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Flexible asymmetric spinning

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ABSTRACT

Metal spinning is used to form shell components, but is constrained by two features: it can only produce axisymmetric shapes; it requires a dedicated mandrel for each product. Examination of pressures between product and mandrel revealed that contact is limited to three well defined areas. This suggested that the full mandrel could be replaced by three rollers. Furthermore, if these rollers could be controlled, they could represent any symmetric or asymmetric mandrel. A seven-axis machine has been designed, manufactured, and used to spin trial parts. The machine design is described, and preliminary results give an indicator of process capability.

1. Introduction

The search for a cost-effective means to produce small batches of sheet formed parts has driven a wave of innovation in the past 20 years, led by inventors in Japan [1]. Many of these innovations have been mobile tool (or 'incremental') processes where the large fixed tools of stamping are replaced by small tools moving in two or three dimensions. Manual versions of these processes, including the Power Hammer and the English Wheel, were widely used in industry until the mid 20th century and when operated by skilled craftsmen, could create a wide variety of sheet parts with useful accuracy. Recent developments have aimed to replicate this achievement, but with computer control replacing the craftsman. Most prominent in the academic literature has been work on 'Incremental Sheet Forming' (ISF) with dozens of research groups world-wide attempting to build on the ideas of Iseki et al. [2] and Matsubarra [3].

Although spinning is a mobile tool process, it is inflexible: the product geometry is defined by an axisymmetric rigid mandrel. ISF aims to overcome these constraints and is often described as a derivative of spinning. However, unlike ISF, spinning is a true net-shape process: on process completion, the tools apply no force to the product, and the product perimeter is free, so when the product is unloaded from the machine it does not change shape. This is in striking contrast to ISF, where extensive springback on process completion causes poor geometric accuracy. Furthermore, ISF, like shear spinning, leads to significant sheet thinning which prevents replication of products made by deep-drawing. Thus, despite great interest in this process among researchers, it has had little take-up in industry.

There is thus considerable motivation to create a new variant of Spinning – to preserve the benefits of true net-shape production and allow 90° wall angles without thinning, while overcoming the constraints of requiring an axisymmetric rigid mandrel. Several attempts have been made to extend the process design. An early design by Boldrini, replaced the mandrel with a single roller, but this is used for adding a short flange to large components, not for producing whole components. More recent attempts are summarised in Fig. 1.

The processes in Fig. 1b–d allow spinning without a mandrel, and are all forms of shear spinning – the outer diameter of the product does not reduce due to the process, so they are limited by thinning. Furthermore, the processes in Fig. 1b and c have limited flexibility, and although that of Fig. 1d has more potential, only experiments making simple cones have been reported. The process of Fig. 1e is inflexible as it retains a rigid mandrel. Can asymmetric products be spun without a mandrel?

2. Analysis of mandrel contact pressures in spinning

Spinning is inflexible because of the mandrel that defines product geometry, so the key to exploring options for creating a flexible spinning process is to examine the interaction between the mandrel and the workpiece. In [10] we reviewed previous work on the mechanics of spinning, and found no analysis of this interaction. Therefore a finite element simulation of spinning was set up in Abaqus. The simulation used 20,000 continuum shell-elements to describe the workpiece. To check the sensitivity of results to numerical parameters, studies of the element type, mesh size and number of through-thickness integration points were performed, and the simulation was validated against results published in [11].

A case study was setup up for spinning a simple can from a 1 mm thick aluminium 5251-H22 blank of diameter 500 mm with spinning ratio 2, using a frictionless working roller of diameter 100 mm. The tool path comprised a sequence of involute curves, following a standard spinning schedule. Rather than simulate the full duration of the process, which would have taken weeks, a sequence of simulations was created each starting from an estimate of the product shape after a given number of passes. Each simulation was then run for 3 s of process time corresponding to three revolutions of the spindle.

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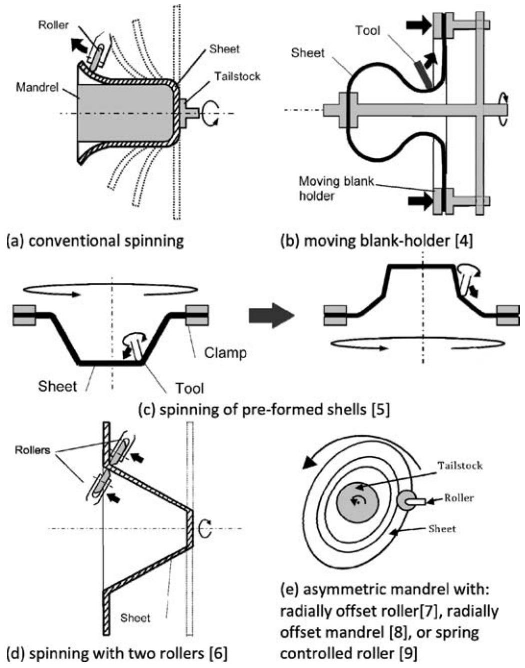

Fig. 1. Recent innovations in spinning process design.

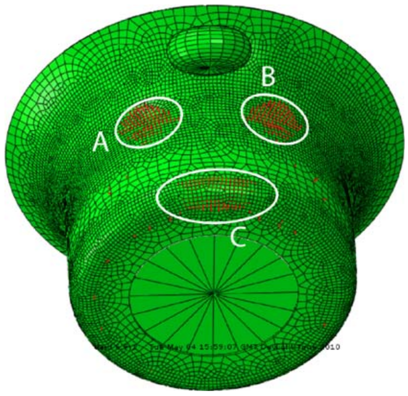

Fig. 2. Contact pressure between mandrel and workpiece in spinning.

Fig. 2 shows the key and surprising result of this analysis, for a simulation representing the point in processing when approximately half of the can has been formed onto the mandrel, with the remaining workpiece shaped to form a bell like funnel, and the working roller currently approximately half way across the bell. The red arrows normal to the workpiece show the contact pressure between mandrel and workpiece, and are clearly limited to three areas (no further significant pressure occurs on the opposite side of the mandrel): A and B at the limit of where the can has been formed onto the mandrel, but offset to either side of the working roller; C at the corner radius of the can where the base turns into the wall. Intuitively these areas arise because the working roller force tends to squash the can and bend it at C, so the contacts A and B oppose squashing and are sufficient to ensure no other contact around the circumference.

The simulations were repeated for different stages in the process, and a range of mandrel diameters and the same pattern of three contact areas from Fig. 2 remained remarkably consistent. Fig. 3 shows that the angle between the two areas of contact at the limit of mandrel contact varies between 10° and 30° during the manufacture of the can, but the pattern of contact remains consistently as shown in Fig. 2.

In further simulations, a non-axisymmetric mandrel was used, and Fig. 4 shows an extreme case, with a 'kidney-bean' mandrel. The contact pressures are at a similar stage to Fig. 2.

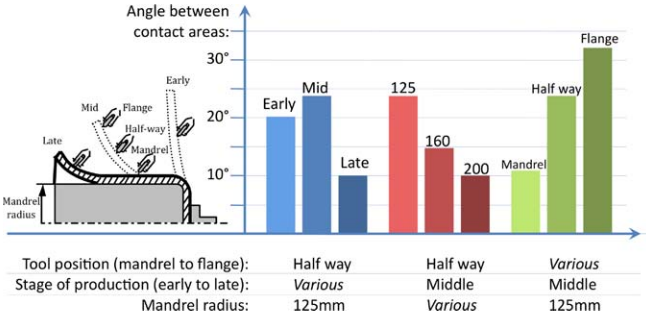

Fig. 3. Variation in radial separation of contact areas during spinning.

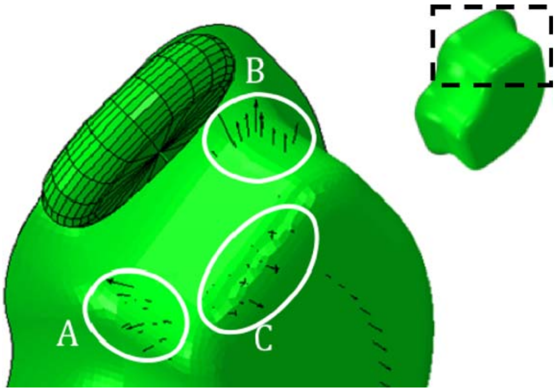

Fig. 4. Contact pressure between mandrel and workpiece during asymmetric can spinning.

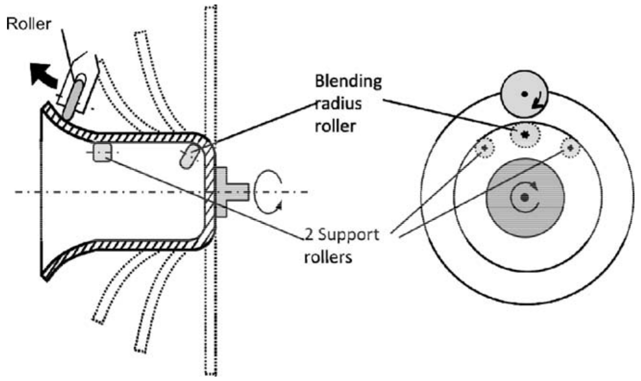

Fig. 5. Schematic process design for flexible asymmetric spinning.

The same pattern of three contact areas is still clearly visible, although the two at the threshold of contact are now not symmetric, and the contact at the base of the can is slightly modified. It appears that the effect of the mandrel in spinning is always limited to three small areas of contact in consistent and predictable locations.

The implication of this analysis is that the mandrel could be replaced, in both axisymmetric and asymmetric spinning, by three rollers: one at the base of the spun product (the 'blending roll') and two 'support rolls' placed to either side of the working roll, and moving along the product as the final diameter is reached. This leads to the schematic process design of Fig. 5.

To confirm this design, the simulation was now set up in reverse – with the mandrel replaced by rollers as shown in Fig. 5, and the simulation used to compare the stress state in the workpiece. Fig. 6 accordingly shows a comparison of equivalent stress and strain in the workpiece in conventional spinning and with the configuration of Fig. 5. The figure confirms that the design based on rollers at the locations where the mandrel applies pressure to the workpiece in conventional spinning leads to very similar pattern of deformation in both cases. The Abaqus simulation was further used to predict the forces on all the