the relative contribution of repeated impacts increases with total coverage for one specific peening regime.

For peening times of up to 10s with this particular regime the majority of the peened area has had only a single impact and total coverage is only 86 per cent. At 20s the coverage is 98 per cent – approaching practical situations for "fully-peened" material – but now the largest proportion of peened area has received five impacts.

Figure 17 Impacts generated by progressive peening

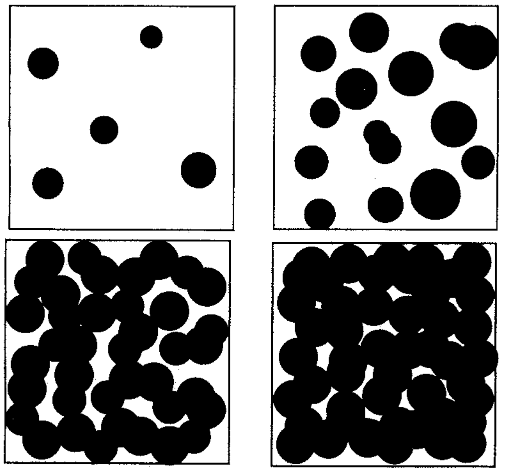
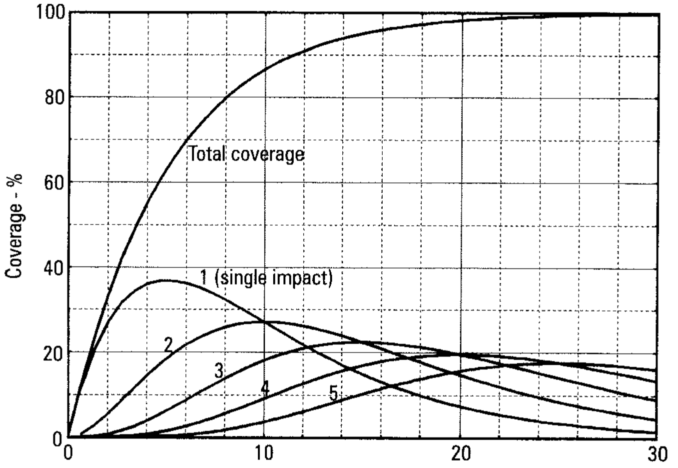


Figure 18 Contribution of different numbers of impacted areas to total coverage



Some specifications call for "100 per cent coverage". Since that is theoretically and practically impossible we have a problem! The answer lies in the methods that are also specified for determining 100 per cent coverage. There is no available method that gives very accurate coverage measurements. Use of a 10 × ocular magnifier is certainly not accurate. It cannot distinguish between 99.9 per cent and 99.99 per cent coverage. A previously-applied fluorescent coating such as Peenscan^{TM} is better but is still not perfect. Hence, in practice, we can satisfy the specification requirement of 100 per cent coverage with a 99.99 per cent coverage. Indeed, any higher per cent coverage would seriously damage the surface because of excessive working.

The most important problem, from a customer point of view, is uniformity of coverage. Having specified a given intensity of peening it is important that the actual coverage does not vary excessively over the component surface. This is dealt with in the next section.

Saturation

Saturation curves are obtained by using Almen strips and an Almen gauge. These are thin rectangular strips made in three different thicknesses but all to the same major dimensions (see Figure 19). Cold-rolled spring steel (SAE 1070) tempered to 44-50Rc, hot-pressed for two hours to remove residual stresses, is used for the strips. Flatness has to be +/– 0.0015" as measured using an Almen gauge.

Shot stream

The shot stream is arguably the most important feature of shot peening equipment. Its characteristics are similar to those of any spray (paint, water, etc.). The stream diverges at an angle determined by the gun design. Hence the specific intensity (shot particles per unit area per second) decreases with distance from the gun. Specific intensity also varies across the shot stream at any given distance from the gun. Good gun design and maintenance will minimise this variation. It should be noted that there is a "sweet point" about 150mm from the gun where the shot is travelling with its maximum velocity. The basic geometry of shot stream divergence is shown in Figure 23.

The cross-sectional area, A, increases with distance from the gun according to the equation:

$$A = \pi.R^2$$

but

$$R = r + D.\tan\alpha$$

so that:

$$A = \pi(r + D.\tan\alpha)^2 \qquad (8)$$

Equation (8) is of vital importance since it determines the specific peening intensity of a given gun. This intensity varies as the reciprocal of A.

Gun and shot stream control

A primary control problem is that a stationary gun cannot deliver a uniform distribution of shot to a stationary flat surface (see Figure 24). The shot stream is more intense in the central region than it is towards the edge of the stream's cone. The obvious answer is to move the stream relative to the component in a progressive manner. For a flat surface this will require X-Y co-ordinated movement as shown in Figure 25.

Figure 23 Geometry of shot stream divergence

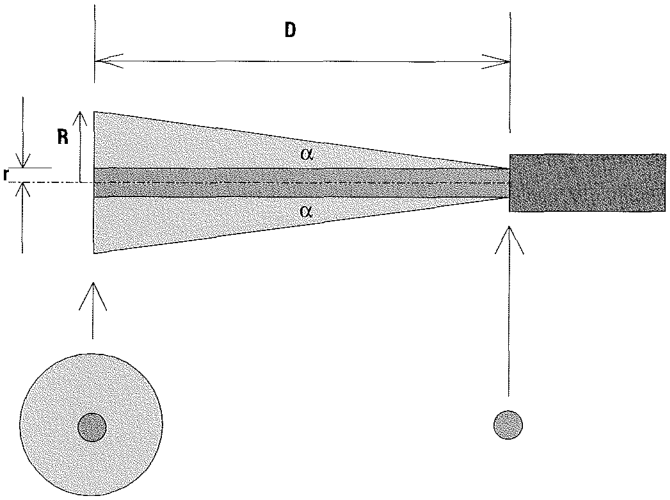
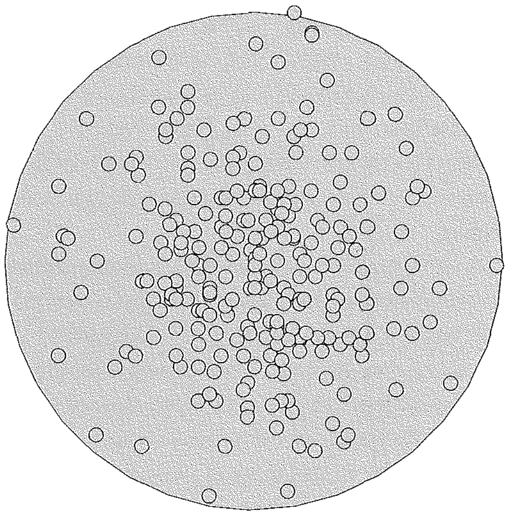


Figure 24 Impacts created by short bursts with stationary gun on flat surface



Reverse tracking of the shot stream should include an initial Y-dimension "offset".

The second major problem is that components are rarely conveniently flat! Consider the simple example of a cylinder that has to be peened over its curved surface (see Figure 26).

Only a small fraction of the shot will actually strike the cylinder – remember that the area

Figure 25 X-Y co-ordinated movement of shot stream to cover square, flat plate

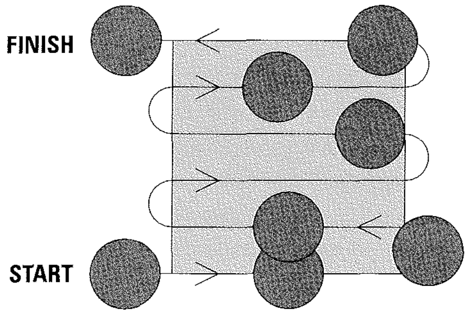
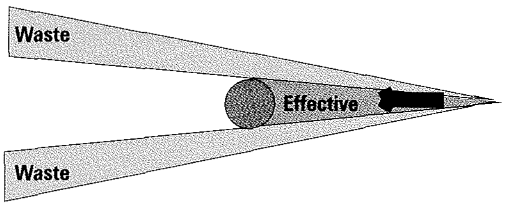


Figure 26 Peening of simple cylinder



is proportional to "distance squared". The shot that does strike the cylinder will vary in effectiveness from a maximum (90° contact) to zero (glancing angle contact). Only a small fraction of the cylinder's circumference is therefore effectively peened unless we rotate the cylinder relative to the gun. Waste can be reduced by either moving the gun closer to the component or by using a narrow divergence shot stream.

A third problem is presented by non-uniform geometry of the component. Any given component has to have a compromise "solution" in that it is normally impossible to peen a component with identical intensities over the complete surface. This solution will often involve several computer-controlled guns moving in three-dimensional space to present the shot stream at reasonably normal angles to all required surfaces (some may be masked-off if peening is not required). Maximum efficiency will be achieved when a large proportion of the accelerated shot strikes the component surface at such angles.

Shot collection and treatment

Referring again to Figure 22, shot is collected after it has been fired towards the component(s) in order to be re-cycled. Simple gravitational forces are normally used in which shot falls under its own weight through a perforated grid into a collecting hopper for transfer to the start of the cycle. Transfer can be effected by bucket elevator, suction or screw elevator.

All of the collected shot should be screened and "air-washed" in order to remove dust and lighter debris. A fraction of the shot should also be passed through a "classifier" in order to remove misshapen and broken shot. The proportion of shot that should be classified is important. Classification costs money but no classification would result in an increasing fraction of misshapen and broken shot. Replacing the misshapen and broken shot also costs money. Quality control parameters are dictated by how closely we wish to sail to the wind!

Mixture controls

There are two primary controls for the mixture of air and shot fed into the shot peening unit – air pressure and shot feed rate. Air pressure is easily regulated but must be specified and controlled to that specification. Control is easier with a large "ballast tank" from which the compressed air is fed. Computer-assisted air pressure control is standard on sophisticated equipment. Precision shot feed rate control is less common. For general applications there is a variety of flow limiting devices that can be used. These include restriction devices (fixed orifice plates, mechanical valves and magnetic field modulated valves) and conveyor devices (auger screw and micro conveyor). For example, Electronics Inc. manufacture a "Magnavalve" unit that monitors and controls the flow of shot to within 0.1kg/minute. Units are manufactured for control of different types of media.

Gun control

The most basic type of gun control is the three-dimensional control allowed by manually-operated equipment. Reproducibility of action is effected using pneumatic simulation of manual control with or without computer control. As with automated car paint spraying the object is to achieve uniform coverage of the component. It follows that a computer-controlled regime is dependent upon the correct parameters being fed into the programme. For symmetrical objects several guns may be brought to bear on the component at the same time.

Gun design is an important aspect of gun control. Several factors can be considered in gun design including:

- Nozzle length – affecting energy transfer efficiency and wear resistance.
- Nozzle diameter – related to the diameter of shot being used.
- Nozzle material – affecting wear rate when using high hardness shot.
- Air/shot mixing – dependent on type of shot supply (suction, direct pressure, non-venting intermittent, continuous blast etc.).

New advances in shot peening

In presenting this section there are two fundamental problems – what is "new" and how can one be objective in one's selection of topics? As a framework, the five previous sections will be used as sub-headings.

Shot peening basics

For too long, shot peening has been regarded as a "black art" in which the perceived benefits are real but the reasons for those benefits were either not understood or were not disseminated by those who did understand. As the benefits of shot peening become integrated into product specifications, it is necessary that the basic concepts are generally understood. The International Conferences on Shot Peening have become an important vehicle for promoting academic and industrial respectability for the newly-developed science of shot peening. A reasonable parallel can be drawn between fatigue and shot peening. Today every engineer becomes acquainted with the basics of fatigue. This forms a basis for integrating fatigue considerations into design specifications. The same should be true of shot peening.

Types of shot peening media

Ceramic shot was introduced in 1981. Since then its use has been developing particularly for applications on stainless steel and non-ferrous alloys. In spite of being ceramic the shot can be used with a low breakage rate. The Almen intensities that can be achieved are intermediate between those for steel shot and glass beads.

Captive shot devices have been developed such as those involving rotating flaps carrying steel shot and "tramping" equipment for peen forming. An alternative, promoted by the author, is the use of a needle peening gun (commonly used in industry as a de-scaling tool).

Residual stress distribution

The big problem with residual stress distributions is that they are very expensive to determine and are subject to a large number of practical variables. Advances have been made in devising methods of predicting the residual stress distribution that will be obtained given knowledge of the controlling variables.

Coverage and saturation

The development of coverage has been the subject of recent studies with the first paper being presented at the Fifth International Conference on Shot Peening (ICSP5) in 1993. These studies have enabled us to determine, quantitatively, the conditions under which repeated impacts can reach the ductility limit for a component.

The inherent defects of the Almen gauge as a method of monitoring saturation have received increased attention. Studies have shown the need for highly-controlled gauge production and for statistically-controlled determination of saturation curves. The large numbers of gauges required for experimentally-based saturation curves has led to current work on saturation curve prediction.

Alternatives to the Almen gauge based on the use of round discs have been proposed since 1993. Edge-clamped discs are continuously monitored for the deflection induced during peening. A complete saturation curve is obtained with a single disc.

Shot peening equipment and its control

Advances in this area appear to have been a gradual improvement and refinement of equipment rather than by involving radical new techniques. A typical example would be the design of flexible tubing carrying a deflector plate for internal peening of small-diameter bent tubes. Wet-blast peening has been introduced with either water-propelled slurry or air-accelerated water-based slurry as the impacting medium. The former is normally only used for fine finishing but the latter does have similar effects to standard shot peening albeit to lesser depths. Computer-based control systems are becoming more sophisticated, e.g. Vacu-Blast's "Vacutrol II".

Other developments

It is worth noting that a very large number of published papers relate to the improvement of some aspect of service performance. This, of itself, has meant that there is a rapidly-accumulating knowledge base. Academic-based research is largely confined to the UK, France, Germany and Japan. Industry-based research appears largely as accounts of isolated examples of component improvement or equipment development. Current areas of study include attempts to quantify the improvement of stress-corrosion behaviour brought about by shot peening.

Further reading

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