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A novel process for transforming sheet metal blanks: Ridged die forming

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ABSTRACT

Up to 20% of all sheet metal produced is scrapped as blanking skeletons. A novel process is therefore designed and examined, aiming to transform tessellating 'pre-blanks' in-plane into the real blanks required for stamping. Prior to blanking, the sheet is formed with a set of ridged dies, from which pre-blanks are cut and then flattened into true blanks. Several different approaches to designing ridged dies are evaluated by simulation and experiment, and the best results demonstrate a potential reduction in blanking yield losses for can-making from 9.3% to 6.9%.

1. Introduction

Around 50% of annual global production of liquid metal is used to make sheets, and around half of this never reaches a final product, but instead is scrapped (and recycled) at different stages of production [1]. These high losses cause a significant increase in the specific embodied energy of the final product (i.e. energy per kg), particularly due to the compounding effect of yield losses along the supply chain [2].

One of the biggest sources of scrap occurs during blanking, when coils of strip metal are cut into shapes for use in downstream forming operations. These shapes rarely tessellate, hence the waste material from between the blanks (the 'skeleton') is scrapped. However, the shape of the blank is dictated by the shape of the final part and the forming process used for its manufacture, and the optimised design of this shape has already been subject to intensive research. An approach to estimating workpiece deformation in deep drawing introduced in [3] and subsequently named the "geometrical mapping method" [4] has been extended [5] for use in optimisation routines [6]. This "inverse approach" describes the target final shape of the workpiece with a mesh of shell elements, and then maps each node on the final configuration to a point on the initial flat blank. By considering only the initial and final blank geometries, this approach gives a rapid solution for the major strains in the workpiece, which can be used to optimise the initial blank geometry to minimise final part thickness variations. The results show a reduction of ~17% in material required compared to the original blank shape. This method has been applied for automotive components [7] and developed using ideal forming theory [8], a faster inverse approach [9], the ESO technique [10] and with approximate modelling [11]. These developments provide faster solutions while offering similar reductions in blank masses. However, despite these reductions, if the initial blanks are cut with blanking-presses from constant width sheets, yield losses may be unimproved.

The use of tessellating blanks, for example using a hexagonal blank to form a beverage can, could largely eliminate these losses. However, without some change to the forming sequence, use of a different blank shape would simply result in higher trim losses after the first stages of forming, moving the scrap burden further down the supply chain but not reducing its magnitude. Is it possible to design a forming process to transform a blank from one shape to another, without reducing final product quality?

This paper first considers the theoretical basis for devising a process to meet these requirements. A candidate, novel process, 'ridged die forming', is then presented as one possible means to create arbitrary in-plane deformation. The process is evaluated by application to a case study on forming beverage cans, with the aim of transforming a hexagonal "pre-blank" into a circular blank for use in can bodies or ends.

2. Transforming blanks with uniform thickness change

An ideal in-plane blank transformation should maintain uniform blank thickness to allow downstream processing and assure final product quality. Assuming incompressibility, this imposes the constraint that, during the transformation (over time $0 \le t \le T$, in the plane x–y, and assumed to have a constant rate), the in-plane strain rates satisfy:

$$\dot{\varepsilon}_{xx}(x,y,t) + \dot{\varepsilon}_{yy}(x,y,t) = -\dot{\varepsilon}_{zz} = -\text{constant} \quad (1)$$

By mass conservation, the required thickness strain rate can be calculated from the change in blank area, A, as:

$$\dot{\varepsilon}_{zz} = -\frac{1}{T}\ln\left(\frac{A_T}{A_0}\right) \quad (2)$$

There is an infinite family of deformation fields (v_x, v_y) satisfying (1) and (2) while transforming a blank between given initial and final geometries. A useful reference case is the pattern of deformation which requires minimum work and hence which

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satisfies,

$$\min_{v_x, v_y} W = \int_0^T \left(\int_V \overline{\sigma \dot{\varepsilon}}\, dV \right) dt \tag{3}$$

where

$$\bar{\dot{\varepsilon}}^2 = \frac{2}{3}(\dot{\varepsilon}_{xx}^2 + \dot{\varepsilon}_{yy}^2 + \dot{\varepsilon}_{tt}^2 + 2\dot{\varepsilon}_{xy}^2) \tag{4}$$

The minimisation of (3) subject to the constraint of (1) can be solved by an appropriate constrained optimisation algorithm applied to a velocity field discretised in time and space. A code was written to achieve this, for a rigid-plastic material, using the finite element method, with reduced integration quadrilateral elements and hourglass control, and a gradient based optimisation method. The code was applied to a test case of transforming a hexagon (the highest order regular tessellating polygon) to a circular blank. Fig. 1 shows one twelfth of the resulting deformation, when the thickness strain rate is chosen so that the final circle perfectly encloses the original hexagon.

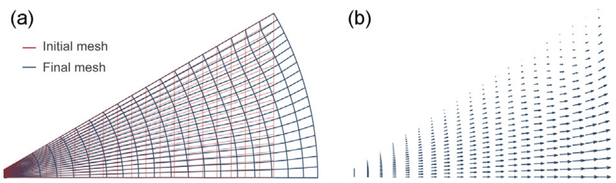

Fig. 1. Minimum work transformation of hexagon to circle. (a) Mesh deformation; (b) deformation vectors (plotted on initial mesh).

In order to create the deformation field of Fig. 1, tools must be applied to create appropriate surface tractions. The required tractions can be calculated, subject to a free choice of hydrostatic pressure, from the deviatoric stresses associated with the strain rates in the deformation field. However, in practice tools can apply surface tractions only by compression and its associated friction. Thus, although it might be possible to create the deformation pattern of Fig. 1 through design of a segmented tool, such a tool is likely to be complex. Potentially a simpler segmented tool could be designed to create a different (non-ideal) deformation field. But an alternative approach that could be easier to implement in practice would be to deform the strip out of plane prior to blanking to create "pre-blanks." Forming within the uncut strip creates a helpful set of boundary conditions at the edge of each pre-blank: material cannot be drawn into the pre-blank, and the sheet must instead stretch. Then, after blanking these pre-blanks can be flattened, during which further in-plane deformation will occur, to create the final, transformed, blank.

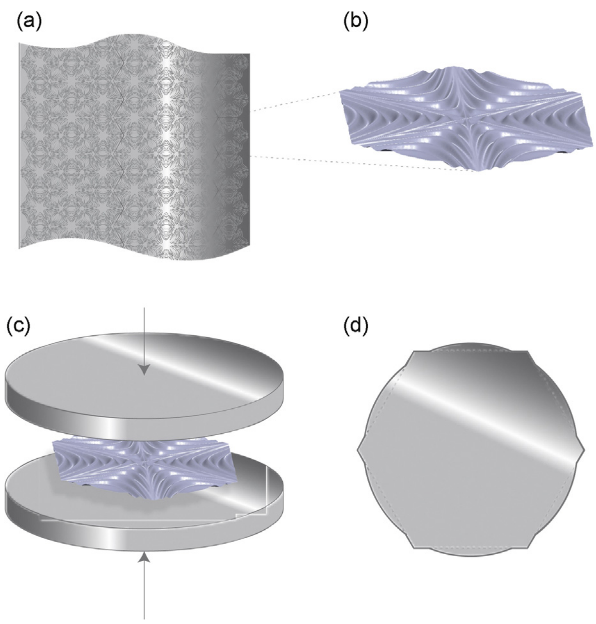

Fig. 2. Overview of concept for ridged die forming process. (a) The uncut sheet is stamped with ridged dies; (b) tessellating pre-blanks are cut from the sheet; (c) the pre-blank is flattened between flat dies; (d) the pre-blank is transformed to the final blank geometry.

The transformation created by this process depends on the geometry of the dies used to form the pre-blanks. After preliminary trials of a range of die geometries, the work leading to this paper has considered dies shaped with a set of many relatively shallow ridges: the attraction of this approach is that the spacing and depth of the ridges allows more influence over the distribution of surface tractions than with a dome-like punch.

The process is illustrated in Fig. 2. The uncut sheet is stamped with ridged dies, shown in Fig. 2(a), to create ridged pre-blanks. The shaped pre-blanks, which (in plan view) tessellate are then cut from the sheet, shown in Fig. 2(b). The cut pre-blanks are flattened, causing a change of the plan-view shape of the blank, to produce the final blank geometry, demonstrated in Fig. 2(c) and (d). The success of the process depends on the design of the ridged dies of Fig. 2(a).

3. Die design methods

Three approaches were taken to the design of ridged dies. Firstly, a design was developed using an analogy to the folding of leaves, based on an approach to designing deployable membrane structures [12]. Many tree leaves consist of a central 'rib', with sets of smaller ribs emanating at a fixed angle on either side of the rib. Folding along these lines provides a degree of control over the plan view geometry of the leaf. De Focatiis and Guest observed that by treating each segment of a regular polygon (e.g. each 1/6th of a hexagon) as a separate "leaf", and arranging the ribs in an appropriate manner, the plan-view geometry of the polygon could be adjusted. In the case of a hexagon, the required rib runs centrally along each 1/6th of the polygon, with the ribs running parallel to the sides of each segment (i.e. at a 30° angle to the central rib). A design with 9 ridges was chosen and the depth of the ridges fixed such that along the central rib, the total length of the die surface was approximately equal to the target radius of the blank. This leads to the design shown in Fig. 3(a).

Secondly, a die parameterisation, illustrated in Fig. 4 and summarised in Table 1, was optimised by repeated trials. Each ridge is defined by a compound Bezier curve, with the gradients at each endpoint chosen to provide C^1 continuity between the different segments of the hexagon. Finite Element simulation was

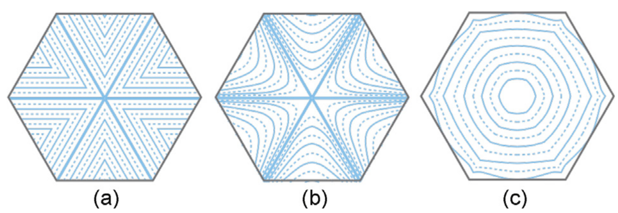

Fig. 3. Summary of three die designs assessed in experimental trials. (a) Die set 1; (b) die set 2; (c) die set 3.

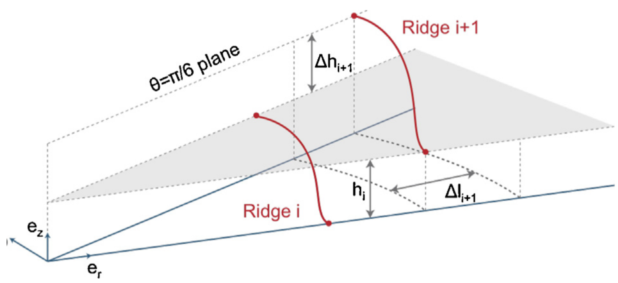

Fig. 4. Parameterisation for die designs by manual optimisation.