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Dimensional Control of Stampings by Grid Strain Measurement

This paper proposes that the dimensional control of stampings requires not only surface measurement but also measurement of the strain distribution in the part. A simple model of forming a smooth panel over a die is presented and used to show how small changes in variables such as friction can affect "shape fixability" and dent resistance. It is argued that this variability in stampings can be controlled by comparing a measured strain distribution with one specified in the design stage.

Introduction

The forming of smooth autobody panels has been reviewed by Hayashi and Nakagawa (1994). They employ the Yoshida classification which divides defects into those of (i) fracture, (ii) fittability and (iii) shape fixability. Fracture is splitting or necking in the side-walls or flanges, or, more rarely, over the face of the punch. Fittability refers to any deviation from the designed shape and may also be described as dimensional accuracy. Shape fixability is concerned with the robustness with which the shape is imposed and retained in the part; this may include the stiffness of the panel to transverse loading, "oil-canning" and shape changes occurring after trimming.

At present, control of the stamping process is based on a number of inspection methods. Fracture or necks are ascertained by visual inspection; this is essentially a "go, no-go" method, but proximity to failure can also be found from circle grid strain measurement at a known critical point. Fittability is determined by clamping a panel in a fixture and carrying out gap measurement. Difficulties arise because, in some cases, the stamping does not have a unique shape but can easily be twisted and warped through a family of shapes and it may not be clear how much force is applied to make the panel conform during measurement. Waviness may be checked using various optical methods of enhancing rippling but judgement is often subjective and the problem may not be apparent until after the panel has been trimmed or assembled. Recurring difficulty with production control of smooth stampings suggests that, in addition to existing methods of surface inspection, it may be necessary to specify the magnitude and distribution of strain over the smooth, exposed parts of the panel.

At the time the part is designed, its shape, in terms of its relation and assembly with other panels, is clearly a matter of geometric specification. There are, however, functional considerations such as the strength of the sheet for dent resistance and the transverse stiffness of the panel (against flutter and oil-canning). These are not specified by geometry or shape, but depend on the strain distribution in the part. Dent resistance also depends on strain hardening. Transverse stiffness, as indicated by Bhattacharyya et al. (1988), is related to residual stress distribution which depends, in turn, on the strain distribution at the end of forming.

In this paper, a very simple model of forming a smooth panel over a die is presented. It is used to show how strain distribution is affected by variables such as friction and that some strain distribution should be specified during design in order to determine the correct adjustment to the tool shape to compensate for springback. A problem, identified by Tan et al. (1992), is that strain measurement can only be used for production control if there is a rapid method to carry it out. The simple analysis is used here to determine the requirements of such a strain measuring system and some suggestions are made about a suitable method.

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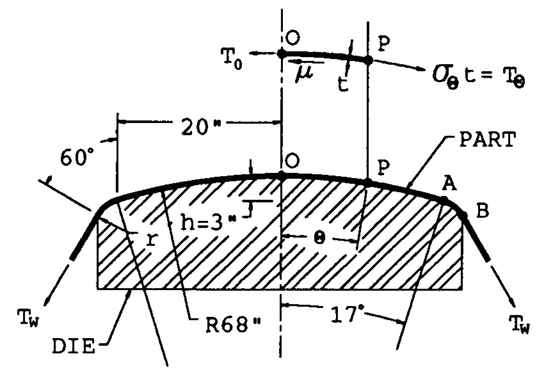

Fig. 1 Simplified forming die

A Simple Model of the Process

Although the forming of outer body panels is a difficult process, the main features can be illustrated well by a simple analysis. We consider the two-dimensional forming of a sheet over a form-die as shown in Fig. 1. This illustrates only part of the forming process; the design of the binder, draw-beads, and blank-holder is not included. The variables in the process are:

Material. The sheet has an original thickness, t_0, and the deformation process is plane strain. A Tresca yield criterion is assumed. For a typical strain hardening sheet, the stress σ_θ at a point P, defined by the angle θ, is,

$$\sigma_\theta = K(\epsilon_o + \epsilon_\theta)^n \tag{1}$$

In the example, $K = 75$ ksi, $\epsilon_o = 0.008$ and $n = 0.22$, and these values are typical for fully annealed, drawing quality steel sheet. The stress, strain curve is shown in Fig. 2.

Geometry. The shape is defined by the profile radius, R, corner radius, r, and the angle of the side wall as shown in Fig. 1, where $R = 68$ in, $r = 2$ in and $\theta_b = 60$ deg. We choose the semi-width between the trim lines as 20 in and the initial sheet thickness, t_o, is 0.03 in.

Tension. The current thickness of the strip is, t, and, from the condition of incompressibility, the thickness strain, $\ln(t/t_o)$, is equal and opposite to the strain along the strip, ϵ_θ; therefore,

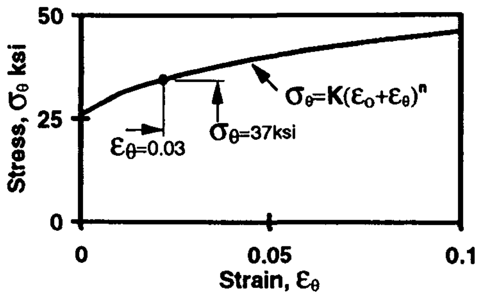

Fig. 2 Stress strain curve

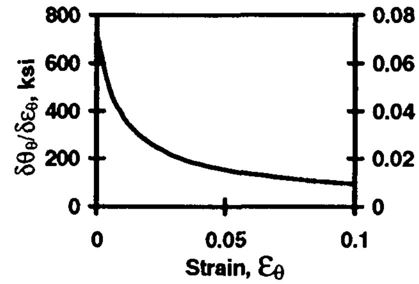

Fig. 4 Slope of the stress strain curve and springback as a function of strain

$$t = t_o \exp(-\epsilon_\theta) \tag{2}$$

The tension, T_θ, is defined as the force per unit width; i.e. $T_\theta = \sigma_\theta t$, or

$$T_\theta = K t_0 (\epsilon_0 + \epsilon_\theta)^n \exp(-\epsilon_\theta) \tag{3}$$

Friction. As the sheet is being stretched out from the centre against friction between the sheet and the die face, the tension will increase from T_o at the center to T_θ, where,

$$T_\theta = T_o \exp \mu\theta \tag{4}$$

The use of a Coulomb friction coefficient, μ, is known to be an approximation. A range of values from 0.05 to 0.4 is given by Wagoner et al. (1994) and in this example we take $\mu = 0.15$.

Minimum Strain. A starting point in the process design is often the degree of strain hardening required in the sheet for dent resistance; this determines the minimum strain level which, for the purpose of illustration, is taken as 0.03 (3 percent), giving a yield strength after forming of 37 ksi, as shown in Fig. 2. The tension and strain over the rest of the sheet may be calculated using Eqs. (3) and (4) and is shown in Fig. 3. Substituting the values of $\theta = 17$ deg at A and $\theta = 60$ deg at B, we see that the strain only increases by 1% over the face of the form die but rises rapidly to 10 percent at B. The corresponding tensions are 1,063 lbf/in at the centre, 1,112 lbf/in at A and 1,244 lbf/in at B.

Springback. An approximate relation for the springback, Δh, in a two-dimensional strip stretched over a form-die between O and A in Fig. 1 is given by Marciniak and Duncan (1992) as,

$$\Delta h = h(\delta\sigma/\delta\epsilon)/E, \tag{5}$$

where $\delta\sigma/\delta\epsilon$, the slope of the plastic stress/strain curve, is very sensitive to the strain level as shown in Fig. 4. E is the elastic modulus. The overcrown, Δh, which needs to be applied to the form die is also shown; this is calculated from Eq. (5) using $h = 3$ in. and $E = 30{,}000$ ksi. Clearly, to design the overcrown, Δh, in the form die, the strain must be specified and to achieve the correct shape in the part, this strain must be reached in the forming process. In the example, for $0.03 < \epsilon_\theta < 0.04$, the overcrown is about 0.02 in which is very small, but the two-dimensional model may not be very representative of springback in three-dimensional stampings.

Edge Tension. The tension, T_w in the side-wall was found from Eqs. (3) and (4) to be 1,244 lbf/in. The maximum allowable tension in the side-wall is related to the tensile strength of sheet; theoretically the strip will reach a maximum load and neck at $\epsilon_o + \epsilon_\theta = n$, or, $\epsilon_\theta = 0.212$, corresponding to a tension of 1,305 lbf/in. In the example, the side-wall strain is about 0.1 compared with the failure strain of 0.212, so there would seem to be a reasonable margin of safety in the operation, but this is not the case. The maximum tension that the side-wall can sustain is, from above, 1,305 lbf/in., so that the actual safety margin in terms of force or tension is only 5 percent.

Minimum Strain. The strain at the center $\epsilon_{\theta 0}$, is very sensitive to the effect of friction. In the example given, a side-wall tension of 1,244 lbf/in and a friction coefficient of 0.15 give a strain at the center of 0.03. For the same tension, the strain corresponding to different friction values is shown in Fig. 5 and ranges from about 0.07 for very low friction to less than 0.02 (2 percent) for moderate friction. Figure 4 shows that as this strain becomes small, the springback will increase rapidly.

Application to Design of Actual Dies

The design of a real die will be more complicated than in the two-dimensional example, nevertheless similar principles apply. The minimum strain to satisfy the strain hardening or strength requirement must be specified first. Following this, some contours of strain over the face of the part must be determined either by modelling or comparison with similar parts. The contours of strain in a deck lid, reproduced from Bhattacharyya et al. (1988), are shown in Fig. 6 and once the minimum strain has been specified, it should not be difficult to anticipate

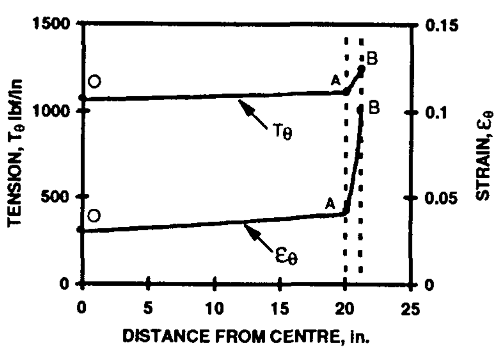

Fig. 3 Sheet tension and strain across half of the die

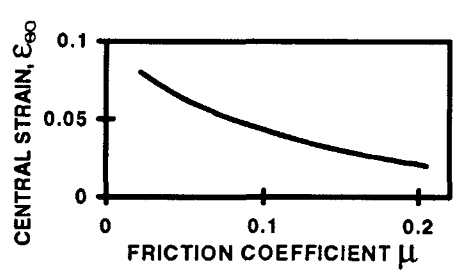

Fig. 5 Variation of strain with friction

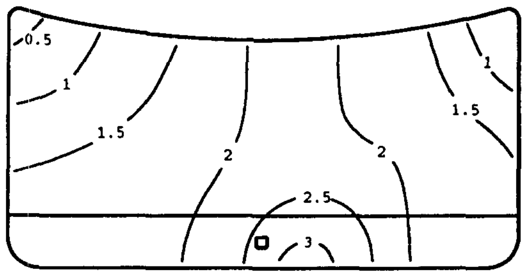

Fig. 6 Contours of maximum strain, %, in a deck lid from Bhattacharyya et al., 1988

the strain distribution over any smoothly curved part using examples such as Fig. 6 as a guide.

The simple analysis indicates that in smooth outer body panels, membrane strains will need to be determined over the face of the part in the range of $0.005 < \epsilon < 0.10$; if the strain is less than 0.005 (0.5 percent), the springback, as shown in Fig. 4, is likely to be excessive. In most smooth panels the minimum strain should be greater than 1 percent, so that the accuracy needed in measurement is not necessarily very great. If a grid of lines of 2 in. pitch is used, a strain of 0.5 percent corresponds to a displacement of 0.01 in and any measurement system that can locate the grid position to within this accuracy would be satisfactory. In the following sections, the techniques for measuring strain are discussed.

Large Strain Measurement

In two-dimensional or axisymmetric deformation, the three principal strains at a point can be determined by measuring thickness and assuming incompressibility. For more general forming processes, some kind of grid marking on the sheet is necessary. The use of grid circles introduced by Keeler (1971) is well-established and is most suitable for measuring strain at a point. If only the initial and final configuration of a grid is known, some assumption must be made about the strain path as discussed by Marciniak and Duncan (1992). The calculation of strain from an array of points or from the intersection of grid lines marked on the sheet was simplified by Sowerby et al. (1982) and this work has been utilized by Nihill and Thorpe (1984), Vogel and Lee (1989) and Tan et al. (1992). The differences in published work are mainly in the technique used to measure the grid and in smoothing, averaging and displaying the results. Provided the calculation leads to the evaluation of the Green large strain tensor, the method used should be selected on the basis of convenience. Measurement techniques fall into two categories, those which employ some kind of co-ordinate measuring device, and those which are based on image analysis and photogrammetry as, for example, by Lee (1994). It is not proposed to review these here but rather to suggest one approach that is suited to the measurement of smooth panels.

Grid Marking and Measurement. A convenient grid for smooth panels is a set of perpendicular lines spaced from 1 to 2 in apart on the blank. After forming, an automatic following system in a co-ordinate measuring device could be used to establish in a computer graphics system a wire mesh model of the formed part. This has the advantage that sheet metal engineers can readily visualize the forming process from the deformed grid and also that systems already exist to convert the information into different outputs such as strain contours, arrow diagrams and forming limit diagrams. It should also be pointed out that the wire mesh diagram of the deformed grid can also be produced easily at the design stage if some strain distribution is assumed. It is anticipated that once the use of overall strain measurement becomes more widespread, typical strain distributions in successful parts will be seen to conform to some simple rules and this will lead to appropriate specification of strain contours at an early stage of design. Techniques also exist for quantifying strain contours or strain signatures. In this way, it is possible to give precise limits for acceptable forming and to move away from the subjective judgments often used in existing practice.

Many stampings are extremely flexible before assembly. Such parts have no single shape but, as mentioned, a family of shapes all linked by easy deformation processes. For assembly purposes, it is necessary to know whether one of these family of shapes is the design shape. The theory of surface deformation, following Duncan and Duncan (1982), suggests that these easy modes of deformation in a flexible stamping are inextensional ones, i.e. the surface twists or warps without lines in the surface stretching or shrinking and without changes in surface angles between lines. Thus for a flexible stamping, the same overall strain distribution would be measured in the sheet for any position in this family of shapes; this greatly simplifies the fixturing of the part in the measurement device.

Concluding Remarks

It is inherent in the stamping process that sheets formed in a single die and which have similar strain distributions will all have repeatable dimensions and stiffness. If the geometry of a stamped part is unacceptable, either the tool shape is incorrect or the sheet has not been formed to the appropriate strain distribution. A simple model shows how strain distribution is very sensitive to variation in friction and material properties. A method of control in the stamping plant based on the automatic measurement of a coarse orthogonal grid is suggested and it is shown that the accuracy of the measurement system is well within the capability of existing hardware.

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