ACADEMIC STUDY

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The Importance of Work

INTRODUCTION

Work and rate of doing work are, arguably, the most important parameters in the Universe. No event can happen unless some work is done at a measurable rate. Even blinking an eye requires that some work is done. Shot peening simply could not happen without work being done on components.

The basic unit of work is the Joule. It is named after the English physicist James Prescott Joule (1818–1889). A joule is equal to the work done to an object when a force of one Newton pushes that object through a distance of one meter. Work is, however, more commonly expressed directly in N.m rather than in joules.

The author's favorite demonstration of Newton meters is illustrated in fig.(1). Imagine that a typical apple is exerting a force of 1 Newton when resting on a table (as happens when there are 10 apples per kilogram). Raising that apple through a distance of 1 meter requires that 1 N.m of work is done on the apple. If the apple is released, it converts that work into kinetic energy, falling with increasing velocity until it lands on the table.

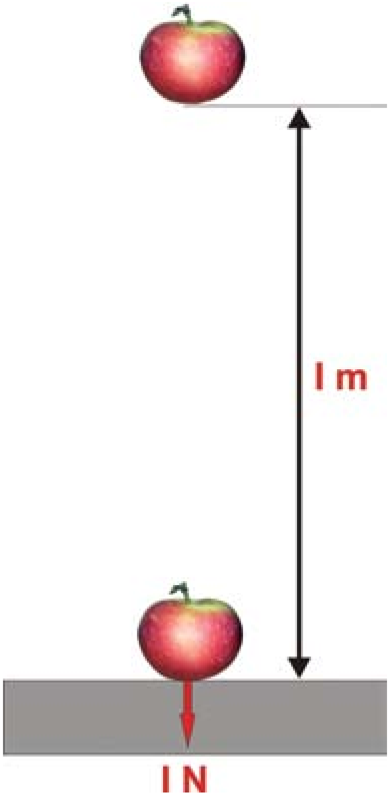

Fig.1. 1 Newton.meter of work done when this apple is raised by 1 meter.

Shot peening is, essentially, a metalworking process. Work has to be done on components in order to generate the "magic skin" of work-hardened, compressively-stressed, material. "Other things being equal," the more peening work done on any component the greater is both peening intensity and indent coverage. It follows that work is of fundamental importance in shot peening. It is also important to realize that units are as important as the magnitudes of quantified parameters.

This article has two objectives: (1) to explain the units that dominate shot peening and (2) to show how the amount and rate of work done affects every shot peening parameter. Only simple arithmetic is invoked—no finite element analysis!

UNITS RELEVANT TO SHOT PEENING

Work done

One Newton is defined as the force needed to accelerate one kilogram of mass at the rate of one meter per second squared in the direction of the applied force. Hence the units for a Newton can be expressed as $kg.m.s^{-2}$.

Imagine a 10 kg bag of steel shot has been lifted 1 meter onto a table. What does the "10 kg" really mean? In the absence of gravity, the 10 kg would not have offered any resistance to being lifted. If, however, gravity is exerting an acceleration of $10m.s^{-2}$ (normal at the Earth's surface) then it will exert a force of 10N on each kilogram. The work done to lift the 10 kg bag 1 meter onto the table is therefore 100N.m.

In terms of the units involved, we have that:

$$\text{Work} = \text{N.m which is also}$$
$$= \text{kg.m.s}^{-2}\text{.m so that}$$
$$\mathbf{Work = kg.m^{2}.s^{-2}} \qquad (1)$$

Kinetic energy

Consider next that the bag of shot is dropped onto the shop floor. As it falls, the bag of shot particles accelerates and therefore achieves kinetic energy. Kinetic energy, K.E., is quantified as half of the object's mass multiplied by the square of its velocity. Velocity has units of $m.s^{-1}$ so that velocity squared has units of $m^2.s^{-2}$. In terms of units we therefore have that:

$$\mathbf{K.E. = kg.m^{2}.s^{-2}} \qquad (2)$$

The units in (1) and (2) are identical, showing that kinetic energy and work units are interchangeable. This interchangeability is of fundamental importance in understanding shot peening.

In order to quantify the kinetic energy of a given mass of shot we use:

$$\text{K.E.} = \text{kg.m}^2.\text{s}^{-2}/2 \qquad (3)$$

Equation (3) is simply expressing that the kinetic energy of an object is “half of its mass multiplied by the square of its velocity.”

Heat energy

When a shot particle dents a component, about 90% of the absorbed kinetic energy is turned into heat. The most familiar heat unit is the calorie, for which:

$$1 \text{ calorie} = 4.2.\text{kg.m}^2.\text{s}^{-2} = 4.2 \text{ N.m}$$

This equivalence of heat, kinetic energy and work allows us to understand the distribution of the work absorbed when dents are formed.

Work rate

Work rate is often expressed in watts. One watt, **w**, is defined as one N.m of work being done every second or

$$1\text{w} = 1\text{N.m.s}^{-1} \qquad (4)$$

The principal power generators for shot peening (air compressors and electric motors) are sometimes rated in horsepower. Horsepower was a unit introduced by James Watt in the eighteenth century to compare the output of his steam engines with the power of horses. It had the advantage of allowing mental images to be created of, for example, a 20 horse-power steam engine being able to work as hard as a team of twenty plow horses. Most countries now prefer work rate to be expressed in watts:

1 horsepower = 750 watts.

By way of an example, consider a situation where a 40 H.P. motor is driving a single blasting wheel. A 40 H.P. motor working flat out is consuming 30,000 watts (40 x 750). Assume that the motor drive just cuts out (due to overload) when the wheel is trying to accelerate 4 kg of shot every second to a velocity of 100 m.s^{-1}. The kinetic energy possessed by 4kg of shot flying at 100 m.s^{-1} is 20,000 N.m ($4.100^2/2$ - using equation (3)). The effective work rate is then 20,000 N.m.s^{-1} or 20,000 watts. That begs the question “why does the motor drive cut out?” No wheel blast system can possibly run at 100% efficiency in terms of motor energy being converted into K.E. of accelerated shot particles. Energy losses include those due to friction. For this example we can, therefore, rate the motor’s efficiency at two-thirds (20,000/30,000). If that efficiency is constant at different wheel speeds then the situation can be represented as shown in fig.2 (which uses a non-linear wheel speed scale for simplicity). As the required kinetic energy per second of the shot stream increases so does the necessary wheel speed (shown as a green line). At a maximum of 20 kw, the wheel cuts out.

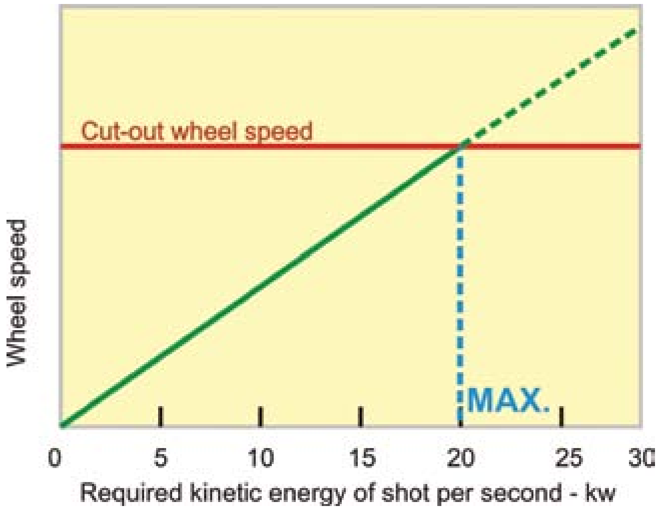

Fig.2. Relationship between wheel speed and kinetic energy per second of a shot stream.

SHOT CHARACTERISTICS CONTROLLING AVAILABLE WORK

Shot density and size

Shot density and size both vary for the major shot peening media: steel, glass and ceramic.

Density is mass divided by volume

For a spherical shot particle, density is mass x 6 /(π x diameter cubed)

Measured density values for steel shot are all about 7,800 kg.m^{-3} whereas those for glass and ceramic shot are about half of that value but do vary significantly with composition.

Table 1, on the next page, is an Excel spreadsheet for steel shot that estimates significant variable parameters.

The estimates shown in Table 1 indicate vast ranges. For example: With a feed rate of 10 kg/minute for S110 (reasonable for air-blast peening) we are throwing more than 100 million shot particles every minute! That compares with about 100 thousand for S1110. Upping the feed rate to 100 kg/minute (reasonable for wheel-blast peening) we would be throwing more than four billion S70 shot particles every minute!

Work absorbed by an impacting shot particle

When a flying shot particle strikes a component, part of its kinetic energy is absorbed by the component and part is retained as the kinetic energy of the rebounding particle. This important principle is illustrated in fig.3. Imagine a large ball bearing being dropped from a height of 1 m onto a steel plate. If it rebounds to height of 0.5 m then half of the impacting

Table 1. Cast steel shot parameters

	CAST STEEL SHOT					
S Number	Size	Density	Mass per particle	Particles per kilogram	Feed Rate	Particles per minute
	mm	kg per m^3	g.10^{-3}		kg/minute	
70	0.18	7800	0.023	43,562,371	10	435,623,706
110	0.28	7800	0.089	11,226,065	10	112,260,654
170	0.43	7800	0.329	3,041,297	10	30,412,972
230	0.58	7800	0.814	1,228,067	10	12,280,672
280	0.71	7800	1.469	680,662	10	6,806,620
330	0.84	7800	2.405	415,780	10	4,157,802
350	0.89	7800	2.869	348,499	10	3,484,990
460	1.17	7800	6.514	153,508	10	1,535,084
550	1.40	7800	11.135	89,809	10	898,085
660	1.68	7800	19.241	51,973	10	519,725
780	1.98	7800	31.760	31,486	10	314,863
930	2.36	7800	53.832	18,576	10	185,762
1110	2.82	7800	91.530	10,925	10	109,254
1320	3.35	7800	153.927	6,497	10	64,966
		7800			10	

kinetic energy has been absorbed. This ratio has been shown, by experiment, to be realistic for steel shot striking steel components.

If we know the mass and velocity of impacting particles, we can then estimate the amount of work that is absorbed. It was shown earlier that the kinetic energy possessed by 4 kg of shot flying at 100 m.s^{-1} is 20,000 Nm. If half of this is absorbed on impact, 10,000 Nm of energy will have been absorbed. With 90% of these 10,000 Nm being converted into 2000 calories of heat (9,000/4.2) we have only 1,000 Nm left for permanent plastic deformation work.

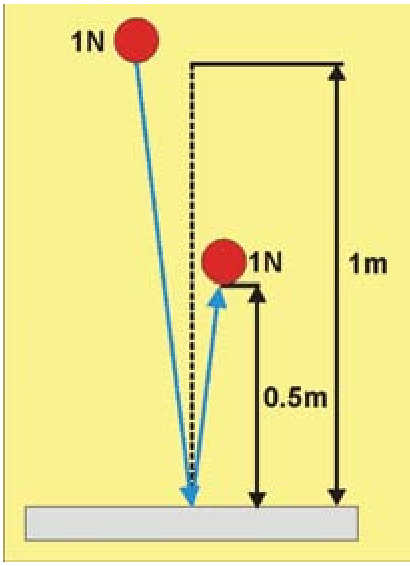

Fig.3. Kinetic energy absorption on impact with a component's surface.

Work required to produce dents

It is an inevitable consequence of conventional shot peening that dents are made by impacting shot particles. The size of these dents depends mainly on shot size, shot velocity, shot hardness and component hardness. For any given combination of these factors, the larger the dent the more work has had to be done to create it. The following analogy is intended to emphasize the relationship between dent size and the work needed to create it.

Navvies digging holes.

Fig.4 is of navvies - as depicted in Ford Madox Brown's painting "Work."

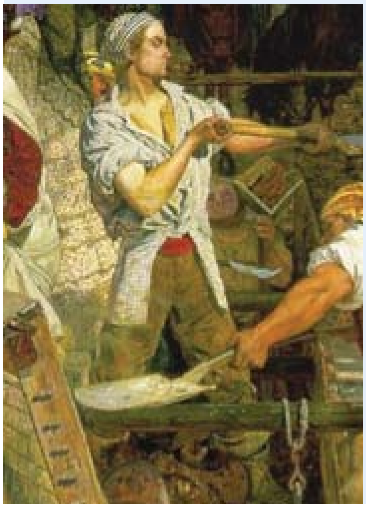

Fig.4 "Work" by Ford Madox Brown depicting navvies.

Imagine that we have a team of twelve navvies that can be employed (for one day only) to dig holes. The volume of each hole would depend upon how many were assigned to dig each hole. With all twelve digging a single hole, the hole's volume would be twice that of each hole generated by two teams of six digging two holes, three times that for teams of four, four times that for teams of three and six times that for teams of two. In other words the volume of each hole depends directly on the amount of work that has been done to create it.

SHOT PEENING PARAMETERS AFFECTED BY AMOUNT OF WORK DONE

Dent Size

It was shown in an earlier article ("Prediction and Control of Indent Diameter", TSP, Spring 2004) that the amount of work that has to be done to create each unit of indent volume is equal to the Brinell hardness value, B, of the component. The work done creating a given indent is therefore the Brinell value multiplied by the volume of the indent. In terms of units, Brinell value can be expressed as N/m^2. Multiplying N/m^{-2} by indent volume units (m^3) we have N.m - which are our basic work units. Using the navvy analogy, the harder the soil being excavated the smaller will be the volume of the hole dug using a fixed amount of work.

The volume, V, of an indent is related to the indent and shot diameters, d and D, as illustrated in fig.5.

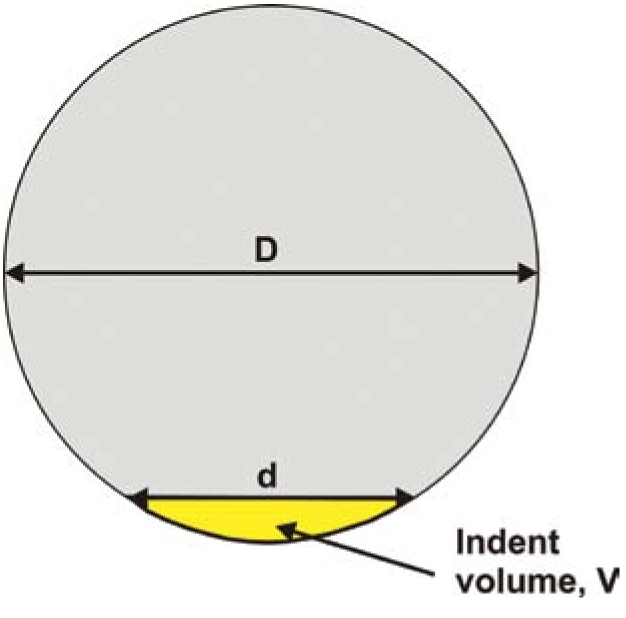

Fig.5. Indent diameter, d, and shot diameter, D.

We have that:

$$V = \pi.d^4/32D \qquad (5)$$

Equation (5) is of huge practical significance. **V** is the volume of the indent. Hence it represents the amount of deformation work that the impacting particle has to do in order to create the indent. It is important to note that this depends on the fourth power of the dent's diameter. Imagine that we want to double the diameter, d, of indents made by shot of a fixed diameter D. Two raised to the fourth power is sixteen (2 x 2 x 2 x 2). That means that we would have to give each shot particle sixteen times as much kinetic energy if the dent is to have a doubled diameter.

The TSP article listed earlier also showed that dent diameter varied with four parameters: shot diameter, velocity and density together with the component's Brinell hardness. A graphical illustration is given as Fig.6 which illustrates the effect of changing the magnitude of each of the four parameters independently. The axis ranges have been deliberately chosen to emphasize the d^4 factor in equation (5).

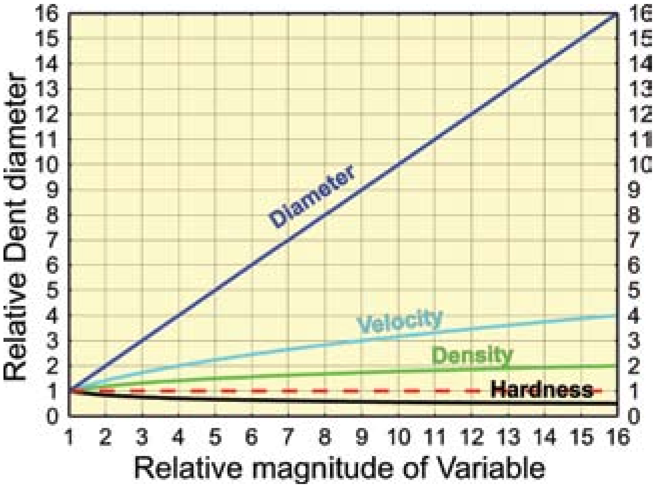

Fig.6. Effect of shot properties and component hardness on dent diameter.

The effects shown in fig.6 can be considered either in isolation or in combination.

In isolation, the other three factors are constant. For example, increasing the shot diameter increases the dent diameter linearly (provided that shot velocity, shot density and component hardness are kept constant). The rate of increase is to the power of one. In other words, doubling the shot diameter doubles the dent diameter. Hence multiplying the diameter of the shot being used by a factor of sixteen will increase the dent diameter by a factor of sixteen. As another example, increasing the shot density (in isolation) by a factor of sixteen only doubles the dent diameter. That is because the increase is proportional to the fourth root ($D^{0.25}$) of density. The fourth root of sixteen is 2 (16 = 2x2x2x2). Dent diameter increase is inversely proportional to the fourth root of the component's hardness. Hence a sixteen fold increase in component hardness halves the dent diameter—other factors being kept constant. Finally, the effect of shot velocity depends on its square root with the square root of sixteen being four. The kinetic energy of a shot particle is proportional to the square of its velocity so the fourth power effect in equation (5) is halved to become a two power effect.

The factors shown in fig.6 can be considered in combination. For example: multiplying both shot diameter and shot velocity by 16 will increase the dent diameter by a factor of sixty-four (16x4).

Overlapping indents are more complicated than isolated dents. Consider the situation illustrated by fig.7. Imagine dent A is produced first, followed by dent B. Because of the overlap, the volume of dent B is less than that for A. It might therefore be expected that the diameter of dent B would have to be slightly larger than that of dent A (to make up for the overlap volume). In practice, dent A causes work-hardening that reduces the volume of dent B produced by a given amount of work. Using the navvy analogy, a team digging dent B would find that the soil adjacent to dent A had become harder to dig.

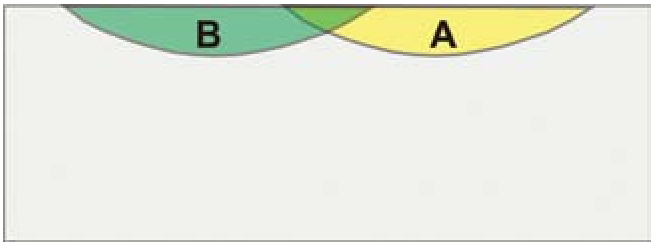

Fig.7. Overlapping dents.

Coverage

The diameter of an individual dent depends on the amount of work done during its creation. Coverage, on the other hand, depends on both average dent diameter and the number of dents generated in each unit area of the component. The increase of overlapping with increased peening is also a vital consideration. Numerous articles have appeared that explain the mathematical basis for the way in which coverage develops with peening time. As a light-hearted alternative, consider the following analogy.

Poppy Field Bombing.

Imagine a scenario in which an air force general decides to test the possibility of destroying opium poppy fields using several bombers. The first bomber drops seven nominally-identical bombs in a random fashion, aimed so that each crater occupies at least part of the poppy field as illustrated schematically in fig.8. Only two craters have contributed wholly to poppy field destruction—one overlaps and four are only partially damaging the poppy field.

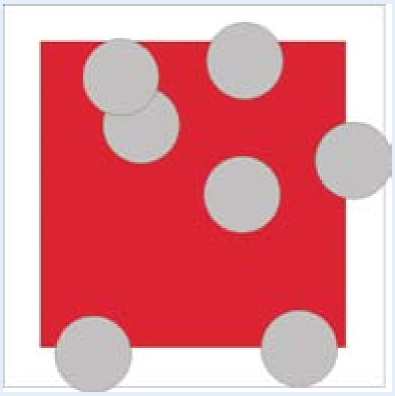

Fig.8. Seven craters distributed randomly.

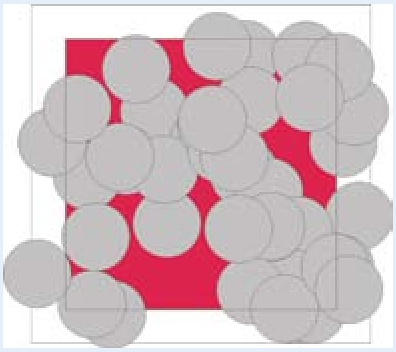

Figure 9. Forty-two craters distributed randomly.

The air force general orders another six identical bombing runs resulting in a total of forty-two randomly-positioned craters as illustrated in fig.9. This does not, however, satisfy the general who is determined to achieve complete poppy destruction and declares so at his staff meeting, adding "Has anyone got any useful suggestions?" Up stood a bright young engineering lieutenant saying, somewhat nervously:

"I've just been to a shot peening Workshop to find out why peening is so useful for prolonging the life of our aircraft parts. They have a similar problem of covering an area with miniature craters. Using a standard equation they can predict how coverage increases with increasing number of dents per unit area. Instead of trying to get 100% coverage they often aim for 98%. It is argued that this may correspond to inducing maximum benefit. Hardening and compressive stress are induced around each of their miniature craters. In our case we might think that with 98% cratering the surrounding poppies might be so damaged that no farmer would feel it worth attempting any harvesting."

"Very useful example of lateral thinking," said the general. "I'll give it some thought. Meeting over."

Peening Intensity

Peening intensity is quantified by the amount of deflection imposed on an Almen strip when it has been peened so that this deflection would have increased by 10% if the amount of peening had been doubled. The greater the peening intensity deflection, the greater is the amount of work that has had to be done on the strip. This work is stored in the strip in two ways. One is the recoverable elastic work associated with the characteristic residual stress profile. The other is the non-recoverable work done to plastically deform the strip. Research, involving applying stress-relieving heat treatment, has shown that the two ways are approximately equal in magnitude.

Fig.10 illustrates the two components of peened strip curvature. Cold-working and residual stress both contribute h/2 to the combined deflection, h. Both components increase with the amount of work that has been done.

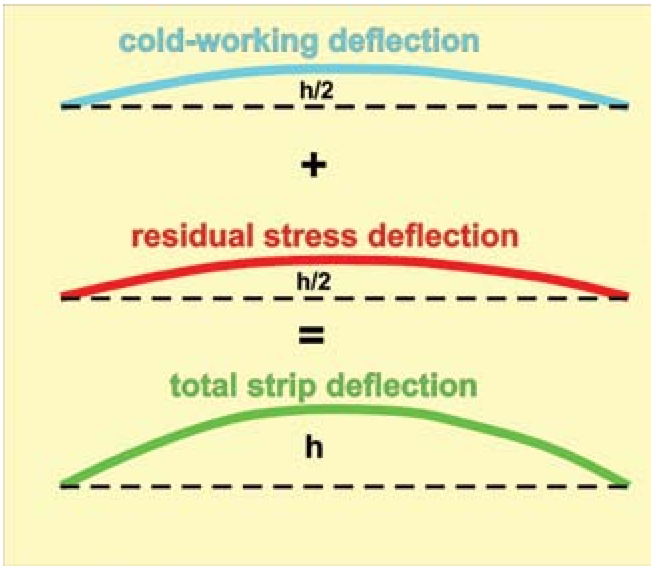

Fig.10. Schematic representation of Almen strip deflection components.

Cold-Working Deflection

Under each dent is a region that has been cold-worked. This corresponds to work having been done. The mechanics of dent formation are quite complicated so consider the parallel example of a tensile test. Fig.11 illustrates a typical tensile force versus plastic extension curve. The work done on the test piece is equal to the area under the load/extension curve.

Residual Stress Deflection

The amount of deflection depends on the work-equivalent of the residual stress profile. It is not stress that causes Almen strip deflection but the force associated with the stress profile. Imagine a large person, weighing say 100 kgs (about 225 lbs. or 16 stones) standing on a plank that is supported at each end. The plank will bend under the weight due to the downward force of about 1000 Newtons. If the plank deflects by a tenth of a meter then 100 Nm of work will have been done.

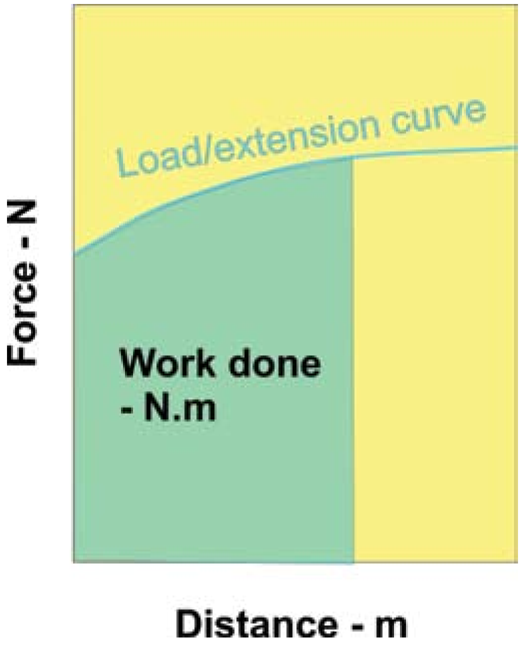

Fig.11. Force multiplied by distance equals work done.

Deflection due to shot peening of an Almen strip is caused by forces parallel to the strip's surface. If, for example, an average compressive stress of 500 Nmm^{-2} exists to a depth of 0.1 mm, we can estimate the magnitudes of the corresponding forces. For the end section of the strip the force will be 20mm x 0.1mm x 500 Nmm^{-2} which equals 1000 Newtons—the same as is exerted by our "large person"! For the side section we have 76 mm x 0.1 mm x 500 Nmm^{-2} which equals 3800 Newtons. The work done in bending the strip to a deflection of, say 0.1 mm, involves complex bending mechanics calculations. Some idea of the work's magnitude can, however, be obtained by simply multiplying the sum of the two forces by 0.1 mm which gives 480 Nm.

SUMMARY

Work and work rate are the unifying parameters that connect all aspects of shot peening. The metric definitions of work (in Nm) and work rate (in Nms^{-1}), can be used to quantify aspects of dent formation, coverage, peening intensity and the capacity of equipment needed to achieve satisfactory peening rates. Of particular significance is the equivalence of heat, kinetic energy and work units. This allows us to understand the distribution of the work absorbed when dents are formed.

The work rate capacity of compressors and wheel-blast motors are essential features of a peening plant's profile. This profile dictates the feasibility of carrying out required peening procedures. ●