Shot peening

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32.1 INTRODUCTION

Shot peening is a process for treating metal parts by controlled high-speed impact of many balls (shot). It is used mainly to increase the resistance of metal parts against fatigue, fretting fatigue, stress corrosion, and corrosion fatigue. It is also used to form slender metal parts to desired shapes, to produce a desired surface topography, to harden surfaces, to close pores, and to test bonds.

Practically all automobile valve springs and suspension springs are shot peened to prevent fatigue failures and most modern airplanes have wing skins formed by shot peening and shot peened to prevent stress corrosion.

The process is extremely flexible: Parts of any shape and of any size can be treated. Control of the process is essential, but the process is more tolerant of minor deviations from the specified parameters than heat treating or precision machining are.

Table 32.1 shows data on nine typical applications. Although each application must be considered individually, the following points can be made.

In general, the process works by plastically deforming a shallow surface layer. The shot impacts must be strong enough to achieve this, and they must cover the surface well enough to subject all of it to the effects of the plastic deformation.

Plastic deformation that extends too deeply into the part decreases the beneficial effect and may be detrimental. This also applies to the presence of sharp corners and to fins on thicker parts.

Peening produces a small extension of the peened surfaces and an extension or curvature of the entire peened part. This must be considered when high precision of dimensions is required.

When used to increase fatigue resistance, shot peening is more effective on harder materials than on softer materials (Example 6 of Table 32.1); is more effective on notched parts and on weakened surfaces than on smooth specimens (Examples 2 and 5 of Table 32.1); is more effective against applied tensile stresses and against shear stresses than against compressive stresses; and is more effective against applied stresses cycling from around zero to a maximum than against fully reversed stresses.

To prevent stress corrosion, shot peening must completely cover the surface.

When forming parts, shot peening is more effective for forming slender parts, for instance, aircraft skins. No dies are required, only checking fixtures.

The reasons for these rules and the methods for predicting effects on fatigue will be discussed in Section 32.5.

32.2 EQUIPMENT USED FOR SHOT PEENING

The equipment used for shot peening consists basically of eight components:

1. The shot, usually steel or glass. Its material, size, and shape are closely specified.[9,10]
2. Devices to remove shot worn beyond specification tolerances—for instance, screens.
3. Machinery to impel the shot—for instance, centrifugal wheels or compressed air.
4. Means to direct the shot stream—for instance, nozzles.
5. Means to expose parts to the shot stream—for instance, conveyors.
6. Means to collect the shot after it has been thrown against the part—for instance, enclosures with rubber curtains.
7. Means to recirculate shot to the impelling device—for instance, bucket elevators.
8. Controls for shot flow, shot velocity, and time of treatment, and means for inspection.

To expose all desired areas of a part to the shot stream it is necessary either to move the part under a stationary stream or to move the shot stream over a stationary part, or to move both parts and shot stream in a required pattern. This can be done by a conscientious operator, but to obtain consistently good results the motions are mechanized. Large wing skins, for instance, may be peened in machines that travel lengthwise over the skins while nozzles reciprocate in the machines transversely to the direction of travel. Suspension coil springs are conveyed through the shot stream in a helical path, rotating while they advance.

Large structures can be peened by machines that are brought to the structure, rather than bringing the structure to the machine (Example 4 of Table 32.1). This method (portable peening machines) has also been used when it was necessary to peen parts of aircraft that were in service.

Effects similar to those obtained by shot peening have also been obtained by peening with air hammers or with rotating impact tools. These substitutes are more difficult to control and are used only when shot peening is not feasible.

Equipment and methods of peening are described in more detail in the literature.[11-13]

Table 32.1 Typical Examples of Shot Peening Applications

	Parts, Sizes in in. (mm)	Peening—Intensity, Shot Size in in. (mm)	Testing	Results ksi (MPa) <cycles> Not Peened	Peened	Increase	Reference
1	Helical compression springs ⅛–¼ (3–6) wire diameter (1a) alloy steel (1b) stainless steel (1c) phosphor bronze	10A, 0.016 (0.4); also other intensities and shot sizes	Stress range to give 10^7 million cycles	(1a) 70 (48) (1b) 45 (310) (1c) 15 (103)	115 (795) 90 (620) 30 (205)	60% 100% 100%	Zimmerli[1]
2	Tractor axle shafts 3.0 (76) diameter, RC50 hard (2a) clean steel (2b) } with stringers (2c) }	(2a) 23A, 230 (2b) 23A, 230 (2c) 13C, 550	Torsion stress zero to 113 ksi (780 MPa)	(2a) <1700> min (2b) <50> min (2c) <50> min	<80,000> <6000> <75,000>	47 times 120 times 1500 times	Eckert[2]
3	Thick tubes, steel, RC36 hard 1¼ (31.8) ID, 3¼ (82.6) OD	8–10A, 170	Shear stress amplitude to give 3×10^5 cycles (internal hydraulic pressure)	16.3 (113)	33 (228)	102%	Findley and Reed[3]
4	Induced draft fans welded T-1 steel plates	Heavy peening at welds on overhaul	Service on 750 MW coal-fired boilers	Cracks 12 in. (300 mm) long after 2 years	No cracks after 6 years		Takhar and Fryzel[4]
5	Notched specimens steel 120 ksi (825 MPa) ultimate tensile strength $K_T = 1.76$ dia. = 0.24 (6)	50 psi (345 kPa) air, 0.031 (0.8) shot	Rotating beam fatigue limit at 7×10^6 cycles	37.4 (258)	62 (428)	65%	Harris[5]
6	Bending specimens 0.35 (9) thick (6a) aluminum alloy (6b) titanium alloy (6c) maraging steel	12A steel shot followed by 2N glass beads	Flight spectrum $S_{max} = 0.9$ ultimate tensile strength $S_{min} = -0.22$ ultimate tensile strength			(6a) 2.7 times (6b) 10 times (6c) over 11 times	Schütz[6]
7	Reactor piping 321 stainless 7½ (190) OD	11A, 230	Boiling solution 42% $MgCl_2$	22 hr	No cracks after 264 hr	Over 10 times	Friske and Page[7]
8	Tensile specimens stainless 26% Cr, 4% N, 0.2% Mo; 0.177 (4.5) diameter	8A, 230	Axial pull in NaCl solution (pH = 2); fatigue strength at 10^7 cycles	40 (280)	65 (450)	60%	Müller et al.[8]
9	Aircraft wing skins	To form contour			Continued use by Lockheed, Boeing, etc.		

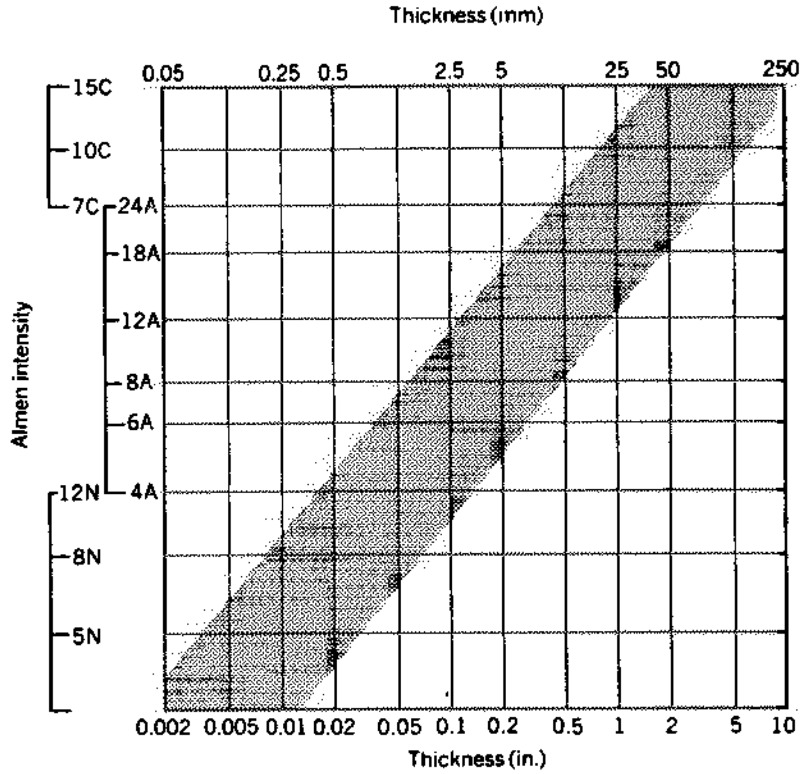

Fig. 32.1 Peening intensities commonly used on steel parts of different thickness.

about 9C the fatigue limit dropped to less than 100 ksi (690 MPa). Unpeened springs had a fatigue limit of 74 ksi (510 MPa).

Another factor may limit the shot size, and thereby the intensity: The shot radius should be much less than the radius of fillets or grooves that must be peened, so that numerous good impacts can be obtained in the grooves. The military specification[9] requires that, unless otherwise specified, the nominal size shot used on fillet surfaces shall not be greater than one-half the fillet radius. (See Fig. 32.2.) For torsion bar springs, approximately 2.4 in. (61 mm) diameter, with splined ends, the SAE recommended[18] intensities of 10C minimum on the body, which required 550 shot, and 11A minimum on the splines, where the shot cannot be larger than 230 because of the radius at the root of the splines. A user of such torsion bars specifies 200% coverage, obtained by passing each bar twice through the process.

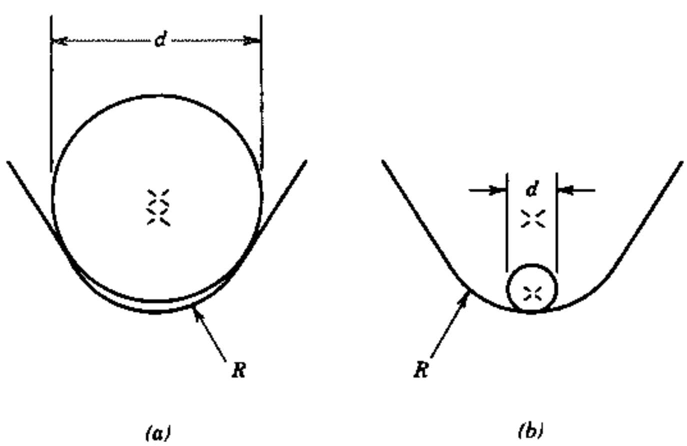

Fig. 32.2 Shot diameter d and groove radius R: (a) shot size too large, $d = 2.2\ R$; (b) maximum shot size permitted by Ref. 9, $d = \frac{1}{2}R$.

As the interior material is not exposed to atmosphere or accidental damage, it is more resistant than the surface to fatigue. Fatigue fractures starting below the surface are not likely unless the tensile stress below the surface is higher than the fatigue limit of smooth specimens of the same material.

When axial loads are applied, peening can bring the fatigue strength of parts with poor surfaces up to that of smooth polished specimens. For bending and torsion it can do much more because the applied stresses decrease toward the inside where peening produces small tensile self-stresses. For notched parts it can do still more because of the greater stress gradient, as, for instance, in Example 5 of Table 32.1 where the increase by peening overcomes the decrease by notching. In most cases peening can bring the fatigue strength of notched parts up to the strength of smooth specimens. It can overcome the notch effect by preventing small cracks that originate in the notch root from propagating toward the interior of parts.

The peak value of the compressive self-stress (P in Fig. 32.2) depends mainly on the material of the peened part and on the restraints imposed on the part during the peening process. In a part peened without restraints the value of P is of the order of half the yield strength of the material, usually somewhat more. Note that the yield strength may be raised by the cold work of peening, and further raised or lowered by repeated working of skin elements in continued peening. The compressive self-stress can be increased by applying tension to the surface while it is being peened.[15,19] The compressive self-stress at the surface itself is almost always somewhat less than the peak value P at some depth in the skin.

Changing the peening parameters (shot velocity and shot size) will change mainly the width of the peak and the depth (D in Fig. 32.3) to which the compressive self-stress extends. It will have only a minor effect on the peak value. The depth D is roughly equal to the diameter of the peening dimples.[16] It also is roughly proportional to the peening "intensity" defined in Section 32.3.

The compressive self-stress has two different effects on fatigue resistance: It increases the resistance to the formation of small cracks, and it slows down or prevents the growth of cracks. The latter effect is far more important than the former. It explains the very large improvement obtained in some cases and the substantial, but smaller, improvements in other cases, as shown below.

The compressive self-stress is also an important element in preventing stress corrosion, and the only factor active in changing the shape of parts to form them.

In analysis, self-stresses are added to mean load stresses, but there is one important difference between load stresses and self-stresses. When the total stress caused by mean load, alternating load, and self-stress reaches the yield strength, then the self-stress will decrease so that the sum equals the yield strength. Load stresses that exceed the yield strength wipe out the original self-stress produced by peening.

32.5.2 Constant Life Diagrams

Haigh diagrams are an excellent means of analyzing and visualizing the effects of self-stresses. They show the yield strength and the fatigue strength plotted in terms of alternating stress versus mean stress.

Haigh diagrams for a smooth part are shown in Figs. 32.4*a* and 32.4*b* and for a notched part in Fig. 32.4*c*.

Figure 32.4 is based on data for G104500 steel (SAE 1045), quenched and tempered to 450 Brinell hardness, 230 ksi (1585 MPa) ultimate tensile strength. Its monotonic yield strength is 220 ksi (1515 MPa), its cyclic yield strength is 140 ksi (965 MPa), and its smooth push–pull fatigue limit 84 ksi (580 MPa) for zero mean stress. For other values of mean stress the fatigue strength of smooth unpeened specimens for the same number of cycles is assumed to increase or decrease linearly, reaching zero at 305 ksi (2100 MPa) tensile stress. The self-stress produced by peening in this material is 125 ksi (860 MPa) compression.

Figure 32.4*a* shows that the fatigue strength for fully reversed loading can be increased to 100 ksi (690 MPa) by peening. The self-stress is reduced from 125 to 60 ksi (860 to 415 MPa) so that the sum of load stress plus self-stress equals 160 ksi (1100 MPa), which is a value of yield strength linearly interpolated between the monotonic and cyclic values. The strength increase obtained by peening is 19%.

A much greater increase (41%) is observed for loading from zero to maximum ($S_m = S_a$) as shown in Fig. 32.4*b*. Without peening the fatigue strength in terms of alternating stress is less than that for fully reversed loading, only 66 ksi (455 MPa). In terms of maximum stress it is 132 ksi (910 MPa). With peening the fatigue strength is increased to 93 ksi (640 MPa) in terms of alternating stress, 186 ksi (1280 MPa) in terms of maximum stress, or a 41% increase. The applied tensile stress does not wipe out any compressive self-stress.

Much greater improvement of long-life fatigue strength (122%) is seen in Fig. 32.4*c* for a notched part with 2.1 notch factor. The Haigh diagram for this part shows the same yield lines as Fig. 32.4*a* because we are not concerned with the onset of yielding at the notch root, but with yielding far below the notch root. The fully reversed fatigue limit is lowered to 84/2.1 = 40 ksi (280 MPa). The line that indicates the formation of small cracks at the root of the notch has the same slope as the

Table 32.2 Fatigue Limits
Predicted by Fig. 32.4 for G104500 Steel at 450 BHN

Condition	Strength, ksi (MPa) Unpeened	Strength, ksi (MPa) Peened	Strength Increase
Smooth, fully reversed	84 (580)	100 (690)	19%
Smooth, zero to maximum	132 (925)	186 (1280)	41%
Notched, $K = 2.1$, fully reversed	40 (280)	89 (614)	122%

will be higher but the yield limitation remains the same. The improvement in fatigue life can still be very worthwhile, as in Example 2 of Table 32.1.

Occasional stress peaks greater than yield strength, imposed in service, may also decrease the effectiveness of shot peening. Comparison of Example 6a with Examples 6b and 6c in Table 32.1 illustrates this effect. The service load spectra for the three materials were in proportion to their ultimate tensile strengths (UTS). The load stress of 90% UTS, applied a few times, reduced the remaining self-stress in the aluminum alloy to a value where it became less effective. For the specimens made of steel or titanium alloy the self-stress remained more effective.

Haigh diagrams are very useful for estimating the improvements obtainable by shot peening. To improve parts with notches or with weakened surfaces, the compressive self-stress should extend to the depth at which the load stresses are less than at the surface, as in the case of notches, or where the material is stronger, as in the case of decarburized steel. To determine the minimum required depth, or to determine the intensity for maximum strength, requires either experience or experiments or a detailed study of the distributions of load stresses and self-stresses.[15,20]

32.5.3 Metallurgical Effects of Peening

The plastic deformations produced by peening change the internal structures of the deformed grains. This can be important in preventing corrosion fatigue, intergranular corrosion, and fatigue at high temperatures, or in producing a strain-hardened surface.

Friske and Page[7] have shown that breaking down surface grains by peening can prevent intergranular corrosion. Müller et al.[8] explain the increased resistance to corrosion fatigue by more densely distributed smaller slip steps. These do not break the passive film, which is ruptured by the larger slip steps in unpeened material. Hornbogen et al.[21] found that the more homogeneous distribution of slip delays the appearance of cracks, but favors their propagation in a precipitation hardening steel. They consider this to be the cause of the superiority of shot peening over cold rolling. Even at 1544°F (840°C), where the self-stress is annealed, they found that the fatigue life of peened specimens was 80 times the life of electropolished specimens.

Wang et al.[22] tested jet engine superalloys at elevated temperatures. Even at temperatures which relieved self-stresses, they found improvements in fatigue strength. The improvements were substantial, around 20%, for notched specimens, and much less or in some cases zero for smooth specimens. They did not venture explanations for this observation.

32.6 QUALITY CONTROL

When shot peening is used to change the shape or the surface of parts, it is checked by the usual methods, such as templates, gages, and profilometers.

Inspection becomes more difficult when peening is used to improve resistance against fatigue or stress corrosion. The self-stresses and the metallurgical changes are not visible on the surface. Control of the process itself, in addition to inspection of the finished part, is then necessary. It is done by checking the qualities of the shot stream and the manner of exposing the part.

The shot stream is checked by inspecting the shot and its peening power. The size distribution is measured by screen analysis according to specifications.[9,10] Shot is also inspected for shape. Only a small percentage of broken or nonspherical particles are allowed.

The peening power is checked by Almen strips. It is important to distinguish the Almen intensity specified for the peened part from the Almen intensity that checks the peening power of the shot stream. The part intensity is obtained by exposing strips in the same manner as a critical surface of the part, and for the same time as that surface of the part. The shot stream intensity might be checked in the same manner, but it can also be checked by exposing strips in another, possibly simpler or quicker, manner which might show a higher reading.

It is important that the intensity reading corresponds to a strip saturated by peening. Saturation means that the curvature of the test strip cannot be substantially increased by longer exposure to the

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