CIRP Annals - Manufacturing Technology 64 (2015) 301–304

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

# Parametric toolpath design in metal spinning

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ARTICLE INFO

*Keywords:*
Sheet metal
Computer numerical control
Spinning

ABSTRACT

Toolpaths in metal spinning are still designed by human operators, largely by intuition: a scientific basis remains elusive. In this paper, a parameterised toolpath is proposed based on a quadratic Bezier curve. Experiments are performed varying each of four design parameters in turn, to investigate how tool force, part geometry and various failure modes evolve with key features of the tool path. Analysis of these experimental results reveals some new features of process mechanics and leads to a proposal for a set of rules that may become useful for automatic toolpath generation.

## 1. Introduction

Metal spinning is economically attractive at low volumes, and can form large parts from thin or thick blanks in a wide range of materials [1]. However, toolpath design for metal spinning relies on craft and experience. With automation, switchover times and defects could be reduced, making spinning more viable.

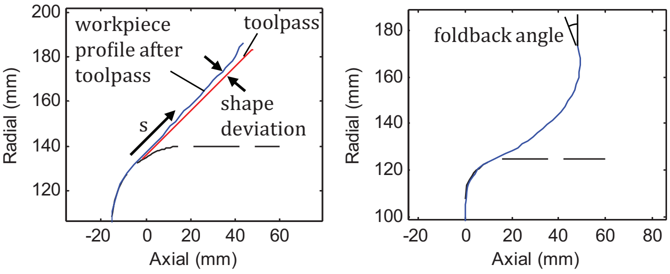
Most research into toolpath design has relied on empirical methods, aiming to achieve target geometries while avoiding failures such as wrinkling or thinning. Based on experiments, Hayama et al. [2] recommended involute paths as did Liu et al. [3] through FE analysis. Wang and Long [4] found that convex toolpaths minimised both tool forces and thinning. Li et al. [5] parameterised the first toolpath with Bezier curves, to show that a more aggressive convex path resulted in higher tool forces and more thinning. However, these results are still insufficient for the design of a complete toolpath.

For this reason, Kleiner et al. [6] and Auer et al. [7] used a statistical approach, with circular toolpaths with a range of curvatures. Kleiner et al. [6] used human judgement to grade the severity of wrinkles from 1 to 6 and optimised the first forward and backward pass. Auer et al. [7] defined a window of toolpaths that avoid wrinkling, and optimised them to minimise thinning. This led to an offline toolpath planning algorithm [8] which is practical, but limited to the parameter region of the trials.

Therefore, in this work, a set of experiments is performed with a parameterised toolpath to explore how the design of the toolpath influences product geometry, tool forces, and the various failure criteria which define the operating window of spinning.

## 2. Methodology

Two key failures occur in spinning: circumferential wrinkling at the perimeter and excessive thinning. Preliminary experiments revealed a third failure, "foldback" as in Fig. 1: if too much deformation occurs early in a pass, the outer edge of the workpiece may fold backwards, eventually inhibiting tool motion. In a sequence of trials, these failures were monitored by a laser line scanner and a thickness gauge. The scans measured the deviation (springback) between workpiece shape and the toolpath, as a function of distance along the meridian, $s$ (Fig. 1a), wrinkles and the "foldback" angle (Fig. 1b) with a confidence of ±0.125 mm in the laser measurements, although the wrinkle amplitude varied more than this in repeated trials; a calibrated dial gauge mounted on long arms, was used to measure part thickness. In addition, tool forces were monitored by load cells, with confidence of ±0.05 kN. Two initial workpiece geometries were used: a flat blank and a 45° cone produced identically for each trial. Only forwards passes were tested for the flat blanks, but for the cone, passes in both directions were used. In all, 74 components were produced.



**a)** Shape deviation measurement **b)** Foldback angle measurement

**Fig. 1.** Workpiece measurements.

The toolpass is parameterised as a quadratic Bezier curve (Fig. 2) – preferences for 'involute' paths in the literature have not been physically justified, and the key feature of either curve is to allow variable but smooth changes of curvature through the pass. The starting point, $\mathbf{p}_0$, is defined relative to the last current contact between the component and the mandrel, and is specified fully by its axial coordinate, $z_0$. The end of the pass, $\mathbf{p}_2$, is defined solely by

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http://dx.doi.org/10.1016/j.cirp.2015.04.077

its axial coordinate, $z_2$, measured relative to the un-deformed edge prior to this toolpass. The “stretch point”, $\mathbf{p}_1$, is defined relative to the mid-point between $\mathbf{p}_0$ and $\mathbf{p}_2$. Increasing $n$ leads to a more concave toolpath (the path would be linear with $n = 0$), while $d$ creates an offset of the centre of the concavity towards the mandrel ($d < 0$) or the perimeter ($d > 0$).

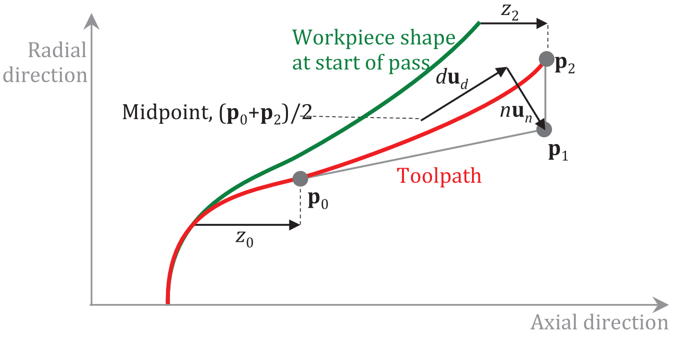
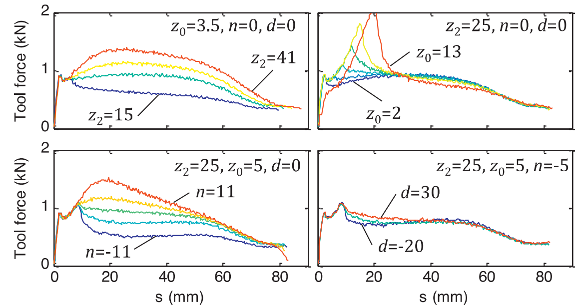


**Fig. 2.** Toolpath parameterisation.

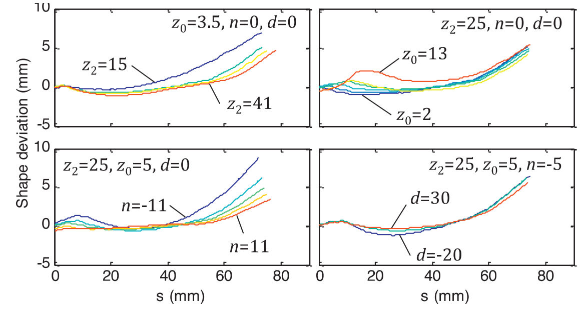
A sequence of trials was performed, starting from a straight-line tool path with a small step forwards at contact with the mandrel ($z_0 = 3.5$, $n = d = 0$) and with increasing rotation created by increasing $z_2$. The rotated straight path allowing most deformation but with least tendency towards the three failure modes was chosen – this required subjective judgement – and in turn, the other three parameters were found similarly. As each parameter value in turn was fixed, three parts were made at this value, to allow some analysis of the repeatability of the results. The trials were all conducted on the flexible spinning machine at the University of Cambridge, UK [9], and limited to a single material (commercially pure, half-hard aluminium sheet, AA1050-H14) with constant (2 mm) thickness and an initial diameter of 375 mm.

## 3. Results

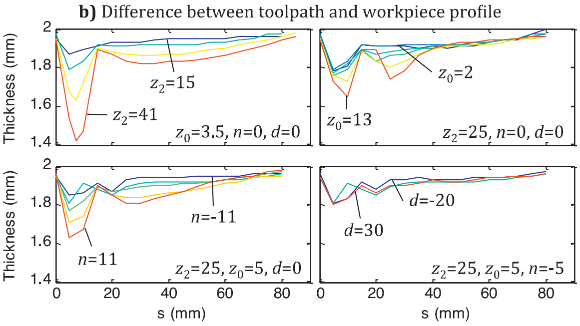
Fig. 3 demonstrates the results of the trials with the flat blank. The intermediate values of the four parameters that define the tool path are shown by the markers of Fig. 3d. The top left of the five sets of four plots in Fig. 3 demonstrates that for the forwards passes on the flat blank, increasing deformation ($z_2$) leads to increased forces – particularly in the middle of each pass, but less shape deviation (springback.) This reflects the ‘locking-in’ effect of membrane stresses, as the blank is deformed from its initially flat state. Maximum thinning of 30% on this first pass is high, occurring where the blank initially makes contact with the mandrel, and increases with increased deformation. Other authors (e.g. [10,11]) have commented similarly that early passes of spinning are like shear-spinning, so this result shows that deformation in the early passes should be limited, to reduce the danger of subsequent circumferential cracking. The tendency to wrinkle also increases with increasing deformation, although it is at a minimum when at least some deformation has occurred – the workpiece has considerably increased rigidity as soon as it is deformed away from its initial flatness. The foldback angle at this first pass is insensitive to any of the parameters, and the value of $z_2 = 25$ selected from these trials was taken forwards as it minimised wrinkling. Craftsmen believe in the importance of ‘locking on’ the workpiece to the mandrel early in the process – which suggests a preference for a high value of $z_0$. The results in the top right of each set of plots suggest that this does reduce wrinkling, albeit at the cost of an increase in maximum thinning arising from the sharp spike in tool force as the tool initially pushes into the workpiece. An increasingly concave toolpath (positive $n$, bottom left of each plot set) is beneficial, as widely reported in the literature: as $n$ increases, the tendency to wrinkle is reduced as is the shape deviation, although this comes at the cost of a significant increase in the average tool force – particularly at the middle of the pass, leading to increased thinning. Strikingly, increasing toolpath concavity reduces the tool force near the workpiece perimeter – and this explains the reduction in wrinkling. For the modest value of $n$ selected for the trials of $d$ (the offset of concavity, bottom right plots) the offset has little effect. Overall, Fig. 3 shows that, in the first pass of spinning, the tool force distribution is highly sensitive to all the key features of the toolpath, unlike the foldback angle which is insensitive. Thinning increases with tool forces, while shape deviation is primarily determined by the overall ambition of the pass ($z_2$). The tendency to wrinkle increases with $z_2$ but decreases with $n$ as the toolpath becomes more concave.



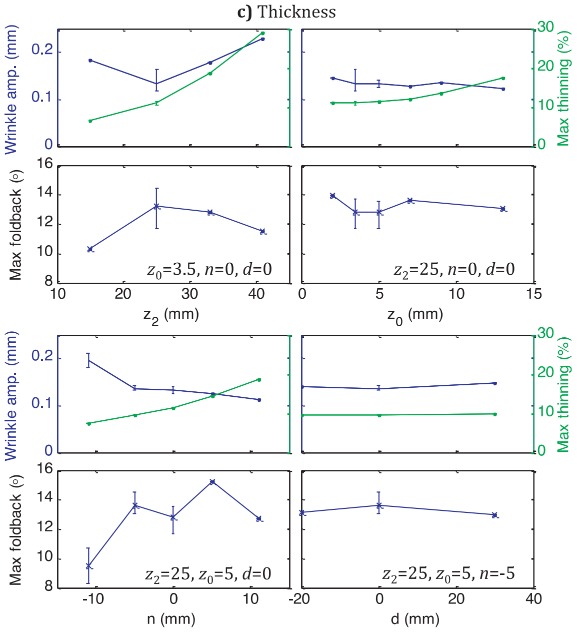
**a)** Tool forces



**b)** Difference between toolpath and workpiece profile



**c)** Thickness



**d)** Wrinkle amplitude, thinning and foldback

**Fig. 3.** Forward pass trials with flat blank.