Recent Developments in Shot Peen Forming

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1. Introduction

In the early nineteen-fifties, Lockheed was already using shot peening to form certain types of aircraft component /1/. During the following decades, further use and development of this process almost certainly remained confined to the aircraft construction industry. In the initial phase, knowledge of the process was purely empirical, but considerable effort has recently been devoted to researching the technological and materials phenomena involved, developing models, and building plant and machinery capable of using computer control systems to achieve increasing component accuracy.

The present contribution reports on these recent developments and on a number of investigations currently in progress at the Institut für Bildsame Formgebung of the RWTH, Aachen. A brief theoretical presentation of the shot peen forming principle is followed by a description of two further variants, in which the process is supplemented by bending and stretching respectively. On the basis of a description of the complex elastic-plastic phenomena associated with shot peen forming, some initial FEM analyses and the problems encountered in connection with them are discussed. As an example, the procedure for calculating the forming parameters in the case of known, simple models is demonstrated and the use of an adaptive model for process controlling discussed. A final section considers some applications for shot peen forming and refinishing, partly developed in collaboration with industry.

2. Principles Underlying the Shot Peen Forming Process and Potential Combinations with Other Processes

Shot peen forming is nowadays generally used where the number of workpieces in a batch is too small to justify investment in mass production processes such as stretching or die bending, or where, for example, three-point bending cannot be used for uni-axially-curved or integrated components. In principle, however, shot peen forming is also suitable for larger curvatures /2/ and, given plant with the appropriate performance capability, for processing large batches.

The extremely flexible shot peen forming process enables difficult uni-axially or multi-axially curved sheet metal geometries, which would require high machine effort and energy consumption if processed by conventional methods, to be produced with elastic pre-stressing similar to that for bending or stretching.

The next section briefly describes the principles of shot peen forming processes with and without pre-stressing.

2.1 Shot Peen Forming without Pre-Stressing

In shot peen forming without pre-stressing - a pure compressive forming operation - the impact of a ball forms an axisymmetric zone of deformation round the centre of the indentation. The deformations caused essentially depend on the component geometry (e.g. length-width ratio or stiffening due to thickness discontinuities or stringers), the direction of rolling, the shot size and velocity and the properties of the material. An appropriate peening strategy, for example line-by-line coverage of the component, enables certain uni- or multi-axial curvatures to be generated /2, 3, 4, 5/.

Fig. 1a shows an idealised distribution of the compressive stresses p_K produced by the impact of a ball on the workpiece, the depth of the plastic zone for an assumed yield and the Mohr's circle for the workpiece surface.

Depending on the intensity of energy of the ball, either convex or concave shot peen forming will result /2/. Convex peening occurs when the impact of the ball causes the workpiece to deform against the direction of peening. If the kinetic energy of the ball is increased to a point at which the workpiece is highly plasticized and deforms in the direction of blasting, the process is termed concave peening.

2.2 Shot Peen Forming with Elastic Bending Pre-Stresses

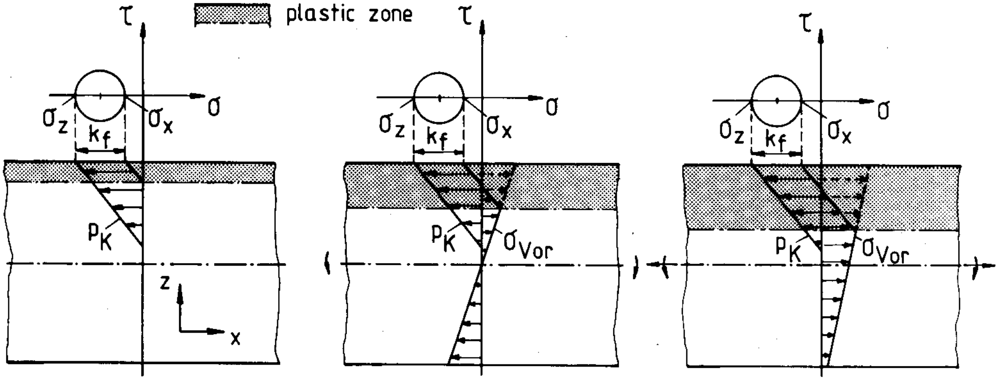
One possible method of manufacturing uni-axially curved components is to employ a bending process. The material must be plasticized throughout its cross-section, or at least in the surface zones, and must in part be bent well beyond the final profile, due to spring-back. Since this sets up tensile stresses on the convex side, damage to the material may result in critical cases.

For these reasons, simple bending is unsuitable for large, complicated parts, for example integral components such as the side shell of the Airbus A 310 /3/. It is necessary to employ a bending process differentiated according to the respective bending moments required, resulting in considerable component handling outlays in addition to the problems already mentioned.

When shot peen forming is combined with a superimposed bending stress σ_{Vor}, the part is elastically pre-stressed in the desired direction of curvature. The necessary pre-stressing forces are well below those required for pure bending. The cost of the necessary bending plant is also relatively low, as the equipment can consist of simple forming plates and hydraulic cylinders (Fig. 1b). The plasticized zone is greater than that of non-pre-stressed components subjected to the same blasting pressure.

2.3 Shot Peening with Elastic Stretching Pre-Stresses

In components which are to be multi-axially curved, the material must flow from the thickness into the length of the material, as in stretching. High stressing forces which cause complete plasticization through the component cross-section are, however, necessary in a pure stretching process. In addition, tools (dies) matched to each component profile are necessary, greatly increasing investment costs.



a) peenforming b) bend + peenforming c) stretch + peenforming

Fig. 1: Stress States and Plastic Zones for Different Shot Peen Forming Variants

With stretching-assisted shot-peen forming, part of the component is pre-stressed (e.g. strip pre-stressing) and the pre-stressed region shot peened. Fig. 2 presents the working principles of a quasi-stretching pre-stressing device. The pre-stressing forces are so low that the pre-stresses remain in the elastic range. A simple milled plate can serve as the contouring tool.

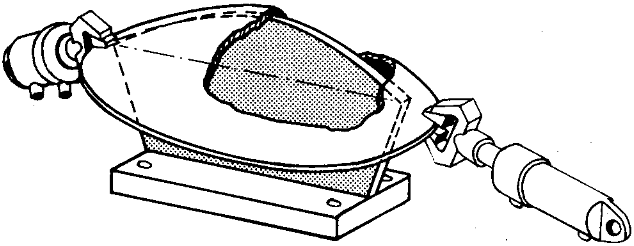


Fig. 2: Concept of a Quasi-Stretching Pre-Stressing Device to Aid Shot Peen Forming

Fig. 1c shows the pre-stressing σ_{Vor} resulting from stretching and the superimposed compressive stress state p_K induced by the shot peening impact. The plasticized zone is deeper than in the cases discussed above. Given a suitable choice of forming parameters, full plasticization of the material without excessive indentation diameters or surface roughness is achievable, allowing material to flow longitudinally. Shell components have been successfully produced at the IBF using this process combination.

3. Theoretical Bases of Shot Peen Forming

3.1 Nature of the Process

Shot peen forming is a sheet metal forming process in which the sheet volume is in general only partially plasticized. Elastic deformations cannot therefore be neglected, as in the case of many other forming processes. The problem under consideration is consequently an elastic-plastic one. As a result of the manufacturing process, the sheet metal to be formed usually has a rolling mill texture , so that the material may generally be regarded as inhomogeneous and anisotropic. In addition, strain hardening of the material is induced by each shot impact. During the forming process, high specific energies are converted into heat, necessitating additional consideration of thermal phenomena. Strictly speaking, therefore, the problem is thermo-mechanically-linked.

In addition, the exchange of energy often takes place so rapidly that the process must be regarded as dynamic rather than static.

All these phenomena occur three-dimensionally, making complete theoretical analysis an extremely complex and indeed at present an insoluble problem.

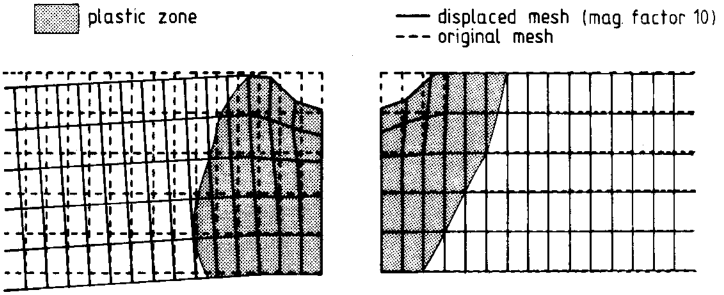
Simplification is therefore required if at least partial predictions of process phenomena are to be obtained with justifiable computation effort.

3.2 Theoretical Description of the Process

The finite element method permits a number of boundary conditions of the process to be determined and simulated. An approach in the recent literature /6/ presents results such as the residual stress distribution and deformation zone for a static penetration test using a flat punch on a plate.

Work carried out at the IBF analyses elastic-plastic penetration in the case of a ball. The primary aim of research was to examine the influence of various boundary conditions such as plane or axisymmetric modelling, supporting forces, penetration depth, strain rate, ball-plate friction and flow stress on deformations, with the aid of the ABAQUS FEM programme package. The objective was to determine boundary conditions which describe the practical process with sufficient accuracy.

The following remarks present some insights and conclusions which can serve as a basis for further computation. Boundary conditions oriented on practical forming parameters were used to carry out a plausibility check of the results. These were, for example, a ball diameter of 6.5 mm, a sheet thickness of 2.5 mm, a penetration depth of 0.06 mm and stress-strain curves for C15 steel. To check plausibility, an initial quasi-static axisymmetric penetration test was simulated. The extent to which results for the deformation processes and the curvature trend differed from those for the FEM computation with plane strain is indicated in Fig. 3. It will be recognized that the deformation zone for plane strain is distinctly larger, so that predictions of other variables calculated by the programme from this case, such as residual stresses, may differ considerably.



a) plane strain

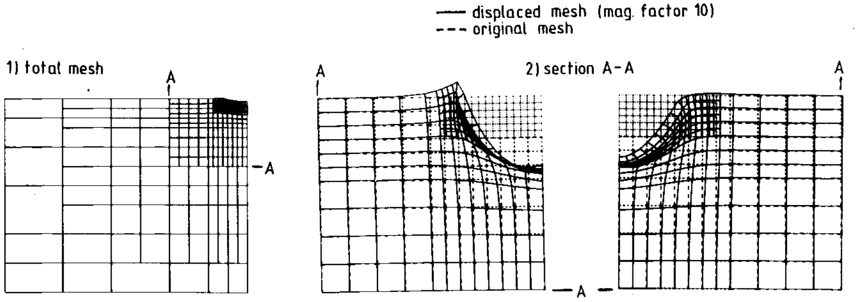
b) axisymmetric strain

Fig. 3: Plastic Zones and Mesh Displacement for Various FEM Simulations

Further research showed that the concave curvatures which can in practice be produced by large penetration depths could not be described by means of axisymmetric penetration tests. For this reason, it is necessary to take the strain rate into account by means of the appropriate stress-strain curve for the material. Estimates showed that strain rates $\dot{\varepsilon}$ in excess of 1000/s are likely to be required under realistic boundary conditions. No stress-strain curves can currently be determined for strain rates of this order of magnitude, however, so that the required curves have to be extrapolated from existing data (max. $\dot{\varepsilon}$ = 90/s).

An extremely fine mesh was generated in order to discriminate between the deformation zones for $\dot{\varepsilon}$-independent and $\dot{\varepsilon}$-dependent computations. Fig. 4 indicates that the strains in the region of the indentation deviate widely from one another. The relatively slight deformation of surface elements in the $\dot{\varepsilon}$-dependent computation may be ascribed to the increased yield owing to the high strain rate. As shown in the illustration, this produces retraction at the boundary of the indentation, whereas the $\dot{\varepsilon}$-independent calculation indicates heaping at the same position.

If the strain rate is taken into account, concave curvatures can also be calculated with deep indentations for the axisymmetric case /9/.



a) $\dot{\varepsilon}$ - constant (static)
$k_f = (660 \cdot \varepsilon_v + 340)\ \mathrm{N/mm^2}$

b) rate ($\dot{\varepsilon}$) dependent
$k_f = (660 \cdot \varepsilon_v + 310) \cdot ((\dot{\varepsilon}_v / D)^{1/p} + 1)\ \mathrm{N/mm^2}$
$D = 10570$, $p = 4{,}87$

Fig. 4: Comparison of FEM Results Using $\dot{\varepsilon}$-Independent (a) and $\dot{\varepsilon}$-Dependent (b) Stress-Strain Curves for a Section of the Mesh

This research was intended to demonstrate that two-dimensional (2D) FEM analysis of a ball indentation is realistic only if axial symmetry is assumed. Results indicate that quantitative residual stress calculations using 2D models are of little practical use. Surface structure, hardening and strain distribution can already be calculated with sufficient accuracy by the 2D finite element method given a knowledge of the strain-rate- and temperature-dependent stress-strain curves and the ball-plate friction.

The objective of future research will be to simulate the effects of a number of axisymmetric indentations by means of a three-dimensional elastic-plastic FEM calculation, in order to predict the effect of shot peen forming on component properties (especially residual stresses).

4. Model for Uniaxially Curved Components

In order to be able to pre-calculate parameters for practical shot peen forming and determine technical feasibility, cost-effectiveness and certain component characteristics such as surface roughness and coverage, simple calculational models are necessary.

The results presented in /2, 3/ on the effects of the impact of one ball of shot on a plate in terms of velocity fields and strains are used as the basis for a simple micro-computer model (KSU model), which currently enables shot peen forming parameters for uni-axially curved components to be pre-determined and relationships to be displayed graphically /7/.

The KSU model is based on a simplification of the deformation zone produced by indentation in terms of an axisymmetric cylinder, and proceeds by way of a kinematically valid velocity field superior to that described in /2/ to an strain distribution which agrees well with measured values. The strains produced by a single indentation are transferred to a multiple-indentation case with the aid of the coverage, allowing an approximation of the component curvature and the machine setting parameters.

4.1 Input Variables

The input variables required for the model are sheet thickness (s), ball diameter (d_K), indentation diameter (d_E), adjusting factor (A_f) and final curvature (K).

It is necessary to note the extent to which these forming parameters influence one another and the advantages and disadvantages to be anticipated. The following example may serve to clarify the relationships involved. If the shot velocity is high the indentation depth will be large and the coverage required to produce a specific component curvature will be lower than in the case of a low shot velocity. In consequence, especially if strongly prestressed components are being formed, short production times can be achieved. This peening strategy involves a risk of under- or over-peening the part, i.e. of either exceeding the desired final curvature or failing to attain it. The subsequent re-finishing work can quickly render the process uneconomic.

Investigations have shown that for convex curves the ball radius should be in the order of the sheet thickness in order to achieve a useful conversion of the kinetic energy of the ball into forming energy. If the abrasive is too small, the intensity of the impacts is insufficient to generate the curve economically. If the abrasive is too large, the majority of the energy is wasted in vibration or the component is fully plasticized, creating a concave curvature.

Since the velocity of the ball forms one measure of energy, but velocity measurement demands considerable technical effort, the mean indentation diameter of the impression left in the workpiece is measured as a substitute variable, using a simple measuring device (e.g. a micrometer lens), and is expressed as a function of blasting pressure. In addition to machine limits, a maximum permissible indentation depth R_{th} given by the function for calculating the chord of a circle:

$$R_{th} = 0.5 \left(d_K - \sqrt{d_k^2 - d_E^2} \right)$$

can be used as a criterion for selecting the indentation diameter. As the simple KSU model is incapable of determining the flow resistances in the component, which essentially depend on geometry and pre-stressing, an adjusting factor A_f is defined. This is discussed in more detail in Section 5. For simple rectangular plates which are to be curved in a single axis, this factor is, for example, roughly 0.5. The factor increases with rising prestressing.

The adjusting factors for new components are roughly approximated from a bank of existing data for similarly-produced components /7/. Precise definition takes place during the process, as described below. Pre-computation using FEM would also be possible.

4.2 Nomogram

The KSU model can present the relationships between the forming parameters in graphic form. Fig. 5 shows a nomogram (worksheet) of this type for a ball diameter of d_K = 4 mm. This may serve as an example of the procedure for calculating the forming parameters. The adjusting factor may be taken as A_f = 1 and the shot flow as m_t = 16.6 kg/min.

Given a sheet thickness of s = 4 mm (1) as in Fig. 5 and a final curvature K = 5 * 10^{-4} mm^{-1} (2), the coverage required to produce the component curvature with a selected indentation diameter of d_E = 0.6 mm (3) is calculated as A^*_M = 54 % (4).

In the upper half of the figure, the blasting time for a component area of 1 m^2 of roughly t_{gm} = 45 min (6) is read off at point (5). The mass per surface required to determine the machine set points is derived from point (7) as m_t = 0.7 g/mm^2.

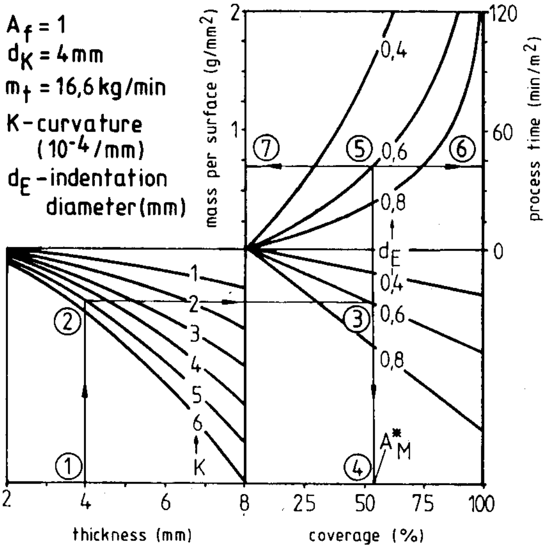


Fig. 5: Nomogram for Pre-Determination of Shot Peen Forming Parameters

Using the same procedure, it can be seen from the nomogram that, for example, the required curvature cannot be produced given a selected indentation diameter of $d_E = 0.4$. By altering the input variables, a cost-effectiveness analysis and an estimation of such component characteristics as coverage, surface topography and curvature can be performed, as can an analysis of process feasibility in terms of plant capabilities.

Calculation of the forming parameters with the aid of the KSU model is currently restricted to uni-axially curved components. Where components of uneven thickness are to be formed, a partial calculation is carried out for the uniform-thickness sections of the component.

5. Computer-Aided Forming Process with Process Controlling

Sheet materials or blanks are usually subject to certain tolerances in respect of residual stresses, material parameters, geometries, etc., which influence forming behaviour to a greater or lesser degree. During production, additional, possibly undetected machine disturbances may occur. Controlling of actual bending behaviour, which differs from component to component, if possible in computer-aided form, permits early intervention in the production cycle and, ideally, can avoid rejects.

The controlling means known from the literature are primarily concerned with permanent controlling and stabilisation of the set process parameters. The CNC airfoil shot peen forming and hardening machine presented in /8/ may serve as an example. The component contour is checked after peening using contour headers.

In the process presented here, an adaptive process model /9/ is used to calculate the curvature for the forming strategy being employed, i.e. the desired curvature for each peening cycle is known. In order to be able to intervene appropriately in the process, there must still be sufficient possibilities for altering the parameters after disturbances to the cycle in such a way that the component will not be over-peened. This is achieved by dosing the calculated coverage in a succession of peening cycles. If deviations between actual and desired values occur after individual cycles, the other process parameters, such as the mass per surface or the shot velocity are corrected accordingly.

It is possible to measure curvature during the cycle, for example with a curvature meter. This, however, requires interruption of the process and unclamping of elastically pre-stressed components. In the latter case, it is also possible to measure the changes in pre-stressing forces as they are relieved during processing and correlate them with the current curvature by means of calculated models or empirically determined relationships.

If the component is pre-stressed to its final contour, the objective is to continue peening until the pre-stressing forces have been reduced to zero. If the pre-stressed contour does not correspond to the final contour, a pre-calculated final force must be attained.

After forming, the quotient of the simulated coverage A_M^* and the actual coverage A^* for the achieved curvature is calculated. This quotient corresponds to the adjusting factor A_f. It is used to adapt the model to other components of the same kind and is fed into the data bank referred to above.

6. Sample Applications

The following section presents some new examples of components processed by shot peen forming or straightening (cf. /4/).

Fig. 6 shows an example of an integral component of a cylindrical segment of the Ariane 4 rocket during production. The part is elastically pre-stressed and is being peened from the stringer side. The process is computer controlled via the force measuring device. Parameters are selected to ensure that no kinks of the type caused by three-point bending can occur.

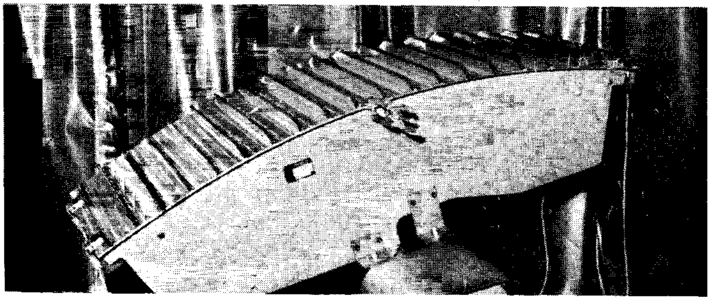


Fig. 6: Integral Part Pre-Stressed to Its Final Radius During Shot Peen Forming

Fig. 7 depicts a cap with a radius of approximately 5000 mm produced from a circular blank (d = 900 mm) by concave peening. In this instance, the part was formed without pre-stressing, continual rotation of the blank and simultaneous movement of the jet being used to generate a spiral peening path and a decrease in coverage towards the edge of the part.

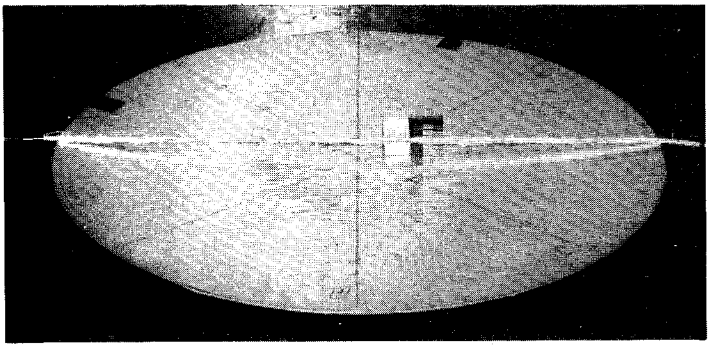


Fig. 7: Example of Concave Spherical Shot Peen Forming

Two further examples indicate the possibility of satisfying tolerances not adhered to by other forming processes through appropriate shot peen dressing. Fig. 8 shows a steel component with a wall thickness of 5 mm, on which the gap measurement (arrows) was reduced from 5 mm to 0.3 mm by partial shot peening.

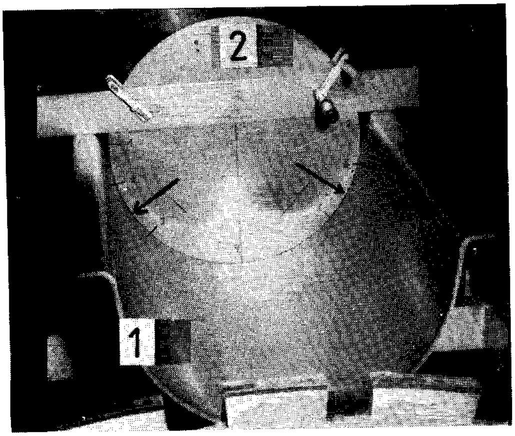


Fig. 8: Steel Component (1) Dressed to Specified Tolerances, with Measuring Template (2)

In another example (Fig. 9), steel rings with wall thicknesses of 11 mm and heights of 39 mm were shot peen re-finished to bring deviations from the average diameter within specified tolerances.

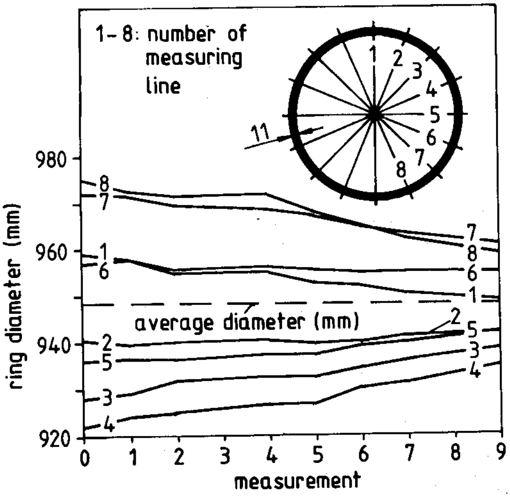


Fig. 9: Changes in the Diameter of a Steel Ring During Targeted Local Shot Peening

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