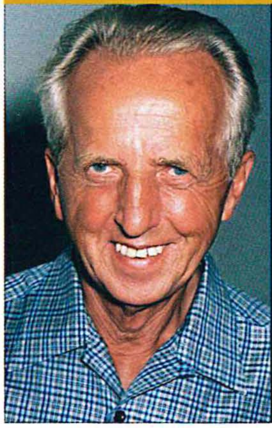

Surface Heating Caused by Peening

by Dr. David Kirk
Coventry University, U.K.

Dr. David Kirk, our "Shot Peening Academic" is a regular contributor to *The Shot Peener*. Since his retirement, Dr. Kirk has been an Honorary Research Fellow at Coventry University and still supervises their Shot Peening and X-ray Stress Analysis laboratories. He is currently writing a book "The Science of Shot Peening". We greatly appreciate his contribution to our publication.

Introduction

Shot particles striking a component's surface lose part of their kinetic energy to that surface. This loss of impact energy is to be welcomed. If no energy were lost then the peening would have been completely useless. Approximately 10% of the energy absorbed by impact with the surface is translated into the stored energy of cold work. The remaining 90% is converted into heat energy. This follows the 'Law of Conservation of Energy' which states that "energy cannot be lost — it can only be converted into other forms of energy". The proportion of shot energy that is absorbed on impact is governed by the coefficient of restitution, ε.

The input of heat energy causes a rise in the surface temperature of the component. With conventional peening, the induced temperature rise is only a few degrees. We can, however, depart from convention to deliberately increase the surface temperature of the component. With intermediate deliberate temperature rises, we can induce recrystallisation of cold-worked surfaces - although the advantage of that is dubious. With large deliberate temperature rises, we can effectively surface heat-treat steel components. This is the equivalent of surface heating processes such as induction hardening and flame hardening. In order to understand the underlying mechanisms, we should consider the source and extent of feasible surface temperature increases together with the phase changes that might then become possible. One approach is to regard the shot stream as a source of surface heating, similar in some ways to flame or induction hardening.

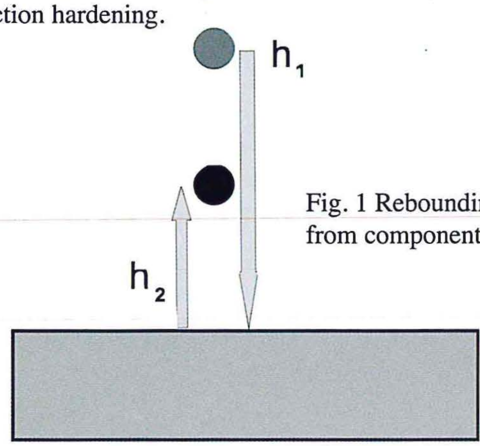

Fig. 1 Rebounding of ball from component surface

Coefficient of Restitution

The 'coefficient of restitution', ε, is the ratio of the velocity at which two bodies separate to the velocity at which they collided. If one of the two bodies is stationary then ε is the ratio of the rebound velocity, v_2, to the impact velocity, v_1. The coefficient of restitution controls the proportion of the shot energy that is transferred to the component surface. The concept of 'restitution' is familiar when related to the height that a ball will bounce when it is dropped onto a hard surface. Perhaps the simplest experiment in shot peening is to drop a shot particle onto a surface from a given height, h_1, and measure the 'rebound height', h_2, see fig.1. The square root of the ratio of heights, $\sqrt{(h_2/h_1)}$, equals the coefficient of restitution, ε.

The kinetic energy, E, of the shot particle when it strikes the component surface is given by the familiar equation:

$$E = 1/2\ m\ v^2 \tag{1}$$

where m = mass and v = velocity.

When a ball is dropped from a height, h_1, it accelerates under gravity, g, so that, ignoring air friction, the velocity on impact with the surface, v_1 is given by:

$$v_1 = \sqrt{(2\ g\ h_1)} \tag{2}$$

Similarly, after impact with the component surface, we have that the rebound velocity, v_2, is:

$$v_2 = \sqrt{(2.g.h_2)} \tag{3}$$

Dividing v_2 by v_1 from equations 3 and 2 gives $v_2/v_1 = \sqrt{(h_2/h_1)}$ or

$$\varepsilon = \sqrt{(h_2/h_1)} \tag{4}$$

The actual coefficient of restitution in shot peening will depend upon a number of factors including the material of the shot and of the component, shape of shot and velocity of shot. In a simple experiment involving dropping a 20mm diameter steel ball bearing from a height, h_1, of 1.00m onto a cast iron anvil the approximate rebound height, h_2, was 0.50m. Substituting these values into equation 4 gives that $\varepsilon = 0.71$.

Using equation 1 we have that the rebounding shot energy, E_2, divided by the impact energy, E_1, is given by $E_2/E_1 = v_2^2/v_1^2 = \varepsilon^2 = h_2/h_1$. Hence, some 50% of the energy of the ball bearing was absorbed on impact.

Surface Temperature Increase Due to Normal Peening

The surface temperature increase due to normal peening is much less than 100°C. As mentioned previously, most of the work done by the impacting shot is converted into heat energy. This heat energy must be accommodated by a rise in temperature. That accommodation takes place somewhere between two extreme situations. One extreme is called 'adiabatic heating' where the heat causes an instantaneous temperature rise without any loss of heat outside the surface layer. The other extreme is called 'isothermal heating' where the heat is distributed to give a uniform temperature rise of the whole component and long times are required. Between these extremes, there is 'intermediate heating' where heat has flowed by conduction into the interior of the component. The three types of curve are illustrated in fig. 2.

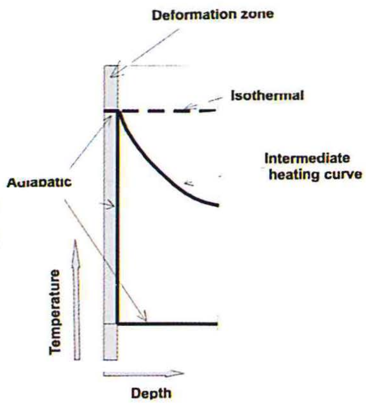

Fig. 2 Adiabatic, intermediate and isothermal heating curves

Initially, adiabatic heating will be examined using a simple model for calculating temperature rise in a thin surface layer impacted for a very short time. The first step is to make assumptions about each of the parameters that will affect the work done within the surface layer and hence the heat generated per unit volume of surface material. As an example of a 'normal peening' situation the following combination of parameters have been assumed:

- fixed nozzle delivering 2mm diameter steel shot at 6.0kg/minute perpendicular to a fixed flat steel plate, impacting a circular area of $1000mm^2$ for 1.0s.
- shot speed of $50ms^{-1}$ on impact, producing 1mm diameter impacts and working the surface uniformly to a depth of 1.0mm.
- coefficient of restitution between the shot and the plate of 0.71.
- 90% of the energy loss on impact is absorbed by the plate and 10% by the rebounding shot.
- 90% of the energy absorbed by the plate is turned into heat energy and 10% into energy of cold work.
- density of steel is $7{,}800kgm^{-3}$, specific heat capacity of steel plate is $420J\ kg\ K^{-1}$.
- heat is generated adiabatically within the 1.0mm thick deformed surface layer.

The next steps are to:

1. Calculate how much heat, $\mathbf{E_H}$, is generated per cubic millimetre of surface: **0.0506J**
2. Calculate how much heat is required to raise the temperature of one cubic millimetre of steel by 1 K (1°C): $\mathbf{0.00328J.K^{-1}}$
3. Estimate the temperature rise in the surface, **ΔT: 15.4K (15.4°C, 27.7°F)**
4. Check the coverage, **C**, produced by the proposed peening parameters (to ensure that they are realistic: **90.9%**

The estimated value of 90.9% for coverage is certainly not excessive. If the peening time were increased to 4s, with other parameters constant, then the coverage would be predicted as 99.99% and the estimated temperature rise, assuming adiabatic heating, four times as great at 61°C. Alternatively, the same increases could be achieved by multiplying the shot flow rate by a factor of four or by reducing the impact area by a factor of four. It may be concluded that the surface temperature increases with 'normal peening' would be insufficient to cause any significant transformation of the component material's structure.

Deliberate Surface Temperature Increases Induced by Peening

The rate of heat input per cubic millimetre of surface must be increased dramatically in order to induce significant heat treatment effects. In order to produce very large surface temperature increases each relevant parameter must be considered.

Flow Rate. There is an obvious practical limit to the flow rate of shot particles through conventional guns. Flow rate is directly proportional to the heat generated so that it should be maximised for maximum heat generation.

Area Impacted. Reducing the area impacted by a given shot stream will increase the heat generated per unit volume of surface.

Peening Time. The heat generated is directly proportional to the time of peening. However, with long peening times there will be substantial heat flow from the surface towards the centre of the component. Hence, the heating will become less and less adiabatic and estimates of surface temperature rises will have to be reduced substantially.

Shot Velocity. Increasing the shot velocity, v, will increase the energy input dramatically. That is because the kinetic energy of each particle is $1/2mv^2$. Velocities as high as $200ms^{-1}$ have been reported which, being four times higher than the $50ms^{-1}$ in the previous calculation, would allow sixteen times the rise in temperature. Shot quality would have to very high to avoid excessive shot fracture at such high velocities.

Shot Size. The smaller the shot size the less will be the depth of the layer in which heat is being generated. If we could have the same total kinetic energy of the shot stream but with tiny particles then the same amount of heat would be generated but in a very thin surface layer. The heat input per unit volume at the surface would therefore be increased substantially.

Coverage. Excessive coverage values are normally avoided since they exhaust the ductility of the surface. If, however, the surface temperature was to rise quickly in the early stages of peening then there would be a substantial element of the 'self-annealing' that occurs during hot working operations. In such a situation, very high coverage values could be tolerated without surface damage.

From the previous considerations it would appear that a combination of high shot velocities and small shot diameters should be capable of inducing very large increases in surface temperatures. This combination is fortuitous in that it is much easier to induce high velocities in small shot particles than in large ones. It would probably be very difficult to have a shot flow as high as 6kg/minute but this could be offset by concentrating the shot stream on a much smaller area of component surface. The following variations on the assumptions listed in the previous section will be used:

- fixed nozzle delivering 100µm (0.1mm) diameter steel shot at 0.20kg/minute perpendicular to a fixed flat steel plate over a circular area of $100mm^2$ for 1.0s.
- shot speed is $200ms^{-1}$ on impact producing 50µm diameter impacts and working the surface uniformly to a depth of 50µm.
- heat is generated adiabatically within the 50µm thick surface layer.

Using the same four steps as for the previous example, we have:

$E_H = 0.27J$, $\Delta T = 1647^{\circ}C$. and $C = 99.999989\%$

The estimated value of 99.999989% for coverage appears to be excessive. If, however, the temperature increase is roughly linear during the one second of peening then the ductility would increase dramatically very quickly. The mode numbers of impacts are fifteen and sixteen. This indicates that the surface heating is closer to 'continuous' than it is to 'intermittent' heating. The estimated temperature rise of 1647°C for the 0.05mm thick surface layer indicates that a range of surface heat treatment effects is possible.

Continued Heating

Adiabatic heating has been assumed for the two sample calculations. This is reasonable if we are estimating short-time-peening temperature rises. As previously stated, adiabatic heating assumes no loss of heat at all from the region in which the heat is generated. With continued heating, by peening, there must be heat transfer by conduction to the sub-surface layers of the component. Long heating times would give 'through heating' of a component. Shot peening would not, however, be a cost-effective way of through heating components!

Structural Changes with Forced Surface Heating

Because substantial increases in surface temperature are feasible then corresponding structural changes can be considered. These changes include most of those that can be induced by any surface heating processes. Some changes, such as softening and recrystallisation of cold-worked material, would be possible but tend to reduce rather than enhance service performance. On the other hand, if austenitisation of carbon steels can be induced – as occurs when using high frequency induction heating – then self-quenching after a short peening time would produce hard, martensitic, structures. Surface martensite is very hard and wear-resistant and therefore produces enhanced service performance. The danger with all surface heat treatments of steels is that rapid quenching can introduce tensile residual stresses. Retained austenite is another problem with, for example, carburised components.

Experimental Study of Temperature Rises Induced by Peening

There are several ways in which temperature rises can be studied experimentally. These include: direct observation of the surface during peening using camera techniques; temperature cycles inferred from observed heat treatment effects and classical thermometry. A very simple technique is to glue a thermocouple to the back of a clamped strip specimen and measure temperature changes during peening. Heat transfer by conduction with 'steady state' conditions, is governed by the classic equation:

$$\frac{Q}{At} = \lambda \frac{(\Delta T)}{d} \qquad (5)$$

where Q is quantity of heat flowing across an area A in a time t. λ is the thermal conductivity of the material and ΔT is the difference in temperature between two planes separated by a distance d.

We can consider an Almen N strip having a thickness, d, of 0.79mm and a thermal conductivity, λ, of $63Wm^{-1}K^{-1}$. With the conditions specified for 'normal peening' in the first example we have heat being generated at a rate of $0.125Wmm^{-2}$ of surface. Substituting these values into equation 5 indicates that there will be a temperature difference of 1.6°C between opposite faces of the strip, once steady-state heat flow has been established. Fig. 3 shows measured changes in temperature during peening of an Almen N strip, peened continuously with S170 cast steel shot.

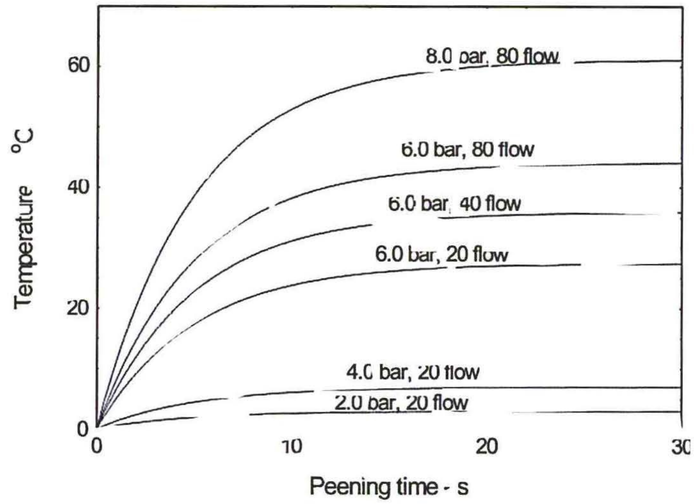

Fig. 3 Heating curves for N strip during peening using S170 shot

Steady-state heating occurs within thirty seconds with the unpeened side of the strip reaching temperatures of between 3 and 61°C depending on the severity of peening. Air pressures from 2 to 8 bar were used with three different flow rates corresponding to 0.49, 0.88 and 1.58kg/minute ("20 flow, 40 flow and 80 flow"). Hence, for a range of peening severities from 2.0 bar, 0.49 kg/minute to 8.0 bar, 1.58 kg/minute the temperatures reached varied from 3 to 61°C. With 2°C added for the temperature drop between peened and unpeened faces, that gives 5 to 63°C as peened surface temperature rises for 'normal peening' intensities ranging from 'very mild' to 'very severe'. This is consistent with the value of 15.4°C obtained in the sample calculation.

Conclusions

These considerations have been based on simple models of behaviour employing classical physical principles. It has been shown that the theoretical predictions of surface temperature rise are consistent with experimental observations for 'normal peening' conditions. With 'forced surface heating' by peening, it has been predicted that very high temperatures can be induced in a very thin surface layer using a combination of very fine shot, high flow rate and very high shot velocities.

Although no experimental evidence of structural changes has been presented here, it is known from published literature that transformations that need such high temperatures can be induced.