Some Theoretical Problems of Shot Peening

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ABSTRACT

Shot peening has long been used both for cleaning component surfaces and for improving the properties of surface layers. This paper reviews various ways of calculating the sizes of dimples formed by shot impacts under various conditions, dimple depths, the generation and magnitude of stresses and their effect on the deflection of a thin strip shot peened from one side only. The calculation results have been tested experimentally on an AlCu4Mg1 alloy; this work has allowed detailed analyses of the coverage, dimple sizes and distribution patterns, and the amount of deflection. Stress calculations were based on the plastic deformation of the surface layer. In the discussion, the newly applied methods are compared with previously published approaches; the relationships between results obtained on flat strips and on cylindrical bars are examined; and procedures are described for determining the peening process parameters by calculations.

INTRODUCTION

Shot peening as a way of enhancing the fatigue properties has lately been adopted on an ever wider scale and not only for steel, but for titanium and aluminium alloys too. New equipment and test methods have been devised, but this has only emphasized the need for a better understanding of the action of shot peening, and for some way of establishing the optimum process parameters by calculations rather than experimentally.

The principal target parameters of this process are the Almen intensity and the coverage. Peening induces compressive stresses in a surface layer of a certain thickness; together with the increased dislocation density, these stresses hamper the nucleation and propagation of microcracks. Several theoretical studies have been devoted to these matters; the present paper concentrates on some selected conclusions and relationships, and on their experimental verification in the shot peening of aluminium alloys.

Coverage

One of the chief tasks in any theoretical analysis of shot peening is to ascertain, and estimate the importance of, the changes which the shot impacts cause on the surface that is undergoing treatment. An equation can be derived for the force which the impinging shot exerts on the surface, and can be used for estimating the dimple sizes. The ratio between the area covered by dimples and the total surface area is known as the coverage, S. Theoretical analyses of shot impingement have been published by several authors |1-5|, who all adopt either an elastic or an ideal plastic approach. For ideally plastic materials, an expression has been formulated which reveals the dimple diameter d resulting from the impact of a spherical particle of diameter D and density ρ at velocity v:

$$d = 2 \left(\frac{\rho v^2}{6\bar{p}}\right)^{1/4} D \qquad (1)$$

where $\bar{p}$ is the mean deformation resistance at the point of impact, and enters a dimensionless parameter $\rho v^2/\bar{p}$ which is called the damage factor. According to |5|, $\bar{p}$ is given by:

$$\bar{p} = 0.6 + \frac{2}{3} \ln C \, R_p0.2 \qquad (2)$$

where C = E.d/RpO.2.D is a term representing the properties of the treated material, E:RpO.2, as well as the amount of plastic deformation, d:D. The value of $\bar{p}$ varies from $R_p0.2$ to 3 $R_p0.2$, most commonly being 2.55 $R_p0.2$. The largest of these values is observed only when deformation is fully plastic and the loading rate is very low, as in hardness testing, but is also applicable when hard shot hits relatively soft material. Various alternative expressions have been evolved |10, 11|.

A formula quoted in the literature |8| for diameter d in hardening materials reads:

$$d = K_y \, D\left(\frac{2}{3}\rho v^2 \frac{n_d + 2}{H_d}\right)^{\frac{1}{n_d + 2}} \qquad (3)$$

where n_d is the dynamic coefficient of strengthening,

K_y - a correction factor for repetitive impacts, and

H_d - the dynamic hardness number.

The magnitude of K_y is estimated by an empirical expression,

$$K_y = 1 + B_y \, (n_y - 1)^{m_y} \qquad (4)$$

where n_y is the number of impacts on an area described by $\pi d^2/4$, and can be ascertained from the coverage; B_y, m_y and n_d are constants characterizing the material's resistance against repetitive impact stressing. The values established in an AlCu4Mgl alloy are H_d = 2350 MPa, n_d = 2.12, B_y = 0.18 and m_y = 0.21.

When several balls in succession impinge on the same spot, the impressions or indentations they create overlap; the probability of at least one shot impacting on area ΔS is defined as

$$P_1 = 1 - e^{-n_y} \qquad (5)$$

Clearly, P_1 varies with coverage S; at S = 98%, n_y comes to 4, at $S \rightarrow 100\%$, n_y works out as 6.

The dimple depth h is governed by the relationship

$$h = D \left(\frac{\varrho v^2}{6\bar{p}}\right)^{1/2} \qquad (6)$$

Stresses in surface layer

The stresses induced by shot peening can arise either by the action of Hertz pressures, as shot impacts on the surface, or else by plastic deformation of the surface layers, caused by tangential forces. The former mode predominates when hard materials are peened with soft shot, the latter when plastic materials are peened with hard shot. The fundamental problem here is to ascertain or predict the stress and strain field perpendicular to the peened surface. Fig. 1 is a schematic illustration of the stress patterns obtained by these two alternative approaches, under the simplifying assumptions commonly employed in such calculations. The literature contains other models too |5, 8, 12, 14|, but in all of them many of the constants that enter the calculations have to be determined experimentally.

The decisive factor is the depth or thickness h_p of the layer affected by the peening. For an AlCu4Mgl alloy, this is estimated by means of an empirical expression |8| :

$$h_p = \frac{5.8\ hD}{d} \qquad (7)$$

When a thin strip is shot peened from one side only, it deflects. The arc height f and radius of curvature R can be exploited for estimating the stress intensity, the estimates being based on the relationship implied by the relevant force equilibrium and moment equilibrium conditions. Several different calculation procedures exist, employing various simplified relations or computer routines. A simple expression for the stress magnitude associated with a stepwise transition at depth h_p has been formulated by Saverin |21| :

$$\sigma = -\frac{4}{3}\ \frac{f}{a^2}\ \frac{E}{1-\nu}\ \frac{H^2}{h_p} \qquad (8)$$

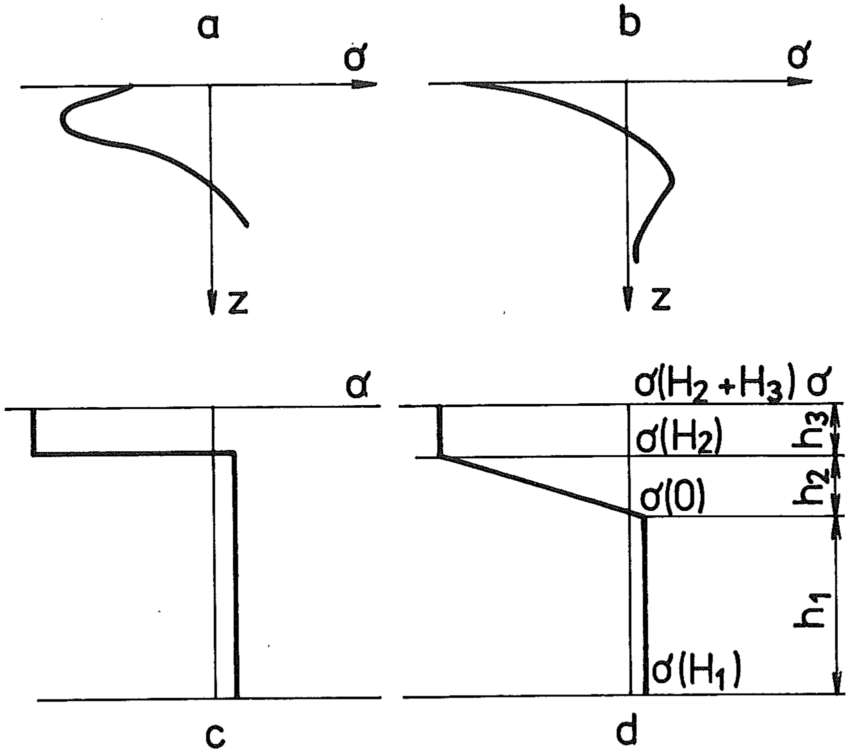

Figure 1. Stresses induced at shot impact sites:
a - by the action of Hertz pressures,
b - by plastic deformation of the surface layer,
c - the simplified scheme underlying the calculations.

It can be demonstrated that this relation remains valid even for the more general cases of stress distribution which require the adoption of an effective depth of the affected zone, h_{ef}. For the stress distribution represented in Fig. 1d, h_{ef} equals $h_3 + 1/2\ h_2$.

Most of the calculation techniques rest on the implicit assumption that before the shot peening, the treated body was free of any internal stresses. Calculations which took into account surface stresses, as well as experimental evidence obtained to corroborate the results of these calculations, all confirmed that their influence was less than 2 to 3% |8|. On the other hand, factors which we must not neglect include stress relaxation at elevated temperatures |14|, or during protracted exposure times, or under the action of external applied forces |23|.

Deflection of thin strips

The dimples caused by shot impacts arise by plastic deformation of the surface layer. The elongation of this layer, i.e.

the change in its volume, induces compressive stresses in the layer. If this treatment is applied to only one side of a strip, that strip will necessarily deflect. The arc height f is proportional to the coverage, and can be established with the aid of a simple equation |5 |:

$$f = K\ a^2 \frac{D}{H^2} \left(\frac{\varrho v^2}{\bar{p}}\right)^{3/4} S^{3/2} \qquad (9)$$

where a is the measured length of the chord,

H - the strip thickness, and

K - the impact effectiveness, which depends on the treated material and the peening conditions.

The literature contains a good many other expressions compiled by various authors; regardless of the approach we adopt, we must bear in mind that the arc height is governed not only by the strip thickness, but also by the properties of the strip material.

Experimental work

Flat specimens of an AlCu4Mgl alloy with an $R_p0.2$ of 430 MPa and E of 71,320 MPa, having the dimensions of the standard Almen strip and thicknesses of 2.38 or 5 mm, were peened on injector equipment, at a pressure of 0,4 MPa, with glass balls that had a mean diameter of 0.26 mm and a density of 3000kg.m^{-3}. The delivery nozzle was 200 mm off the treated surface.

Coverage was assessed, both by the linear intercept and the point counting methods, on five photographs taken in the lengthwise centre line of strips peened for 0.75, 1.75, 3.3, 6 and 12 seconds. The results are presented in Table 1. The point counting method produced less scatter, but the average coverages S ascertained by both methods are in good mutual agreement. On the photograph of a specimen that had been peened

TABLE 1
Coverage after various peening times and their standard deviations

Time (s)	A S(%)	A σ	B S(%)	B σ
0.75	50.9	0.5	52.6	1.8
1.75	76.8	0.3	77.8	1.2
3.3	85.5	0.4	85.3	1.2
6.0	94.7	0.2	94.9	0.8
12	97.9	0.2	98.2	0.4

A - line intercept
B - point counting method

for only 0.75 seconds, the area density of dimples was measured by means of seven probes of various sizes; 45 measurements were taken with each of them. Calculations then indicated an impact rate q of 78.7 balls per mm^2 per second. This figure enables us to compute the process duration needed to produce the desired 98% coverage: at n_y = 4, the relation

$t = \frac{4n_y}{\pi d^2 q}$ yields t = 8 seconds, a time in close agreement with experimental findings.

The dimple size was investigated along with the frequencies of incidence of various dimple classes. Fig. 2 is a summary of the findings made on 432 dimples. The average dimple size was 0.09 ± 0.02 mm. For the experimentally ascertained mean impact velocity of 56 $m.s^{-1}$, calculations render an average diameter of d = 0.097 mm, which is reasonably close to the experimental finding. The scatter in the dimple sizes was largely due to scatter in the size of the unscreened glass balls, which varied in actual diameter from 0.21 to 0.32 mm, and in their impact velocities, which ranged from 45 to 80 $m.s^{-1}$. For the maximum ball size and velocity, the theoretical d_{max} is 0.145 mm; for the minimum values, d_{min} comes to 0.067 mm, or less than half the maximum figure. Some even smaller dimples were detected, but these are attributable to velocity drops caused by collisions between balls, or by rebounds, or by the impingement of previously crushed balls.

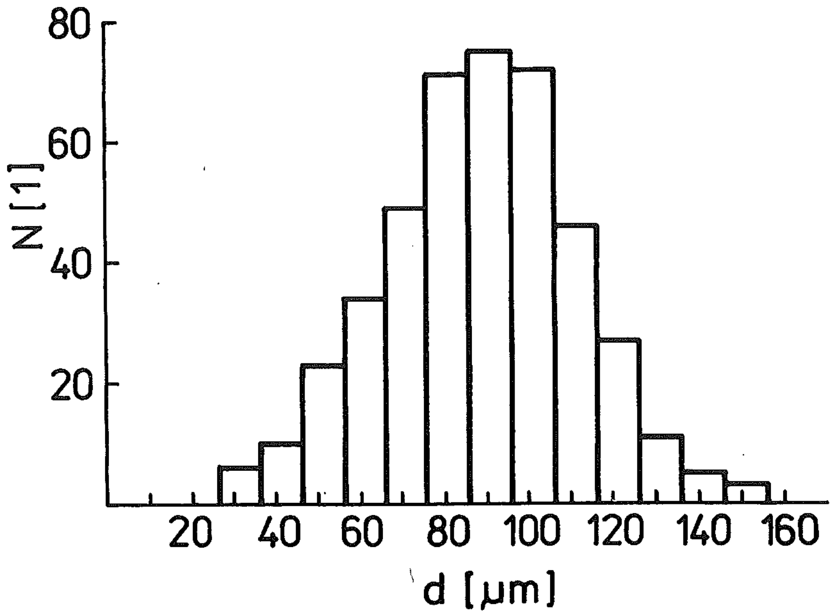

Figure 2. Dimple size distribution after 0.75 seconds of shot peening

Fig. 3 shows how arc height f grows during the peening of strips of two different thicknesses. The curve for strips

2.38 mm thick indicates that, like the 5 mm strips, they reached saturation level at f = 0.075 mm after 3 to 4 seconds, well before the desired 98% coverage was attained. The maximum arc height can also be established by calculations; very good agreement with experimental results was obtained at K = 12.6.

A comparison af arc heights recorded on strips of two different thicknesses revealed that $f_1:f_2=H_2^2:H_1^2$. Thicker specimens, 7 and 10 mm thick, appeared to conform to this law too, but their arc heights, 0.009 and 0.004 mm respectively,were difficult to measure exactly.

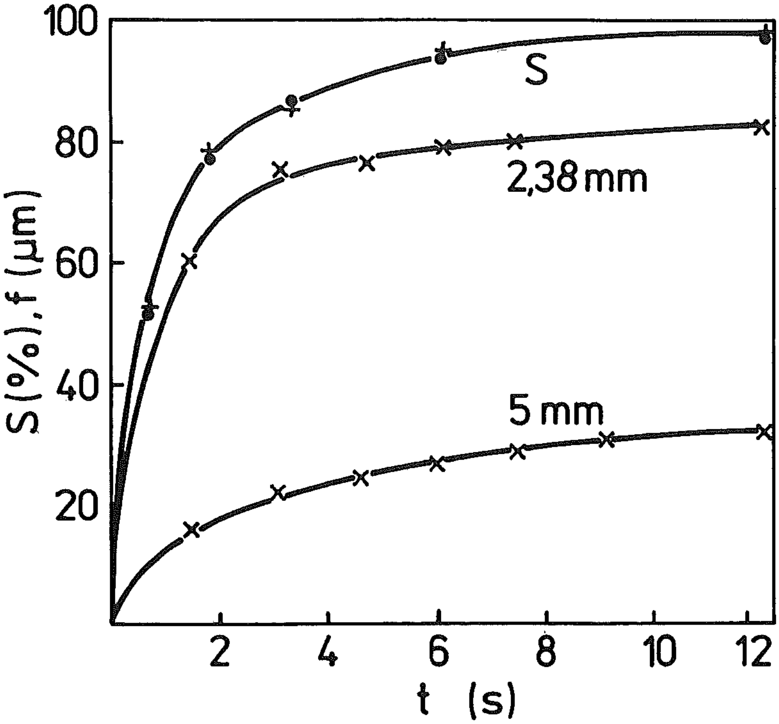

Figure 3. Dependence of coverage S and arc height f on the duration of peening.

Residual stresses were investigated by the X-ray sin ψ^2 technique, using CrK_α radiation, after three peening periods. The compressive stresses on the surface were 300 to 340 MPa, the maximum of 374 MPa was observed 0.015 mm beneath the surface. At greater depths the compressive stresses declined rapidly, diminishing to zero some 0.140 to 0.240 mm bellow the surface, and then giving way to tensile stresses in the strip interior.

Stress calculations were based on a method postulating a constant volume change of the surface layer |13| due to peening, $\Delta V/V = 3\ \varepsilon_3^0$. The calculations were also utilized to investigate various possible stress patterns, which were described by the corresponding changes in thickness h_2 and h_3 as defined in Fig. 1. An example of the resultes thus obtained is shown in Table 2, which lists the figures for a thickness of 2.25 mm and a volume change of $\varepsilon^0 = 0.005$. These figures indicate that tensile stresses within the strip are relatively small; the greatest differences were found in the h_2 layer, a fact that confirms the importance of the actual stress distribution. Results comparable with the experimental findings were gained for instance for a h_2 of 0.05 mm and h_3 of 0.10 mm, i.e. h_{ef} = 0.125 mm. The arc height proved to be practically independent of the stress distribution. Stress calculations founded on the radius of curvature or on the arc height measurements produced results that differed from those quoted above by about 1 per cent. Similar calculations for strips 1.3, 5 or 7 mm thick also yielded results in the literature |14| that in soft material the maximum stress can attain 0.8 $R_p0.2$ were confirmed both by our calculations.

TABLE 2
Arc heights and residual stresses for various stress distributions

Thickness (mm)			f (mm)	Stress (MPa)			
h_1	h_2	h_3		$\sigma(h_1)$	$\sigma(0)$	$\sigma(h_2)$	$\sigma(h_2+h_3)$
2.15	0.00	0.10	71.5	44.8	86.7	453.6	447.5
2.15	0.02	0.08	71.9	45.1	87.0	512.1	507.2
2.15	0.05	0.05	72.3	45.5	87.4	630.0	626.8
2.15	0.10	0.00	72.7	45.9	87.7	986.7	986.7
2.15	0.05	0.10	67.6	43.1	81.4	348.0	342.2
2.10	0.10	0.10	66.7	42.2	77.8	276.7	271.0

Arc heights f were measured on length of 31.8 mm.

Further calculations were performed to examine the effects of the changes of E in the surface layer that are produced by strain hardening. A change of E by 15% altered the computed stress levels and arc heights by no more than 10%.

Discussion

The preceding paragraphs prove that the values of the fundamental physical variables, which indicate how shot peening alters the properties of the surface layer, can be ascertained by calculations. The decisive variables are the dimple size, the depth of the affected zone, and the stress intensity. The dimple size is best estimated by equation (3): this expression incorporates the dynamic hardness value and hence takes into account the strain hardening effect; but it has a drawback in that it necessitates knowledge of the values of empirical constants. The dimple depth or h:d ratio is also a measure of plastic deformation, and a criterion of the geometrical similarity of the peening process and treated material properties. It is better expressed in terms of d:D, for instance by the following relation|8|:

$$\frac{h}{d} = C_o(\frac{d}{D} - B_o) \tag{11}$$

For an AlCu4Mg1 alloy, C_o is 0.248 and B_o is 0.023. This formulation makes it easier to determine the thickness of the layer affected by plastic strain, as defined by equation (7). As the d:D ratio varies from 0.05 to 0.6, the h:d ratio spans an interval of 0.06 to 0.14; in our case, h:d=0.06 and hence h_p worked out as 0.1 to 0.2 mm, since h_p is governed mainly by the larger dimples. The values obtained by these calculations were in close agreement with those found experimentally.

The compressive stresses are more difficult to determine. The proportion due to Hertz pressures is relatively well defined mathematically and, under some simplifying assumptions, is straightforward to calculate. Calculations based on the surface layer deformations call for knowledge of the properties of thin surface films, and these properties are as yet impossible to establish by experiments; these methods therefore rely on estimates and assumptions not backed by any hard evidence. Procedures utilizing an elastic model can at best yield only very approximate results. We consequently prefer the alternate loading theory |8|, because its approach is closest to the actual sequence of events in shot peening processes. Both calculations and experiments conducted with aluminium alloys have shown that peening entails a cyclic strain hardening process, even though the number of cycles strengthening the surface layer is generally only two or three. Aluminium alloys are known to have anisotropic properties in their surface layers too, but the decisive factor is the residual strain in that layer. Calculations taking this approach have to employ relevant elasticity modules, and must define a boundary between the domains of linear and power-law approximations, which may be located as deep as 0.17 mm. Applied to our experimental conditions, this procedure rendered a surface stress magnitude of 390 MPa; the real surface stressing will naturally be lesser, because the result is distorted by the simplified view taken of the course of plastic deformation.

A reversed procedure is feasible too: we can start out from the assumption that the compressive stress in the surface layer cannot exceed 0.8 $R_p0.2$, and derive our requirements on the depth of the affected zone and on the dimple size from this assumption. After selecting this depth and dimple size accordingly, we must then choose such process parameter values which will enable us to attain these targets, or adapt the parameter values if we require less than the maximum possible stressing.

It would be wrong to regard the compressive stresses as the only significant effect of peening: another important effect is the increased dislocation density caused by plastic deformation. This increment cannot be assessed by calculations, and may vary widely from one spot to the next. Nevertheless the dislocations, their density and their distribution strongly affect above all the fatigue behaviour, i.e. the nucleation and propagation of very short cracks.

All the equations presented above are based on the implicit assumption that the spherical shot impinges on the planar treated surface perpendicularly. In practice, however, this is clearly an exceptional case. Even given an entirely flat surface the shot will still impinge at various angles, because (especially when the nozzle is relatively far from the treated surface) the stream of shot impelled at the surface is conical rather than cylindrical. The different impact angles produce different effects on the treated surface. Even worse complications ensue when this surface is not flat, but shaped, as component surfaces generally are. In that case our calculations must take into account not only different impact angles, but also the way they alter the actual process duration. For example, calculations show that if we are peening a cylindrical surface that rotates during the treatment, we must double the processing time to achieve the same coverage, and increase it by a factor of 2.5 to attain the same Almen intensity, as when we are peening a flat strip.

Relatively little has been published about the way various impact angles influence that outcome of shot peening |22|, and even that little deals chiefly with steel; no such analyses are available for aluminium alloys, nor for complex component shapes. The only measure normally taken in practice in such cases is to check the actual Almen intensity, by fastening Almen strips. The aim is to ensure an equal impact energy and measurements performed in practice confirm that the outcome depends substantially on differences in the shot size and on the actual impact velocity.

To ensure satisfactory results in shot peening operations, the shot must be screened by size; must be as regular and uniform as possible in its particle shape; and care must be taken to maintain a uniform impact velocity by precise adjustment of the delivery pressure and accurate dosing of the shot. That is why in modern shot peening equipment so much effort is devoted to provisions for monitoring and regulating the key process parameters.

Conclusion

Relationships for calculating or estimating the effects of various process parameters on the resultant properties of shot peened surface layers have been experimentally investigated on a type AlCu4Mg1 aluminium alloy. The principal factors examined were the coverage, dimple sizes, and the calculated residual stresses. The computed results were in good agreement with experimental findings, but the calculation procedure calls for knowledge of several material constants which have to be ascertained by experiments for every alloy that is to be treated. That limits the usefulness of the existing calculations methods, and stresses the need for their further development and refinement. As shot peening techniques gain ever wider acceptance in industrial practice, calculation methods have an ever greater role to play in determining the process parameters and ensuring compliance with the specified target values in routine operations.

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