Shot peen forming sheet metal: finite element prediction of deformed shape

L V Grasty, BSc, PhD
Ling Dynamic Systems Limited, Royston, Hertfordshire

C Andrew, MA, PhD, CEng, FIMechE
Manufacturing Engineering, Department of Engineering, University of Cambridge

Shot peen forming is a production process used to create curved metal parts from sheet. It is commercially important despite the fact that its mechanisms are not fully understood; peen forming programmes are currently generated using experience and trial and error. The purpose of this work is to increase the predictability and range of application of the process by advancing its understanding.

Finite element analysis proved to be a satisfactory procedure for studying shot peen forming. The stress distribution in a sheet arising from multiple indentations, as occur in shot peen forming, was modelled. A technique of squeezing the upper layers of a finite element model was shown to be a good simulation of the stress distributions resulting from shot peen forming, and provided a much more tractable analysis with respect to computing time and resources.

Key words: sheet metal, forming, shot peening, finite element analysis (FEA)

1 INTRODUCTION

Shot peen forming is a metal forming process used to create curved metal parts, particularly from sheet. The forming tool is a stream of metal shot or glass or ceramic beads, propelled at the workpiece pneumatically or mechanically, and striking the sheet surface with sufficient energy to cause its surface to deform plastically. The plastic deformation sets up a residual stress distribution through the sheet thickness which is resisted by the bending of the sheet convex towards the peening stream.

Shot peen forming is currently in commercial use, primarily in the aerospace industry, for the shaping of large sections such as wing skins. It is also used for straightening slender components that have become distorted during machining. It is a viable commercial process despite the fact that it is little understood and is commonly referred to as a ‘black art’. The knowledge that does exist tends to be locked up with current users, who guard their knowledge as a valuable trade secret. The process would almost certainly find wider application if it were better known and understood. It is dieless, eliminating both the high initial costs needed to produce a die set and the storage and set-up costs that militate against small batch production. The machinery it requires is relatively inexpensive, and its incremental nature means that parts can be inspected in-process. Examples of some possible alternative applications are shown in Fig. 1. It will be seen that the pattern of coverage defines the final shape, which generally involves double curvature, although the process of building up coverage in strips encourages single curvature (Fig. 1b).

In addition, the presence of an imposed strain (bending) on the component during peening will affect the final form. These influences serve to underline the potential versatility of the process, but they make the analysis significantly more complicated, and it may well prove more effective to approach them by development in tandem with research.

Much has been written about shot peening as a fatigue life improver, but shot peen forming has received little consideration. The majority of previous work may be found in references (1) to (4). The generation of a peening programme involves a mixture of (sometimes considerable) experience of similar components and then some intelligent trial and error. The aim of the present work is, by providing understanding and hence predictability of the process, to improve practice on current applications and extend the range of potential applications. It will, however, be restricted in the first instance to consideration of the (relatively) simple case of a steady buildup of coverage over the total area of the component, with no imposed strain.

2 ASSUMPTIONS

The process parameters of shot peen forming are: size, density and velocity of shot; coverage (percentage of the surface receiving one or more impacts); and the order and pattern of building up the coverage.

In practice, the size, density, velocity and coverage are not separately defined with absolute precision. Thus, the size of shot is often defined by a sieving process, and a given batch will contain a range and distribution of shot diameter, although in some special cases machined balls can be used to provide greater accuracy and consistency (but at greater cost). Velocity is difficult to define ab initio for an air blast machine, as it depends on the detail design, and varies with mass flow. Coverage is similarly imprecise in definition, often being defined by the average number of indentations within a prescribed area. The common method of defining the process parameters is in their effect in combination on a standard test piece, namely the deformation (rise) their combination causes on a standard strip (3 x 0.75 inches, or 7.02 x 1.9 cm) of spring steel called an Almen strip. This has the advantage of being closely linked...
Fig. 1 Components shaped by peen forming

with the full process and of allowing control of it, but the disadvantage that it is not a fundamental test and does not aid predictability [see reference (5)]. The first requirement for specifying the process is, therefore, to be able to relate the process parameters as above to the individual indentations of the shot into the surface. This has been undertaken in a separate piece of work (6). For the present work it will be assumed that the surface indentations can be specified.

The order and pattern of building up the coverage also has a significant effect on the final shape. However, the first step in the research has to be consideration of a steady buildup of coverage over the total area of the component, and this is what will be described here.

3 ANALYSIS

Analysis was by the finite element analysis (FEA) method, utilizing a proprietary FEA package, MARC, running on a Sun Microsystems SPARCstation 2 computer, with MENTAT for pre- and post-processing. The first requirement in applying FEA is to verify its functioning. This was undertaken in the present work by comparing the output of the FEA with past analyses and experimental work for the following cases of indentation by a spherical indenter into:

(a) axisymmetric half-space, elastic;
(b) axisymmetric half-space, elastic-perfectly plastic;
(c) axisymmetric half-space, kinematically work-hardening;
(d) axisymmetric finite depth, kinematically work-hardening.

Agreement was satisfactory in all cases. An example is shown in Fig. 2, comparing FEA prediction for case (d) with the experimental results of Goldsmith and Lyman (7) who measured '...the force-indentation relations governing the contact of hard steel balls and plane surfaces on various metals...'. The FEA was based on the material characteristics and geometry quoted in reference (7).

The axisymmetric FEA of a single indentation as above is efficient in computing cost but is not applicable to general and bounded shapes and multiple and interacting indentations as occur in shot peen forming. A full three-dimensional FEA was, therefore, utilized, and was verified by using it to analyse the same problem as the axisymmetric case. One result is shown in Fig. 3.

Although the coarseness of the three-dimensional mesh is evident, the three-dimensional analysis is effectively verified.

3.1 Multiple indentations

Having been verified as above, the three-dimensional FEA was then applied to the problem of sequentially applied, adjacent multiple indentations. The problem was reduced to that of just nine indentations on top of a block, as shown in Fig. 4. The dimensions of the indentations were consistent with those observed experimentally firing a 1.0 mm shot at an aluminium alloy AL5247 specimen of similar thickness. The indentations were equally spaced and did not overlap.

The analysis was undertaken under two sets of conditions. In the first, the nodes defining the floor of the block were fixed in the z direction throughout the appli-
c caption of all nine indentations, and then released, this single release being elastic.

In the second, the floor nodes were held in the \( z \) direction during each individual indentation, but then released after each. The \( z \) coordinates after (elastic) release were then used as the fixed values for the next indentation, and the process repeated incrementally.

In both cases, the loading gave rise to a double curvature of the block. As measured by the rise at the centre of the floor compared with the corners, the rise was approximately 30 per cent higher for the second incremental set of conditions.

The resulting plastic strain distribution for the first, single-release, set of conditions is shown in Fig. 5. Undulations are visible under the individual indentations, and the order of indentation has also had some influence. Nevertheless, it is reasonable to regard the strain distribution as a series of layers.

Clearly, an analysis for every indentation would result in excessive computation in a practical situation.
An equivalent loading system was, therefore, proposed in which the upper layers were subjected to a squeeze pressure as shown schematically in Fig. 6, such that they underwent a small plastic deformation. Once again, the analysis could be carried out under two sets of conditions. In the first, the floor nodes would be fixed in the \( z \) direction during a single squeeze, and then released. In the second, the first squeeze would be followed by a second, of the same pressure, but using the new floor \( z \) coordinates resulting from the first squeeze as the fixed floor; this process could be repeated in increments until no further significant increase in deformation arose.

The single-squeezed layer model was applied to the case of the block in Fig. 4. The squeezed layer covered the central 36 squares of the block, an area similar to that directly under the nine indentations. The depth of the layer was approximately 50 per cent of the sheet, corresponding to that depth undergoing plastic strain due to the indentations, as shown in Fig. 5. A range of squeeze pressures was tried, and the one that gave the same curvature (floor centre rise) as the indentation case was found to be 330 MPa, approximately twice the yield stress of 157 MPa assumed in the indentation calculation. The residual stress in the block was determined, and is shown as a function of depth in Fig. 7, for comparison with that for the case of nine indentations (\( \delta_{xx} \) stresses only, for clarity). There is good correspondence, suggesting that the squeezed layer model is, at least in this context, satisfactory.

For the second analysis, releasing the \( z \) coordinates of the floor between squeezes at the same pressure of 330 MPa, the rise at the centre of the floor was approximately 30 per cent higher than the single squeeze case, after 5 squeezes.

The incremental analytical procedure was then applied to two simple sheet components: one a strip of 10 \( \times \) 50 \( \times \) 0.9 mm and the other a circular disc of 25 mm diameter and 0.9 mm thickness. Assuming the same material and the same squeezing conditions as for the block of Fig. 4, the strip deformed primarily into a lengthwise circular arc, cut with a small crosswise curvature as shown in Fig. 8. The circular disc deformed to an essentially spherical shape. An unexpected outcome from the circular disc analysis was the prediction of a tensile plastic strain on the underside (unpeened side) of the deformed disc.

### 4 EXPERIMENTATION

Peening was undertaken in a Vacu-Blast PB100 shot peening cabinet. This is normally a manually operated machine, but for this research it had been adapted by the addition of an \( X-Y \) table, providing controlled motion of the specimen under the shot stream, and by a mechanical shot feed system ensuring constant and adjustable mass flow of shot. A constant-pressure air supply was provided by a Plusair SK26 screw compressor, and the shot used was chilled cast iron, size 1.0 mm diameter average.

The shot stream conditions were: shot velocity 19 m/s (corresponding to an air pressure of approximately 1 bar); shot mass flowrate 9.2 g/s; peening duration 15 s. Under these conditions, the specimens were approaching saturation peening; that is, longer peening duration would not have caused more than a 10 per cent increase in deformation.

The material of the specimens was annealed aluminium alloy type 5251, cut from sheet 0.9 mm thick. Yield properties were deduced from a bulge test and

![Fig. 7 Comparison of residual stresses in squeezed layer model and multiple indentation case](image)
found to be: tensile yield stress 157 MPa; strain hardening rate (assumed linear) 120 MPa/unit strain. Young's modulus was taken from standard data at 68 GPa.

Experiments were conducted on the same two shapes as were analysed in the previous section: the strip and the circular disc. They were peened evenly over one surface and were free to distort during peening. The strip deformed into a circular arc, with a slight cross-curvature and a rise at the centre of approximately 3.1 mm. The same peening conditions caused the disc to deform into an essentially spherically curved shape, with a rise at the centre of 0.9 mm.

A Keeler grid had been etched on the underside of the disc before peening. The dimensions of this grid before and after peening were measured with a travelling microscope and the surface strain arising from the peening thus deduced. This is not an accurate method of measuring low strains, but the estimated value of strain at the disc centre was $0.7 \pm 0.4$ per cent.

5 DISCUSSION OF RESULTS AND LIMITATIONS
The experimental rise of the strip was compared with that predicted by the FEA for various squeeze pressures, and an appropriate equivalent squeeze pressure selected. This pressure was then substituted into the analysis for the disc, and predicted a rise of 1.0 mm, which compares with the 0.9 mm measured.

The same loading system predicted a surface strain on the underside, at the disc centre of approximately 0.4 per cent. This compares with the $0.7 \pm 0.4$ per cent measured.

The correspondence of prediction and experiment gives confidence that the model used and the associated FEA are reasonable representations of practice. A number of shortcomings will, however, be evident:

1. The procedure followed has not started from fundamentals, that is from peen physical characteristics, velocity, coverage. However, the correlation obtained indicates that were such information available, prediction ab initio would be feasible. Indeed, the peen formed strip, leading to definition of the equivalent squeezed layer, can be regarded as a better-understood and relevant version of the current Almen strip.

2. The FEA in its present form has to be applied to the whole of the specimen. To maintain an acceptable aspect ratio of element, this leads to a large number of elements for a realistic size of sheet component and an expensive computation. Thus the present method has been limited to small components. Development of the method to allow the analysis of realistically sized components without excessive computation is needed.

6 FURTHER RESEARCH AND DEVELOPMENT
The success of the present work in relation to small, simple shapes, and the indication during experimentation of a considerable potential for producing shapes of a wider variety and under greater control than with current practice, encourages further work. This should encompass both further effort to understand the fundamentals of the process and a development programme that cannot wait for the fundamental understanding. The former should include: direct correlation between machine parameters and the process parameters of shot size, velocity, and coverage; further correlation between process parameters and the resulting plastic strain field, for a range of materials; extension of the analysis to include realistically sized and pre-stressed components; the effect of pattern and sequence. The latter should start with a systematic and controlled study of simple but realistically sized components, both pre-stressed and unpre-stressed, in bending and torsion, exploring and building up an ordered experience base.

Further information about the work described here may be found in reference (8).

ACKNOWLEDGEMENTS
The authors would like to thank their industrial collaborators, British Aerospace (Military Aircraft Division), Delcam International and Impact Finishers, for the provision of equipment, software, consumables and advice, and the SERC ACME Directorate for its support.

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