Investigation of Shot Peening as a Forming Process for Aircraft Wing Skins

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The technique of generating curvatures in thin sheets by shot peening is well established for forming airplane wing skins to controlled contours. Success used to depend on the peening machine operator's skills; therefore, a systematic experimental investigation was conducted into the effects of workpiece geometry and process variables on resulting curvatures. Most of the tests were conducted on 6 × 24 in. (152 × 610 mm) 2024-T3 and 7075-T6 aluminum alloy sheets of up to 0.5 in. (12.7 mm) thickness. Shot of 0.023 to 0.066 in. (0.6 to 1.7 mm) diam was used in a wheel-type machine at speeds up to 250 ft/s (80 m/s). The radius of curvature R *of a peened specimen can be expressed as* $R = A + B/S$ *where* S *is the shot density (weight per unit area) and* A *and* B *are parameters which are functions of other process variables. Specimens with a length-to-width ratio of* $L/W = 1$ *have equal stiffness in the* L *and* W *directions but developed a predominant curvature the direction of which was affected by secondary variables such as the rolling direction in the sheet. However, transverse and longitudinal radii of curvature were almost identical in thicker specimens of* $L/W = 1/4$ *and could be used to predict the transverse curvatures of long workpieces peened under production conditions, as confirmed by production-scale experiments.*

Shot peening is well established as a method for improving the fatigue life of highly stressed mechanical components.[1–4] For a number of years, the aircraft industry has used shot peening also as a forming process.[5–8] The local material flow induced by shot peening and the resulting residual stresses cause the workpiece to change its shape; this makes peening a most attractive technique for forming gentle and complex curvatures on aircraft wing skins. The technology of controlling the curvature has reached a sophisticated level through practical development that has depended, to a considerable degree, on the skill of the peening machine operator.

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The objective of the present work was to improve our understanding of the interrelationship between the complex curvatures generated in the work materials, the shot peening process variables, and the workpiece geometry. An attempt was made both to provide phenomenological explanations of the test results and to develop useful quantitative relationships. Residual stress distribution, dimple dimensions, and surface roughness were studied to a limited extent. Consideration of fatigue life was beyond the scope of this paper.

BACKGROUND

Shot peening is carried out by impacting the workpiece surface with cast iron or steel shot discharged either from a nozzle with a blast of compressed air or

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from a rotating wheel. The shot indents the surface and causes plastic flow both normal and parallel to the plane of the surface, similar to a Brinell hardness test indentation. The flow parallel to the surface—a lateral expansion—is resisted by the subsurface material, thereby setting up a high residual compressive stress in a relatively thin surface layer together with a moderate, compensating tensile stress in the substrate (Fig. 1).

The principal variables in a peening operation are shot size, shot velocity, angle of incidence of the shot stream with respect to the workpiece, and peening coverage. Shot size governs the geometry of indentation and, thereby, the extent of the deformed layer. Shot velocity, for a given shot size, determines the depth of indentation and, hence, the depth of deformation. Likewise, peening coverage—the fraction of the total area that is indented—influences the average depth of the deformed layer as well as its continuity.

For commercial process control, the effectiveness of peening is expressed as "Almen intensity". A steel strip of standardized dimensions and hardness is clamped and peened by the shot stream to be characterized. The arc height is measured after unclamping the strip. The arc height initially increases with the duration of peening, but eventually reaches a maximum steady value which is termed the "Almen intensity" of the shot stream.[1,2] The intensity thus determined specifies an overall effect, allowing the shot peen operator reasonable latitude in selecting individual process variables. Shot size and the number and speed of traverses (which determine coverage) can, obviously, be varied within certain limits. The shape of the shot stream and the angle of incidence can also be varied with suitable nozzle design. The velocity of the shot in compressed-air machines depends primarily on air pressure but is affected by nozzle design, resistance to air flow in the system, and the rate at which shot is fed into the air stream. In wheel-type machines the shot is fed at the hub of a rapidly rotating wheel, the shot travels along radial partitions and leaves the wheel at its periphery. Shot velocity is more controllable, being dependent almost entirely on wheel speed.

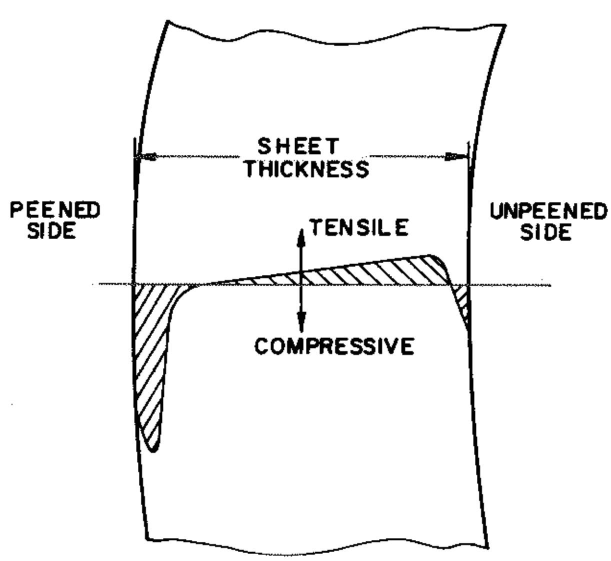

Fig. 1—Schematic of residual stress distribution in a shot-peened sheet.

The residual compressive stress induced by shot peening (Fig. 1) has three principal effects on sheet materials. First, if the sheet is peened on only one side, a convex curvature is induced such that the moment due to the compressive residual stresses near the peened surface alone is equal to the moment due to the subsurface tensile stresses plus the compressive residual stress on the opposite side of the sheet. Second, the residual stresses increase fatigue life and endurance limit by reducing the maximum surface tensile stress at a given imposed stress amplitude. Third, shot peening is beneficial in improving the stress corrosion characteristics of the surface.

The complex curvature develops in response to a variety of process conditions. Not surprisingly, no successful theoretical treatment has yet been developed and investigations of peen-forming have been limited to experimental studies of some of the controlling variables.

In Japanese research, reported upon by Mihara,[9] half-hard aluminum sheet of 0.4 to 1.4 mm thickness was impacted by 0.4 to 1.6 mm diam steel shot propelled by an impeller at 1000 to 4000 rpm. The sheets were either rectangular and peened to form a single curvature (a bend), or circular and formed a bulge upon peening. Shape development was rapid at first and tapered off with time; the bulge (or bend) height increased in a parabolic fashion with shot energy, provided that a minimum shot energy was available. Overpeening was also possible: excessive peening time caused a reduction of the bend height or created a reverse curvature in the bulge. The shape of the domes was hemispherical or sometimes conical; in the latter case the energy of the shot was believed to be insufficient to cause further deformation once the angle of incidence diminished with increasing bulge height. As might be expected, surface roughness increased with shot energy and shot size; it did not, however, change with time, once 100 pct surface coverage was obtained. For increased efficiency, it was suggested that peening may begin at higher shot energies and then be finished at lower energies for a better surface finish. A comparison with rubber die bulging revealed that shot peening produced greater surface hardness, and that the favorable compressive stresses induced during peening enhanced the formability of less ductile materials.

In the work of Meguid, Johnson and Al-Hassani[10] mild steel, aluminum and copper sheets of 3 to 6 mm thickness were shot blast with an airjet apparatus giving shot velocities of 20 to 300 m/s. High-speed photography revealed the behavior of individual shot particles in the stream. This work confirmed the effects of shot energy and peening time on the development of shape. The depth of deformation zone was found to increase with increasing shot velocity and diminishing workpiece hardness, and to decrease with lower angles of incidence. Saturation (100 pct coverage) was reached more slowly with larger shot.

Industrial use of very large steel balls or shot has also been reported;[7,8] the shot was freely dropped onto the soft Al-clad surface of heat-treated aluminum alloy components to achieve the desired curvature.

EXPERIMENTAL MATERIALS AND TECHNIQUES

Materials and process conditions were chosen to be representative of those successfully employed at the Boeing Company.

Materials

Large, 48 × 144 in. (1.22 × 3.66 m) sheets of 2024 and 7075 aluminum alloys were obtained from four different major suppliers in gages shown in Table I. The yield stress and modulus of elasticity measured in the rolling and transverse directions showed only small variations with thickness, orientation, or location within the same sheet, and were very similar in materials obtained from different suppliers.

The majority of the tests were conducted on 6 × 24 in. (152 × 610 mm) specimens. A variety of other sizes, as referred to later, were included for selected tests. The specimens were obtained by saw cutting from the large as-received sheets. Shearing was avoided since strain hardening of the edge could stiffen the specimens and affect the curvature developed by contour peening.

Equipment and Fixtures

The peening experiments were performed on a Wheelabrator machine with a shot-throwing capacity of 600 lb/min (270 kg/min) at 2200 rpm. The wheel is mounted overhead and throws shot along a radius of the worktable (Fig. 2) with a practically 90 deg angle of incidence. The amount of shot thrown per minute depends on a valve opening and wheel speed, and can be controlled to a reasonable extent. Cast steel shot were of 0.023, 0.039 and 0.066 in. (0.6, 1.0 and 1.7 mm) sizes. By changing the pulleys on the motor, wheel speeds of 900, 1500 and 2200 rpm were obtained, corresponding to calculated shot velocities of 104, 174 and 257 ft/s (32, 53 and 78 m/s), respectively. At these speeds, and with 0.023 in. (0.6 mm) shot, the Almen A intensity values were 0.008, 0.010, and 0.016 in. (0.20, 0.25, and 0.41 mm), respectively.

The curvature was measured with a rigid aluminum bridge. A precision dial gage indicator was mounted at the center, while three pairs of stainless steel pins, set symmetrically, provided gage lengths of 2.5, 5, and 10 in. (63.5, 127, and 254 mm). Pairs of pins protruded to different distances from the surface plate, so that an outer pair could be utilized for measuring larger speci-

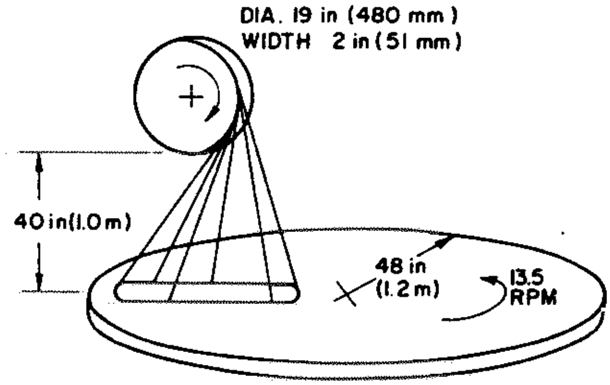

Fig. 2—Arrangement of shot peening wheel and work table.

Table I. Properties of Workpiece Materials

Alloy	Gage in.	Gage mm	Temper	Average Yield Strength ksi	Average Yield Strength N/mm²	Average Elastic Modulus 10^6 psi	Average Elastic Modulus kN/mm²
2024	0.063	1.6	T3	53	365	10.3	71
	0.18	4.6	T3				
	0.5	12.7	T351				
7075	0.063	1.6	T6	77	530	10.0	69
	0.18	4.6	T6				
	0.5	12.7	T651				

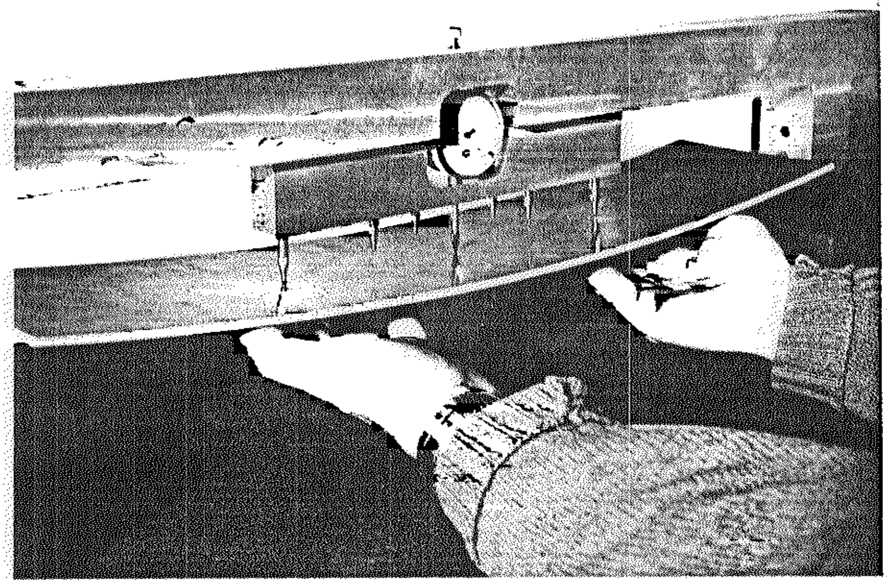

Fig. 3—Method of measuring curvature.

mens without any interference from the inner pairs (Fig. 3). Essentially, the fixture found the sagitta for a chord of precisely known length; the curvature, which was assumed to be circular, was then readily calculated from the formula:

$$R = \frac{(L^2/4) + a^2}{2a}$$

where L is the distance between the two pins of the set used, and a is the sagitta (that is, the difference of the dial gage reading from the referenced reading).

Test Procedure and Evaluation

All parts of the peening machine were completely cleaned to remove old shot, then new shot of the required size was fed in. The machine was run for a few hours to condition the shot by removing rust, scale and sharp corners. The worktable was completely covered with a thick rubber pad on which the specimens were placed without constraint (not clamped in any way). The worktable was started first, and then the wheel; when both attained steady speeds, the valve that admits the shot was opened. To obtain more uniform peening over the entire surface, the specimen was rotated by 180 deg about a vertical axis through the center of the specimen after half the scheduled exposure time had elapsed. At the end of the run, the valve was closed first.

The Almen strip method of process control was found unsuitable for the present purpose because coverage and Almen arc height were too low. Instead, for any given shot size and valve opening, the weight of shot hitting per unit area per unit time was directly measured by placing a series of small cans along a radius of the worktable. The peening tests were then conducted for a preselected duration. The total weight of shot hitting a unit area of the specimen is called shot density and is the independent variable plotted on the X-axis in most of the figures in this paper.

Coverage was estimated visually (for full coverage) or by photographing the specimen at 30 or 50 times magnification and measuring, with a planimeter, the areas of dimples in the photograph. Because of possible local variations and the somewhat subjective nature of the method, coverage data should be treated as approximate only. Dimple diameters were estimated by inspecting the samples at a low magnification. The dimple depth was measured with a profilometer and as the shot was spherical, it could also be calculated from dimple diameter. A commercial profilometer was used for measuring surface roughness.

A majority of shot-peened specimens had curvatures in both major planes (*i.e.* along the center lines of the specimen in the two principal directions, along and across the rolling direction). Generally these curvatures were different, necessitating biaxial residual stress measurements. For the purpose of this program, it was also desirable to measure the variation of residual stresses from the top layer of the specimen down.

The most widely used method is based on measuring the changes in curvature of a specimen as thin layers of material are successively removed. It is then possible to calculate the stress distribution that had existed in the original specimen before any of the surface layers were removed. Richards[11] used this method to study residual stress distribution in aluminum which had been shot blasted on an air-type machine. Treuting and Read[12] developed the method for biaxial stresses. Denton[13] described several other methods of residual stress measurements. From a review of all methods, it appeared that, for the accuracy required in this investigation, the residual stress distribution in the top layer could be obtained only with the layer-removal method which, while time consuming, presents no undue experimental difficulties and requires no calibration. The residual stress distribution was measured on 1 in. (25.4 mm) wide × 6 or 8 in. (152 or 203 mm) long strips cut from the peened specimens with the strip length in the direction of interest. Thin (approximately 0.004 in. or 0.1 mm thick) layers were removed in a solution of sodium diphosphate and sodium hydroxide from the peened side until the strip became virtually flat. The stress distribution was then calculated using the formula in Ref. 11 with the help of a computer program.

RESULTS AND DISCUSSION

Contour forming was the primary objective of this investigation and, thus, experimental observations and their discussion are presented with direct reference to the contour generated. Contour is described by longitudinal and transverse radii (or corresponding curvatures, *i.e.* the reciprocals of radii). The term "longitudinal" refers to the direction of rolling the sheet; in other words, the length of the original 144 in. (3.66 m) long sheet, whereas the direction of "feed" indicates the direction in which the sheet traveled in the stream of shot.

Effects of Work Material and Specimen Thickness

Experiments in which all process variables were kept constant showed that the location of the specimen within a sheet, the particular sheet within the same material designation, and the origin of sheets with regard to supplier did not affect the curvatures produced. Thus, the results are applicable without regard to the small differences in properties normally found in nominally identical sheet materials.

The geometry and orientation of specimens relative to the original rolling direction were most significant factors. In 2024 the transverse radius of curvature was the smaller one almost without exception (Fig. 4) whereas in 7075 the longitudinal radius of curvature was smaller (Fig. 5). This held irrespective of whether the original rolling direction was placed in the direction of feed or transverse to it. Samples of square configuration (L/W = 1) showed an essentially single curvature (with one of the curvatures approaching infinity); samples with a 4 : 1 aspect ratio (L/W = 4 or 1/4) acquired practically identical radii in the two principal directions; samples with an aspect ratio of 2 : 1 were intermediate in their response and the longitudinal and transverse curvatures sometimes interchanged their magnitude in response to specimen orientation relative to the shot stream. Because the longitudinal and transverse radii were very similar to each other on specimens of 4 : 1 aspect ratio and were also insensitive to specimen orientation, this geometry was chosen for investigating other variables. The reasons for this behavior could be found from further experiments.

For otherwise identical conditions, thinner specimens developed tighter curvature than thicker ones (Fig. 6), except for the 0.063 in. (1.6 mm) thick specimens peened at high shot densities (Fig. 6) or with large diameter shot (not separately shown). The high energy of the large shot caused overpeening by deforming the workpiece through its entire thickness (indentations were visible on the nonpeened side), and resulted in a larger radius and

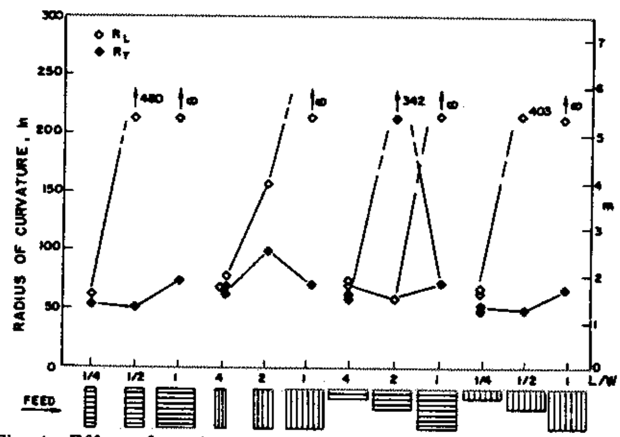

Fig. 4—Effect of specimen aspect ratio and orientation on curvature (0.18 in. thick 2024 alloy sheet, 24 in. in the major direction, 1500 rpm wheel speed, 0.066 in. steel shot at 5.94 lb/ft² density).

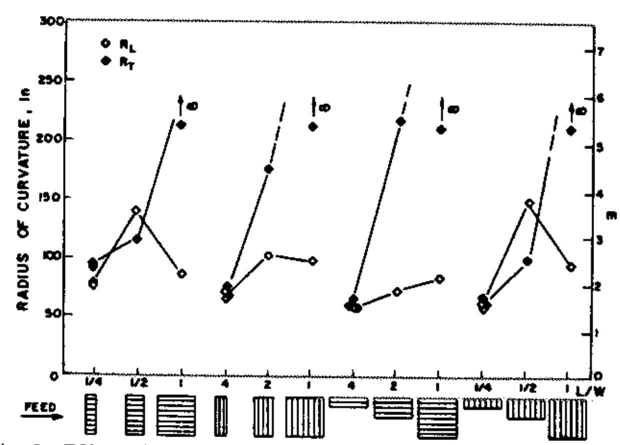

Fig. 5—Effect of specimen aspect ratio and orientation on curvature (conditions the same as in Fig. 4, but material is 7075).

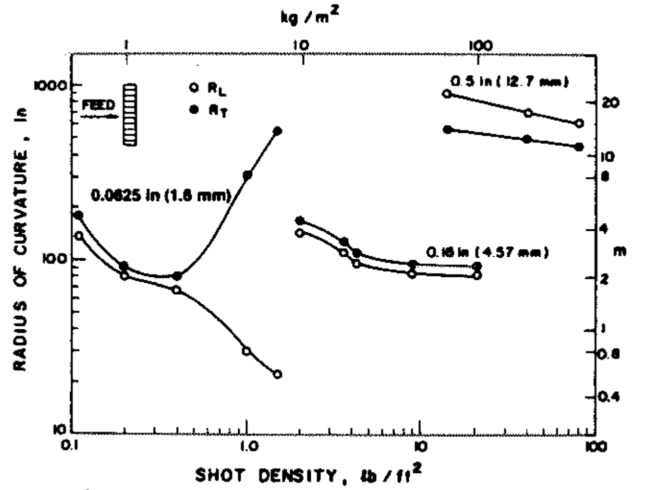

Fig. 6—The effect of sheet thickness on curvature (7075 aluminum alloy, 0.023 in. shot, 220 rpm).

eventual flattening of the sheet. Peening at high shot densities with smaller shot caused the transverse and radial curvatures to assume different values (Fig. 6), with most of the curvature concentrating in the shorter L direction. This is what could be expected from considering the relative stiffness in the two directions of a curved sheet, and should be the normal result (as confirmed later in the full-scale trials). Only when the specimen is thick relative to its L and W dimensions can the observed equality of R_L and R_T hold. For the 6 × 24 in. (152 × 610 mm) geometry used here this "relative thickness" was reached with the 0.18 in. (4.6 mm) sheet.

Influence of Peening Variables

As expected, the radius of curvature decreased (that is, curvature increased) as wheel speed and/or shot density increased (Fig. 7). However, this increase gradually diminished, as indicated by the flattening out of curves in Fig. 7, indicating that curvature cannot be increased indefinitely simply by increasing the shot density. To obtain a desired radius, it is necessary to manipulate shot size as well as wheel speed and shot density. For a given velocity and shot density, larger shot possesses greater energy and leads to a smaller radius of curvature (Fig. 8).

Data given in Figs. 7 and 8 are typical of all results and suggest a hyperbolic relationship between radius of curvature and shot density. An unpeened specimen has no curvatures; that is, the radii are infinite. On the other hand, specimens peened at high shot densities approach a limiting radius, leading to a relationship of the type

$$R = A + B/S \qquad [1]$$

where R is radius, S is shot density, and A and B are

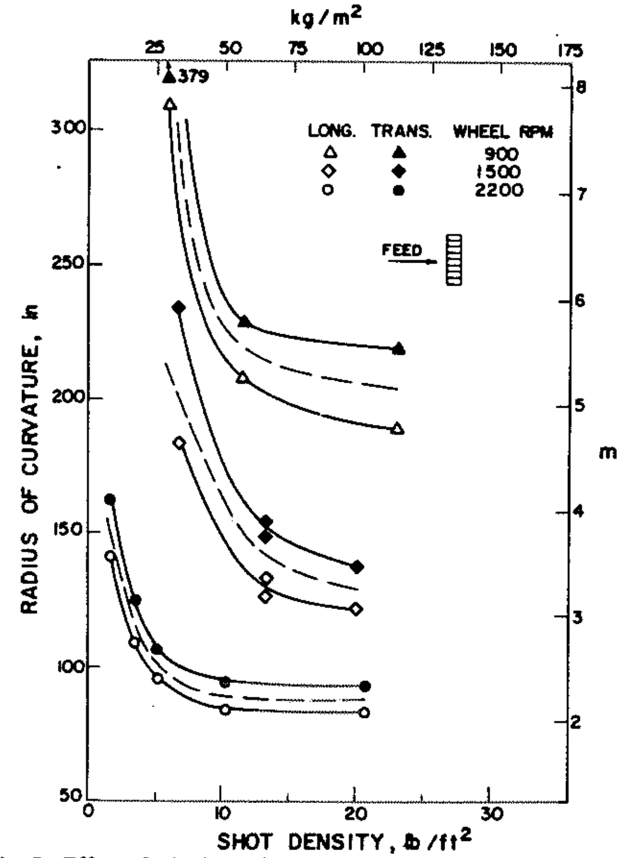

Fig. 7—Effect of wheel speed (shot velocity) on radius of curvature (0.18 × 6 × 24 in. 7075 specimens, 0.023 in. steel shot).

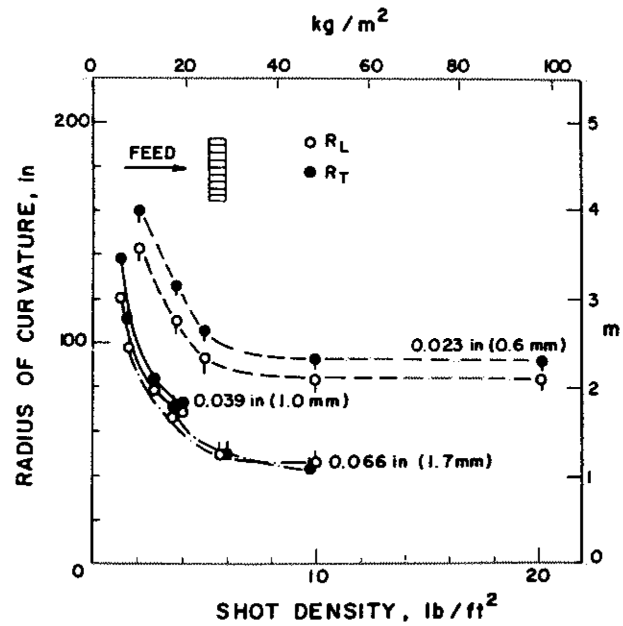

Fig. 8—Effect of shot size on radius of curvature (0.18 × 6 × 24 in. 7075 specimen, 2200 rpm).

constants. Since the transverse and longitudinal radii were reasonably close, the constants A and B were found by curve fitting to the average of the two radii (as shown in broken lines in Fig. 7). Although drawing the curves through the data points was somewhat subjec-

Table II. Calculated Values of Parameters *A* and *B*

Material	Wheel Speed, rpm	Shot 0.023 in. (0.6 mm) *A*	*B*	Shot 0.039 in. (1.0 mm) *A*	*B*	Shot 0.066 in. (1.7 mm) *A*	*B*
2024	900	150	1340	60	520	—	—
	1500	90	420	30	400	20	280
	2200	60	150	35	100	25	120
7075	900	160	810	105	530	—	—
	1500	95	660	80	410	20	390
	2200	75	120	35	120	20	160

Specimen size, 0.18 × 6 × 24 in. (4.6 × 152 × 610 mm). Units: (*R*: in. and *A*: in., *S*: lb/ft^2, and *B*: in. · lb/ft^2). For S.I. units, multiply values of *A* by 0.0254, values of *B* by 0.124, express shot density *S* in kg/m^2. Then, the formula $R = A + B/S$ gives the radius of curvature *R* in meters.

tive, the fitting procedure gave good results in most cases (Table II). The calculated values for both parameters showed some definite trends.

For the 2024 aluminum alloy specimens and 0.023 in. (0.6 mm) shot both parameters decreased with increasing wheel speed indicating that, as expected, the radius decreases (curvature increases) as the wheel speed increases. With the larger shot of 0.039 in. (1.0 mm), the parameter *A* had similar magnitudes at 1500 and 2200 rpm, whereas the parameter *B* continued to decrease with increasing speed. This suggests that parameter *A* tends to reach some limit at larger shot sizes and speeds. This was found also with the 0.066 in. (1.7 mm) shot.

Similar trends were seen for the 7075 aluminum specimens, except that parameter *A* reached a limit only with the larger 0.066 in. (1.7 mm) shot. For any given speed shot size again had a greater effect on *A* than on *B*. This leads to the reasonable conclusion that parameter *A*, the limiting radius, is strongly dependent on and increases with the yield strength of the material, indicating that for a given amount of energy, lesser deformation can be obtained on a stronger material. In comparison, parameter *B* is affected more by shot speed and governs the radius at low shot densities.

Surface Deformation

Coverage (the percentage of surface covered by peening marks) and the dimensions of individual indentations followed trends to be expected from considerations of shot energies.

When shot density was increased for a given wheel speed, total coverage increased (Fig. 9). For any given shot density, increasing wheel speed increased the coverage because of higher shot energy at higher speeds. For a given wheel speed and shot density, coverage is greater

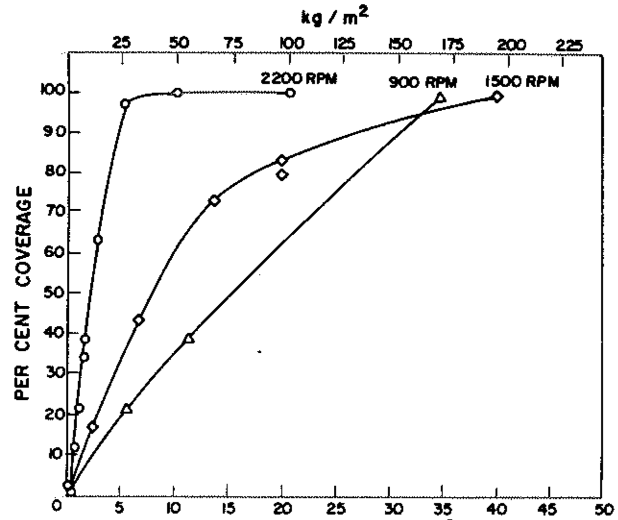

Fig. 9—The effect of wheel speed on coverage (0.023 in. cast steel shot).

with a smaller shot size (Fig. 10). This can be expected as the weight of the shot is proportional to the cube of its radius, whereas the area of a dimple or impression is proportional to the square of its radius. Thus, for a given shot density, the smaller shot delivers a much larger number of particles and, consequently, the number of impressions and coverage are also higher.

The diameter and depth of the peening impressions were measured at low shot densities when the individual impressions could be clearly identified. Both dimple depth and diameter increased with increasing shot diameter and shot speed (Table III). In this table, "relative shot mass" is proportional to shot diameter cubed; "relative kinetic energy" is the "mass" multiplied by the square of rpm, and the product given by the square of dimple diameter multiplied by dimple depth is proportional to "relative work of deformation", the work

Table III. Diameter and Depth of Dimples under Different Experimental Conditions

Shot Size, in.	Relative Shot Mass	Ratio	Wheel Speed, rpm	Relative Kinetic Energy	Ratio	Average Dimple Diam, in.	Relative Work of Deformation	Ratio	Average Dimple Depth, in.
0.023	12.2	0.042	900	10	0.007	0.008	0.32	0.003	0.0005
0.023	12.2	0.042	1500	28	0.02	0.012	1.44	0.015	0.0010
0.023	12.2	0.042	2200	59	0.042	0.014	2.95	0.03	0.0015
0.039	59.6	0.206	900	48	0.034	0.016	2.56	0.026	0.0010
0.039	59.6	0.206	1500	134	0.096	0.020	10.0	0.10	0.0025
0.039	59.6	0.206	2200	288	0.21	0.025	15.6	0.16	0.0025
0.066	290	1.0	900	235	0.17	0.026	13.52	0.14	0.0020
0.066	290	1.0	1500	653	0.47	0.038	50.5	0.52	0.0035
0.066	290	1.0	2200	1404	1.0	0.042	97.0	1.0	0.0055

For S.I. units, 1 in. = 25.4 mm.

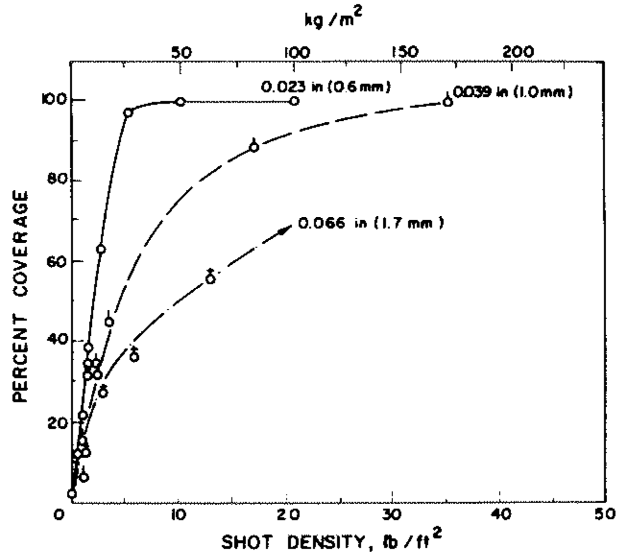

Fig. 10—Effect of shot size on coverage (wheel speed 2200 rpm).

done to make the dimple. A comparison of "work of deformation" with "kinetic energy" will show that efficiency is greater with heavier shot and higher speed; however, this does not necessarily represent desirable production conditions because of surface deterioration.

Surface roughness was measured only on specimens with nearly full (100 pct) coverage, since only on these specimens was the surface finish uniform. The roughness increased—that is, a poorer finish resulted—when shot size and speed were increased. Therefore, when larger shot is needed to obtain tighter curvatures, it may be necessary to peen the surface again (or finish peening) with smaller shot to refine the surface finish.

The above observations allow an interpretation of the parameters in Eq. [1]. The parameter A is the limiting radius for a specimen and depends on the dimensions of the individual impressions which, in turn, must depend mainly on shot size, wheel speed, and the yield strength of the material, or, in general, on shot energy relative to work of deformation. The parameter B seems to arise from the combined effects of neighboring impressions. Therefore, it is strongly influenced by wheel speed which affects coverage (Figs. 9 and 10).

Residual Stresses

A few specimens peened with 0.039 in. (1.0 mm) diameter steel shot at 1500 or 2200 rpm and some unpeened specimens were subjected to residual stress measurements. Even the unpeened specimens showed residual surface stresses, sometimes tensile, sometimes compressive, of the order of 5000 to 15000 psi (35 to 104 N/mm²). After peening, high compressive residual stresses were found near the peened face. In general, both the magnitude of the maximum compressive stress and the depth of the compressed layer increased with wheel speed and coverage. With one exception of doubtful accuracy, the maximum compressive stress was always less than 30000 psi (200 N/mm²) and occurred at a depth of up to 0.011 in. (0.28 mm) below the peened surface. Neither the magnitude nor the pattern of residual stress distribution could be meaningfully correlated with specimen curvature. The rather limited data suggest that the development of any quantitative relationship between residual stress and curvature will be an extremely difficult task, partly because the narrow strip cut out for residual stress determination will have a much greater thickness than the original larger specimen, thus the stress pattern will also be different.

SCALE-UP TO PRODUCTION

The purpose of this investigation was to establish practical and useful guidelines for generating controlled curvatures. The data given in Table II can be used for calculating the expected radius of curvature but only within the range of process variables and specimen sizes studied. For practical applications, it is essential to allow for curvature changes resulting from increasing the size of the workpieces by one or two orders of magnitude.

To explore the effects of workpiece geometry and orientation, a number of 0.18 in. (4.57 mm) thick specimens of one constant dimension, but of different L/W ratios and different orientations relative to the rolling direction, were peened at constant wheel speed, shot size and shot density. Typical results have already been shown in Figs. 4 and 5. Specimens of $L/W = 1$ have equal stiffness in both principal directions, and the longitudinal and transverse curvatures would be expected to be roughly equal. This equilibrium is, however, unstable and easily upset by second-order effects such as rolling direction and the associated residual stress distribution and directionality of mechanical properties in the specimen. Most of the curvature will usually develop in one of the two principal directions. This means that no generalized prediction can be made from samples of square configuration. Curvatures at an aspect ratio of 2 : 1 are still strongly influenced by second-order effects. This was the reason for choosing the $L/W = 1/4$ ratio for the exploration of process variables.

In practical applications the workpiece has a large length-to-width ratio, and prediction of the transverse curvature only is of interest; the longitudinal curvature is virtually nonexistent because of the very substantial longitudinal stiffness of a transversely curved long plate. One could argue, of course, that the small specimens of $L/W = 1/4$ ratio used in the exploratory experiments too should show a lesser curvature in their longer (transverse) direction (as the thinnest specimens did, Fig. 6) but the relatively small length-to-thickness ratio of the thicker specimens appeared to make them behave as though they were part of a longer workpiece. The question then arises whether it is indeed possible to make a valid scale-up from small specimens to full-size workpieces.

First of all, it needed to be proven that the curvature of a short specimen was representative of a longer workpiece. To this end, the square specimens of Figs. 4 and 5 were cut into quarter and half lengths, and the radii developed after cutting were indeed found to be similar to those measured on the shorter pieces which had been directly peened.

For a further scale-up of the workpiece, large-scale peening tests were conducted at The Boeing Company's facilities at Auburn, Washington, on a machine normally utilized for contour peening of large aircraft wing skins. It has twelve 15 in. (380 mm) diam wheel-type (Wheelabrator) units which throw shot at the wing skin as the vertically mounted part moves in a horizontal direction. The speed of wheels can be continuously varied up to 2000 rpm. Two 0.18 in. (4.6 mm) thick, 48 in. (1.22 m) wide and 144 in. (3.66 m) long 2024-T3 aluminum sheets were first cut into half along their rolling direction and then into specimens ranging from 3 in. (75 mm) to 144 in. (3.66 m) length. The specimens were attached to a board by wire passed through holes in their edges, with the 24 in. (610 mm) width dimension in the vertical position. The board with the attached specimens was moved through the peening machine in a vertical plane, at a speed of 10 ft/min (3 m/min), while it was peened with 0.023 in. (0.6 mm) cast steel shot from two 15 in. (380 mm) diam wheels spaced 20 in. (510 mm) apart. The speed was 1900 rpm and 250 lb/min (113 Kg/min) shot was admitted per wheel. Peening was done in only one pass from one side. The two wheels were known to give a very uniform intensity because of their overlapping shot patterns.

Assuming that uniform intensity also means uniform coverage and that only half of the shot thrown falls on the specimens, the shot density was

$$\frac{250 \text{ lb/min}}{10 \text{ ft/min}} \frac{1}{(20/12) \text{ ft}} = 15 \text{ lb/ft}^2 \ (= 74 \text{ kg/m}^2).$$

The resulting coverage was between 80 and 90 pct.

The results of these tests (Fig. 11) are in agreement with the predictions. At an aspect ratio of around unity the radii show the large variations found previously, even though the longitudinal radius now does not reach infinity, no doubt because of the great sensitivity of this aspect ratio to secondary factors such as sheet properties and shot peening pattern. At the large L/W ratios of practical interest, the transverse curvature was of similar magnitude to that found on the much shorter specimens. The longitudinal curvature, on the other hand, increased to very large values, as would be expected from stiffness considerations. Because most of the strain is forced into a transverse curvature, it is reasonable that R_T at high L/W ratios should be slightly smaller than at the small L/W ratios. At the lowest L/W ratio the longitudinal curvature (which is actually in the shorter direction of the specimen) is tighter, as would be expected from stiffness considerations.

It is interesting to note that the radius of curvature

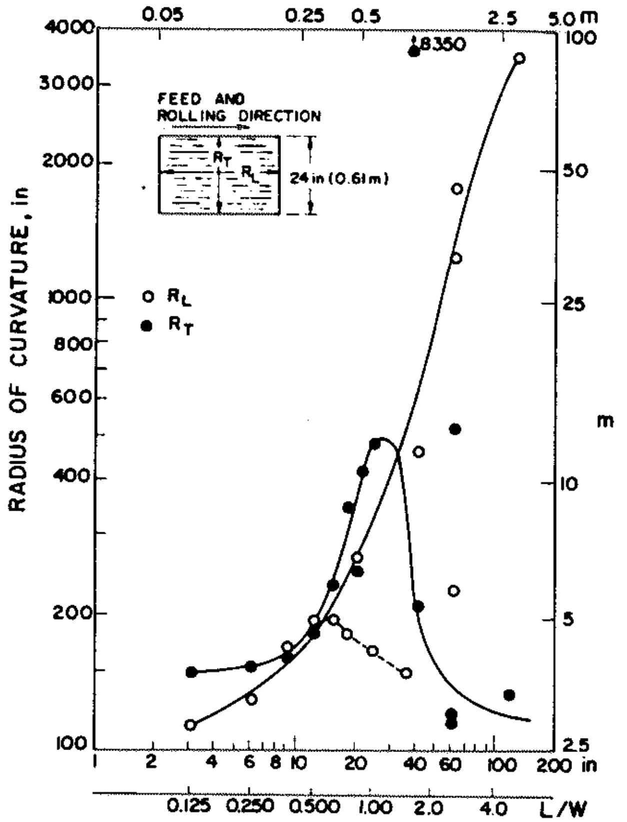

Fig. 11—Radius of curvature of specimens peened in production facility (0.18 in. thick 2024-T3 aluminum alloy, 0.023 in. cast steel shot, 15 in. diam wheel at 1900 rpm, 15 lb/ft^2 shot density).

predicted from Eq. [1] and the parameters in Table II (with A and B interpolated for 1900 rpm) is 86 in., whereas the radius measured at Boeing was 120 in. The agreement is quite satisfactory if one considers the differences in peening procedures. In the small-scale experiments the specimens rested in a horizontal position on a rotating table and were repeatedly peened, with curvatures developing gradually. In the large-scale trials the specimens were hanging in a vertical plane and were subjected to a single pass under a relatively heavy flow of shot.

SUMMARY AND CONCLUSIONS

Shot peen forming experiments were conducted on relatively small-size 2024 and 7075 Al alloy sheet specimens with shot size, shot speed (peening wheel rpm), shot density (defined as the weight of shot applied per unit area), and specimen length-to-width ratio as the major variables. Resulting curvatures in the two principal directions, coverage, dimple diameter and depth, and residual stresses were measured. The feasibility of transferring practices from small-scale experiment to full-scale production was explored in trials conducted at The Boeing Company facilities. The following conclusions could be drawn:

The curvature reflects the energy available in the shot stream relative to the stiffness of the sheet. Thus, curvature increases (the radius of curvature decreases) with increasing shot diameter, shot velocity, and shot density, and with decreasing thickness and yield strength of the workpiece material.

For a given shot size and velocity, the radius of curvature reaches a limiting value with increasing shot density, and the relationship between radius and shot density can be described by a hyperbolic function. Therefore, to attain a radius of curvature smaller than this limiting value, it may be necessary to increase the shot size.

When the shot energy is sufficient to cause deformation through the sheet thickness, a condition of overpeening is reached and the radius of curvature becomes larger again (the sheet flattens out).

The depth (and diameter) of dimples increases with increasing shot energy and decreasing flow stress of the workpiece material.

Coverage, expressed as the percentage of workpiece surface indented by the shot, increases with increasing shot density. For a given shot density, smaller shot gives greater coverage because of the larger number of shots delivered.

Surface roughness can be meaningfully measured only on workpieces with 100 pct coverage. Roughness increases with shot size and shot velocity, and may become unacceptable when small radii of curvature are desired, necessitating finish peening with smaller shot to improve surface finish.

Residual stresses were always compressive on the peened surface; however, their magnitude and distribution through the workpiece thickness could not be meaningfully correlated with curvature.

Specimens with a length-to-width ratio near unity have equal stiffness in the two directions, leading to a basic instability of curvature. The direction of smaller curvature is governed by secondary factors such as rolling direction of the sheet and direction of feed during peening. When the length of the workpiece, measured in the rolling direction of the sheet, is greater than its width, the greater stiffness in length results in a lesser curvature (larger radius) in that direction and a tightening curvature (lesser radius) in the width direction. When the length-to-width ratio of the specimen drops much below unity, the radius in the stiffer width direction becomes larger. Most importantly, the transverse curvature (measured across the rolling direction) of a short and relatively thick specimen is very close to that of a very long one; this allows the establishment of process variables on small workpieces.

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