1995013

Finite Element Simulation of Shot Peening

A. Levers, British Aerospace Airbus Ltd.,
Broughton, nr Chester CH4 0DR, UK

A. Prior, HKS (UK) Ltd,
Genesis Centre, Birchwood, Warrington, WA3 7BH, UK

Introduction

The finite element method is well suited to the analysis of structures containing complex residual stress patterns, for example the springback of press-formed sheet components after removal from the tool.

It is clear that this method could also be used to examine the deformation of a component that contains a residual stress field created by shot peening. The difficulty in this simulation is to identify the residual stress pattern created from a given shot peening process and to validate the deformation arising from that stress field during and after the peening process.

In this paper we describe two investigations currently being undertaken into the use of finite element analysis for the examination of shot peening. The first uses an explicit finite element program to analyse in detail the stress field created by individual and repeated shot impacts. The second uses the implicit finite element method to create stress fields in relatively simple structures and predict the resulting deformation.

The combination of these two methods has enabled the deformation of peened components to be predicted for a wide range of peening parameters and provides a valuable tool in the design and use of peening processes.

Empirical Methods

A number of empirical methods have been developed to characterise the deformation and stress field resulting from shot peening.

For the peening equipment currently in use at Broughton, the velocity of the shot can be found from the following equation:

$V = 4.9623\ (P)^{0.58253}$ (1)

where
V = shot velocity
P = Peening pressure

Again, for the equipment currently employed, the diameter of the indentation in aluminium alloy 2024 T351 can be predicted from the peening pressure using the following equation:

$D = -0.045998 + 0.2191385\ \ln (p)$ (2)

where
D = Diameter of dimple
P = Peening Pressure

A generally applicable empirical equation proposed by Shaw and DeSalvo (1970) and modified by Al-Hassani gives the depth of plastically deformed material under a shot impact:

$hp/R + 3.00\ (Z/R)1/2$ (3)

where
hp = Plastic layer depth
R = Indenter radius
Z = Depth of indentation

It is an objective of this work to establish both the accuracy and applicability of this general function, and the empirical equations related to the equipment and material specific to Broughton.

Explicit Analysis

Whilst the above empirical methods have proved useful in predicting deformation of peened components, it is also important to investigate the fundamental mechanisms by which plastic strains are generated in the component under single and repeated shot impacts. To this end the explicit finite element method has been used to simulate the impact of various shots sizes at a number of velocities. The resulting plastic deformation has been used to evaluate the accuracy both of the empirical techniques and the implicit finite element methods.

The shot impact analyses are carried out using a two-dimensional deformable mesh and a rigid ball. The finite element model for this impact analysis is shown in figure 1 below.

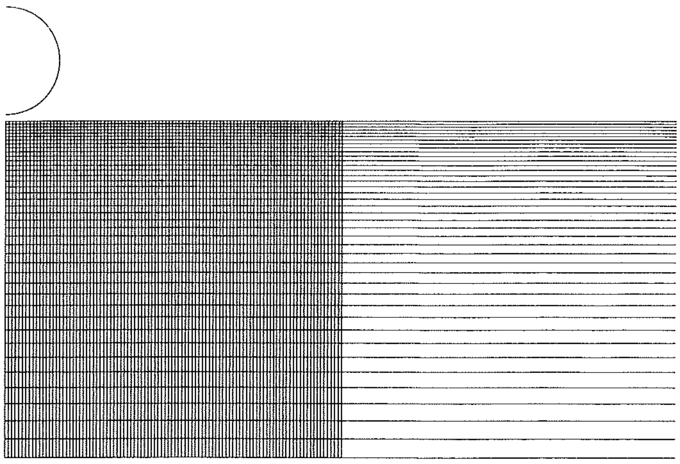

Figure 1. Axisymmetric FE mesh for single shot impact

The shot is 1.588mm in diameter and has a mass of $1.646x10^{-5}$kg. At an impact velocity of 42.53m/s equation (2) predicts a dimple 0.76mm in diameter in 2024 T351 aluminium plate. Simple trigonometry provides an estimate of the dimple depth of 0.09mm. Equation (3) can then be used to give an estimate of the depth of plastically deformed material, in this case 0.83mm.

In order to improve the visualisation of the results the axisymmetric mesh has been rotated through 180 degrees to show a 3D shape. The dent arising from the impact of the rigid ball is approximately 0.72mm in diameter and 0.063mm deep, when measured from the lip of the crater.

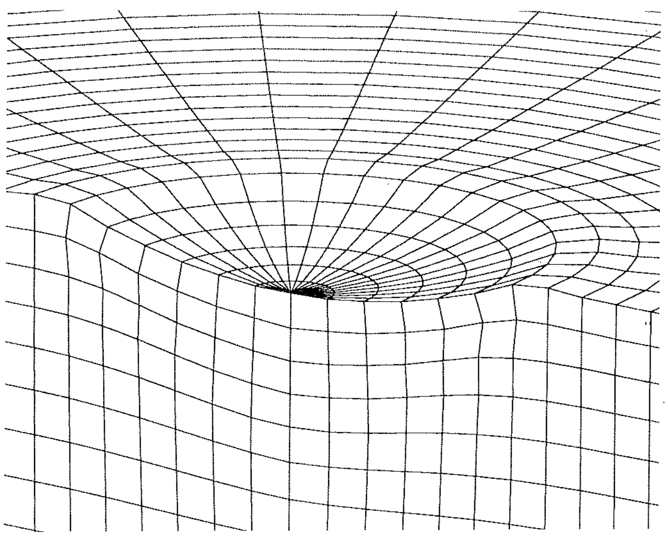

Figure 2. Indentation from single shot impact

These results also show the plastic strain distribution through the top of the plate. The depth of this zone is approximately 0.84mm, measured from the bottom of the crater.

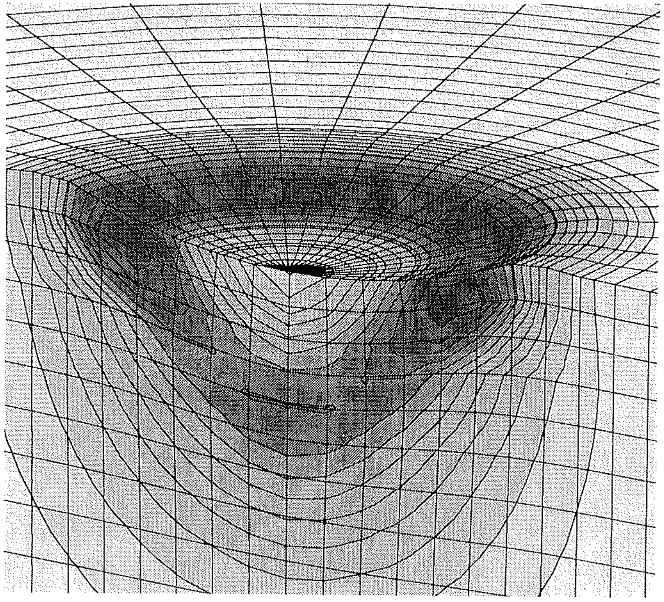

Figure 3. Contours of equivalent plastic strain

We can compare these results with the residual plastically deformed layer and surface deformation predicted by the empirical equations.

It can be seen that, under single shot impacts, the results are in reasonable agreement with the predicted values from equations (1), (2) and (3). The accuracy of these results is clearly affected by the mesh density (in this case the element size is typically 0.05mm) and also by the measuring technique, since the crater lip can rise above the free surface by as much as 15% of the crater depth. Given these approximations, the quality of the results is encouraging. The analysis predicts a crater diameter within 6% of the empirical equation and a depth within 35%. Of more importance is that fact that the plastically deformed material extends to a depth which is within 1% of the empirically predicted value.

Further refinement of these predictive equations may therefore be possible with more detailed modelling of single and multiple shot impacts rather than expensive experimental programs. Similarly there is considerable scope to analyse shot impacts at various angles of incidence, with different material properties, rate-dependent yield and including the effects of temperature dependence of the material and lubrication.

Implicit Analysis

In ABAQUS, the software used for this work, it is possible to create an implicit finite element model with a stress field as part of its initial condition. Subsequent analysis will then provide the deformation and resulting residual stress pattern when all the boundary conditions are removed. The main problems with this approach are that it is difficult to predict the initial stress field created by peening and that it is not possible to set up plastic strains as an initial condition.

An alternative method is to apply loads to the structure that in some way mimic the shot peening process, such that the correct stress field is created. An example of this approach is the 'squeezed layer' technique whereby the mesh near the surface of the component is deformed by applying pressure loads which induce elastic and plastic deformation. On release of these pressure loads, and the constraints on the structure, the residual deformation and residual stress pattern can be found.

The following example illustrates this technique. The test piece, shown in figure 4, consists of an initially flat plate of dimensions 150mm x 30mm x 5mm. A finite element mesh is created with 5 elements through the thickness. The mesh is biased such that the top three elements fall within the plastic layer, the thickness of which is predicted by equation (3).

The basic boundary conditions are designed merely to prevent rigid body motion. One corner is fixed in all translational degrees of freedom, the diagonally opposite corner is fixed in X and Y and one further corner is fixed in Z. These boundary conditions remain in force throughout the analysis. During the loading steps, in which the pressures are applied to each of the upper layers of elements, the nodes at the base of the plate are constrained in the Z direction.

Plate deformation is then achieved by releasing the base node constraints.

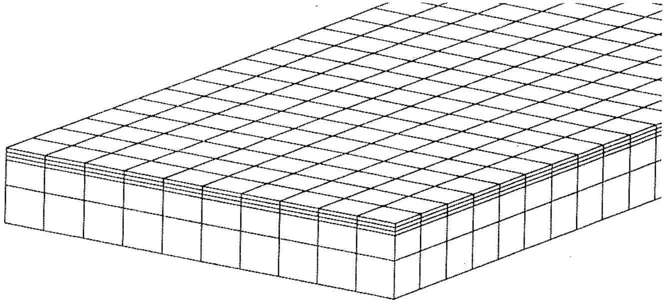

Figure 4. Biased mesh for squeezed layer model

The uniform pressure load is applied to the upper and lower faces of each of the top layers of elements, apart from a border of one element all around the edge which is left unloaded since edge effects can adversely stress the component.

The load causes elastic and plastic deformation in the top three layers of elements and gives rise to the contours of plastic strain shown in figure 5.

Continued on next page

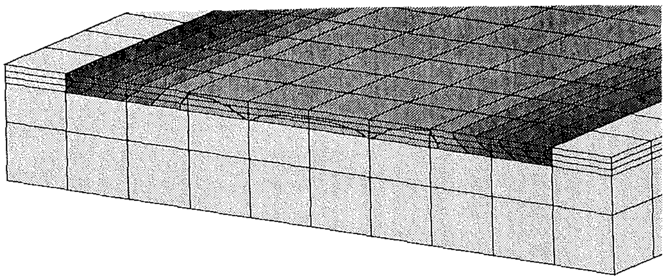

Figure 5. Contours of plastic strain after squeeze load

The residual stress field created by the squeezed layer loading will give rise to plate distortion when the boundary conditions are removed. In this simple example the plate bows outwards as shown in figure 6. Note that the distortions are magnified 200 times so that they can be seen more easily.

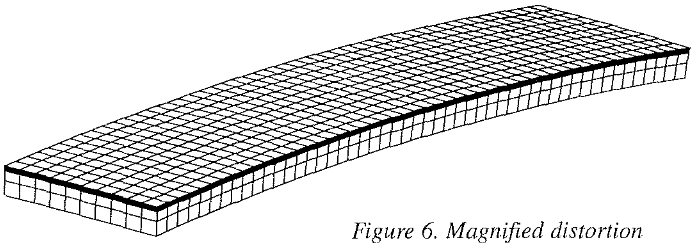

Figure 6. Magnified distortion after squeeze load

Recent work has concentrated on determining the magnitude of the pressure load required to produce a given distortion when the boundary constraints are released.

Initial pressures 30% higher than that required to produce material yielding are applied to the plate model. Subsequent steps are then used to apply additional varying increments of pressure in order to create a variety of final plate deformations.

Test specimens of identical shape and property to those modelled in the finite element analyses are then peened using a variety of peening parameters, i.e. shot size, shot velocity, specimen coverage and media flow rate. The specimen curvature is measured in both the longitudinal and transverse directions and a database of curvature vs peening parameters is created.

This database can then be employed to analyse more complex structures undergoing a non-uniform peening process. Given the data from the explicit analyses and the empirical equations it can be seen that the squeeze layer method can be applied with different pressures and different depths in various parts of a structure, in order to mimic a real peening process.

Conclusion

Simulation of the shot peening process has been carried out using both implicit and explicit finite element techniques. The results have shown that there is good correspondence between the stress field obtained from single and multiple shot finite element analyses and empirical equations. Similarly the squeeze layer technique has proved effective in creating residual stress fields and subsequent distortions in analyses of test specimens.

Note: All the analysis was carried out using the ABAQUS/Standard and ABAQUS/Explicit finite element programs. For further information about these products contact Alan Prior at the above address or telephone +44 (0) 1925 810166.