SHOT-PEEN-FORMING, RECENT TECHNOLOGICAL AND THEORETICAL DEVELOPMENTS

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ABSTRACT

Shot-peen-forming and shape-punch-forming combined with elastic prestraining are methods for forming large integrally stiffened panels with very different wall thicknesses. A theoretical model based on the plastic flow of material shows how to calculate the curvature.

KEYWORDS

Shape of tools, elastic prestraining, forming strategy, curvature of sheet parts, modelling, forming process control.

INTRODUCTION

Shot-peening for the purpose of metal forming (KSU = shot-peen-forming) as well as shape-punch-forming (FSU), a method basically related to shot-peening, have been increasingly used in the production of structural parts for the aircraft and space industries in the Federal Republic of Germany in recent years.

Results of the shot-peen-forming process concerning the flow of material and the deformation zone, strain rates, strains and stresses as well as forces, temperatures and residual stresses in dependence on the number of shot-impacts have already been discussed at the 1st International Conference on Shot Peening (Kopp and Hornauer, 1982) and elsewhere. In the same way it was possible to demonstrate essential characteristics for the geometry of sheets by this method (Hornauer, 1982).

The influencing of structural part geometry by control of the local flow of material is now another approach employed to raise the precision of the method, to use the characteristics of the methods entirely (saving on preparation and reworks as well as on a prestraining device), and if possible to improve also the mechanical properties. Hence, the recognition of these interrelations has been studied at our institute of the University of Aachen in recent years.

The aim of the research work is the precalculation of the integral effect on the entire structural part and the achievable geometry by applying the knowledge of the local processes in shot-peen-forming and shape-punch-forming.
process. Further, it is intended to improve the reproducibility of the method by adaptive control of the forming process.

FACTORS INFLUENCING THE MATERIAL FLOW

The essential process parameters which influence plastic strains are: elastic prestraining of the structural part, selection of the metal forming tools with an appropriate contact zone and the selection of the metal forming strategy suitable for the structural part.

Prestraining

Many curved structural parts in aeronautics and astronautics show a curvature merely in one direction. To suppress the characteristic curvature in the second direction, the structural part can be prestrained elastically in the direction of the desired curvature. In this way the state of stress shown in Fig. 1 arises.

The stress in the x-direction results from the lateral contraction. In this way the structural part would be curved up in the x-direction (anti-clastic-effect). This is prevented by the forces of prestraining, by which, however, tensile stresses in the x-direction arise at the convex surface. The indentation of a ball into a so prestrained structural part results in an elliptical indentation with the long main axis in the y-direction. In a curved structural part without prestraining the long elliptical main axis must be in the x-direction. The dependence of the ellipse shape on prestressing (Fig. 1) is shown in Fig. 2, and the dependence of the curvature relation $K_y/K_x$ is shown in Fig. 3.

Fig. 1. Prestressing principle (a) for the influence of the local flow of material and (b) the stress circles of Mohr at convex surfaces.
Fig. 2. Relation of indentation diameters to the prestressing (parameter: ball diameter $d_K$).

Material 7075 T73
Geometric relation $l_y/l_x = 1.2$
Thickness of the sheet $s = 3.9$ mm

Fig. 3. Curvature relation $K_y/K_x$ to the prestressing in $y$-direction for two different ball diameters (variation of ball velocity and mass per surface)

Tool Geometry

For thick-walled structural parts and structural parts with gradual wall thickness and different profiles expensive prestressing equipment must be established because of very high forces required for prestressing or as a consequence of the curvature gradients, produced by the moment of inertia break in order to keep the curvature relation within the desired limits. The so-called shape-punch-forming can present an alternative. As known from the fields of the metal forming processes - forging or rolling - the geometrical relation of the tool and the workpiece exert an influence on the flow
resistance and hence on the local flow of material. Shape-punch-forming is based on these principles (Fig. 4). By the impulse exchange of a pneumatic pin with a shape-punch that is guided in special ways over the structural part, the desired uniaxial curvature can be achieved without prestraining. Figure 5 shows a comparison of surfaces after shot-peen-forming and shape-punch-forming.

![Fig. 4. Shape-punch-forming.](image)

**Forming Strategy**

The influence of the nozzle path on the geometry of the structural part has already been discussed in principle before. In the following some quantitative results, determined in the mean time, are presented. By this it becomes evident that the forming strategy, that is for example the form of the nozzle or of the shape-punch, can be specifically used for the control of the curvature relation.

The curvature of a structural part will differ if it is formed in one big step or in several little steps (Fig. 6). Not only the method of treatment, but also the sequence of the peening operations is of importance. The same is true for the sequence of these processes.

**MODEL FOR THE CALCULATION OF THE PARAMETERS OF THE FORMING PROCESSES KSU AND FSU**

The following explanations refer to the elemental model conceptions of the shot-peen-forming and shape-punch-forming processes. The basic model was already introduced at the 1st International Conference on Shot Peening (Kopp and Hornauer, 1982).

This model depends on a connection of the force indentation relation described by Hertz with the force for plastic indentation in a rigid plastic solid. This results in a correlation of the geometry of the area between the tool (ball or shape-punch) and the workpiece and the relevant process parameters (Fig. 7). Figure 8 shows further assumptions, concerning the depth of the plastic zone.
Fig. 5. Structure of the surface of shot-peen-formed and shape-punch-formed structural parts.

From this knowledge velocity fields can be developed for different limiting conditions which make the determination of the local strain distribution and finally the predetermination of the curvature of the structural part possible. Figures 9-11 show the velocity fields in the cases of a flattened ball indented in stress-free material (Fig. 9), a flattened ball indented in material loaded with stress (Fig. 10), and a flattened cylinder indented in material free of stress (Fig. 11 and analogous Fig. 10), as well as the equations for the strain rates. Figures 12, 13 shows the corresponding strain distributions. A comparison between measured and calculated values in the case of a ball indented in stress-free material is shown in Fig. 14.

In this connection there is a conformity of radial strain distribution, produced below the ball centre, with the one calculated by the model except in the surface area. This was considered at the 1st International Conference on Shot Peening (Kopp and Hornauer, 1982). In addition, the radial strain distribution concerning the whole plastic field has since been experimentally determined (Fig. 15).
Fig. 6. Peen-forming sheets with the same mass of shots per surface but with locally different sequences of nozzle paths.

Fig. 7. Calculation of the relation indentation diameter to the tool diameter with the aid of a function, based on experimental results (produced with one tool diameter).

<table>
<thead>
<tr>
<th>Tool</th>
<th>Ball</th>
<th>Cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prestressing</td>
<td>= 0</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>Deformation zone</td>
<td>Cylinder</td>
<td>Elliptical cylinder</td>
</tr>
<tr>
<td>(idealize)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Velocity field</td>
<td>Axial</td>
<td>Elliptical</td>
</tr>
<tr>
<td></td>
<td>symmetrical</td>
<td></td>
</tr>
<tr>
<td>Depth of the</td>
<td>$h_0 \cdot d_E$</td>
<td>$d_E &lt; h_0 &lt; d_E$</td>
</tr>
<tr>
<td>plastic zone</td>
<td></td>
<td>$h_0 = f(d_{Cy}, d_E)$</td>
</tr>
</tbody>
</table>

Fig. 8. Assumptions of the model in the case of different forming conceptions.
Fig. 9. Axial symmetrical velocity distribution within the deformation zone.

\[ v_r = \frac{v_k \cdot r \cdot z}{h^2} ; \quad v_z = \frac{-v_k \cdot z^2}{h^2} ; \]

\[ \xi_r = \frac{\partial v_r}{\partial r} ; \quad \xi_z = \frac{\partial v_z}{\partial z} ; \quad \xi_{\theta} = \frac{v_r}{r} \]

Fig. 10. Elliptical velocity distribution produced by prestressing a workpiece.
Assumption: deformation zone = rectangle (plane strain)

\[ v_x = 0; \quad v_y = \frac{2v_w z y}{h^2}; \quad v_z = -\frac{v_w z^2}{h^2} \]

\[ \dot{e}_z = 0; \quad \dot{e}_y = \frac{\partial v_y}{\partial y}; \quad \dot{e}_x = \frac{\partial v_y}{\partial z} \]

Fig. 11. Plane velocity distribution within the deformation zone.

\[ dt = -\frac{dh}{v_x}; \quad \varepsilon = \int_{t_0}^{t_1} \dot{\varepsilon} \, dt = \frac{h_i}{h_o} \int \dot{\varepsilon} \, \frac{dh}{v_x} \]

\[ \varepsilon_r = \varepsilon_0 = z \left( \frac{1}{h_i} - \frac{1}{h_o} \right); \quad \varepsilon_z = -2z \left( \frac{1}{h_i} - \frac{1}{h_o} \right) \]

Fig. 12. Calculated axial symmetric strain distribution within the deformation zone.
\[ \varepsilon_x = 0; \quad \varepsilon_y = 2z \left( \frac{1}{h_i} - \frac{1}{h_o} \right); \quad \varepsilon_z = -2z \left( \frac{1}{h_i} - \frac{1}{h_o} \right) \]

Fig. 13. Calculated plane strain distribution within the deformation zone.

Workpiece: aluminium 7075 T 7351
Ball: 100 Cr 6; d = 18 mm

Strain \( \varepsilon_r, \% \)

Surface

Depth below surface (mm)

| \( v_x \) | \( v_y \) | \( v_z \) | \( d_e \) |
| 9.3 ms\(^{-1}\) | 14 ms\(^{-1}\) | 30 ms\(^{-1}\) | 2.7 mm |
| 39 ms\(^{-1}\) | 3.4 mm | 4.7 mm | 5.5 mm |

Fig. 14. Comparison of calculated and measured radial strain below the indentation centre.

This progress of strain is considered in the model by a corrective factor, as shown below. A more precise local precalculation of the metal forming process as well as the effect on the structural part will be carried out in the future by the aid of finite elements. Based on the knowledge within the single plastic zone, the curvature of the whole structural part can be predetermined with the aid of the following model conception for different tool geometries.
Specimen: aluminium 7075 T 7351; 
\( d_f = 5.5 \text{mm} \)

Ball: 100 Cr 6; \( d = 18 \text{mm} \)
\( v_k = 39 \text{mm/s} \)

Fig. 15. Local radial strain distribution at different points below a ball indentation.

Each indentation of the tool plasticizes a small field of the sheet and produces a characteristic strain distribution for example, \( \varepsilon_{rpl} \) (Fig. 16a). The model for the calculation of the structural part curvature assumes that the effect of this strain distribution on the curvature should be the same as the effect of a fictive strain, divided equally on the whole surface plane of the structural part (Fig. 16b).

The strain distribution \( \varepsilon_{rpl} \) is given by the multiplication of the strain distribution \( \varepsilon_{rpl} \) of one indentation by the degree of coverage \( A^* \). In this connection the actual changing progress of strain must be considered in the plastic zone by a corrective factor. This factor is still determined empirically at the moment. Presuming plane cross-section in the structural part, the permanent strain \( \varepsilon_{rblo} \) can then be calculated at the surface of the structural part. In doing so, one proceeds from the conception that the structural part consists first of all of single, according to the plastic strain distribution, different extended layers. Corresponding to the condition of plane cross-sections, these layers must be elastically linear strained or compressed across the whole cross-section of the structural part (Fig. 16b). The curvature of the sheet can then be calculated from the equation

\[
R = \frac{(s - k)}{\varepsilon_{rblo}}.
\]

A comparison of calculated and measured values is shown in Fig. 17. A further improvement of the tolerances of the structural part can be achieved, above other things, by an adaptive control that is still in development at the moment. A testing installation and first results for the analysis of the connection between the elastic and plastic processes are shown in Fig. 18. In this way the manufacturing flow at integral parts should be further optimized in future, e.g. as presented in Fig. 19.
(a) Radial strain in the plastic zone, calculated according to the rigid-plastic model.

(b) Linear radial strain across the whole thickness of the specimen.

Fig. 16. The transformation of the rigid-plastic strain into a linear distribution across the whole thickness of the specimen (KSU and FSU).

<table>
<thead>
<tr>
<th>Degree of coverage $A^%$ (%)</th>
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<tbody>
<tr>
<td>Ball diameter $d_e=6.50\ mm$</td>
</tr>
<tr>
<td>Indentation diameter $d_I=1.54\ mm$</td>
</tr>
<tr>
<td>Corrective factor $X=0.43$</td>
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<tr>
<td>25.5</td>
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Fig. 17. Axial symmetric curvature of sheets in comparison with the model calculation as a function of mass per surface.
Fig. 18. Control of the prestressing forces in the forming operation (principle).
Fig. 19. Shot-peen-formed external fuselage shell of the Airbus A310.

REFERENCES
