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Parametric toolpath design in metal spinning

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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.

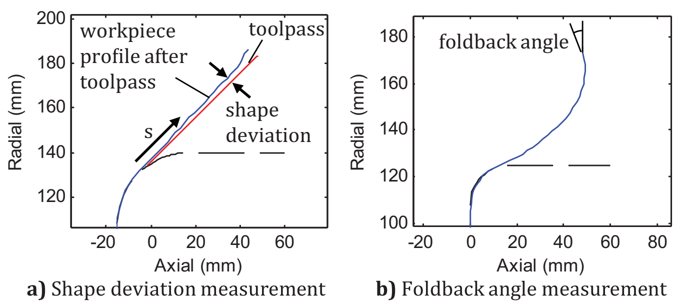

Fig. 1. Workpiece measurements.

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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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 ($d > 0$).

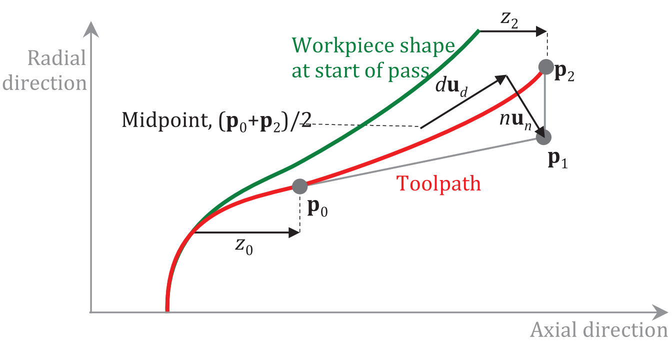

Fig. 2. Toolpath parameterisation.

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

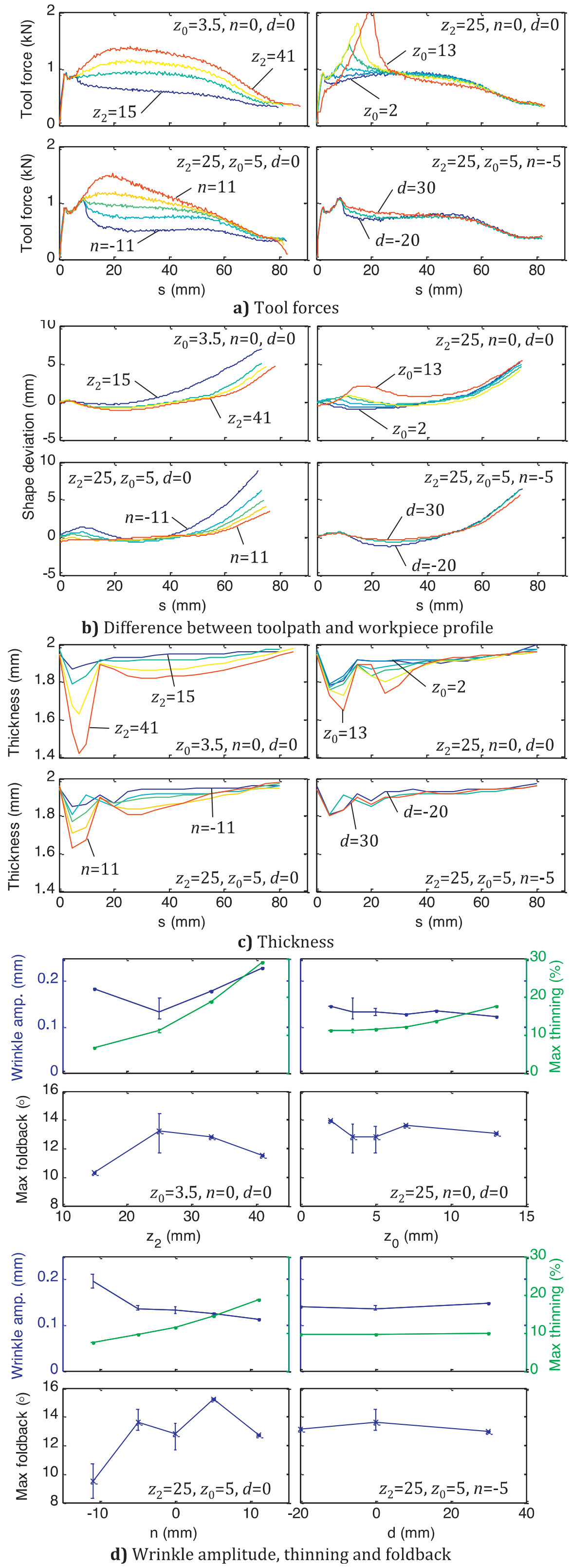

Fig. 3. Forward pass trials with flat blank.

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.

Fig. 4 shows a subset of the equivalent results with a conical workpiece Increasing the total ambition of the pass, z_2, increases the forces and maximum thinning as before, although before the pass in Fig. 4, maximum thinning had already reached 35% from the work of creating the cone. In contrast to craft experience, wrinkling was minimised at the extreme values of z_2. This may be related to the increase in foldback angle: when the tool moves into the workpiece near the base, the workpiece folds outwards. This will relieve compressive stress and might help to straighten out wrinkles and is consistent with a strategy used by craft spinners to eliminate wrinkles with an aggressive forward toolpass combined with a back-stick to push out the edge of the workpiece. As z_0 increases, more of the workpiece is 'locked on' to the mandrel, improving stability but with a slight increase in thinning. However, high values of z_0 eliminate foldback, but increase wrinkling. Convex passes lead to wrinkling and shape deviation, so more concave passes are again preferable.

The results of Fig. 5 contrast strongly with those of Fig. 4. (The spatial axes of the two graphs are oriented identically so for Fig. 5a, time moves from right to left, as the tool moves inwards.) z_2 is fixed by the workpiece geometry achieved at the end of the previous pass, so the top left plot for each set is missing in this case, and the results show that as z_0 increases, the forces and tendency to wrinkle and foldback grow quickly. In contrast to the forwards pass, a concave tool pass increases wrinkling, and reduces shape deviation. The backwards pass causes little thinning, presumably because the inward direction of the tool is acting to draw material in towards the mandrel.

Comparing the results of Figs. 3 and 4, the tool force associated with the preferred path is quite similar: a period of approximately constant force (around 1 kN in this case) followed by a linear

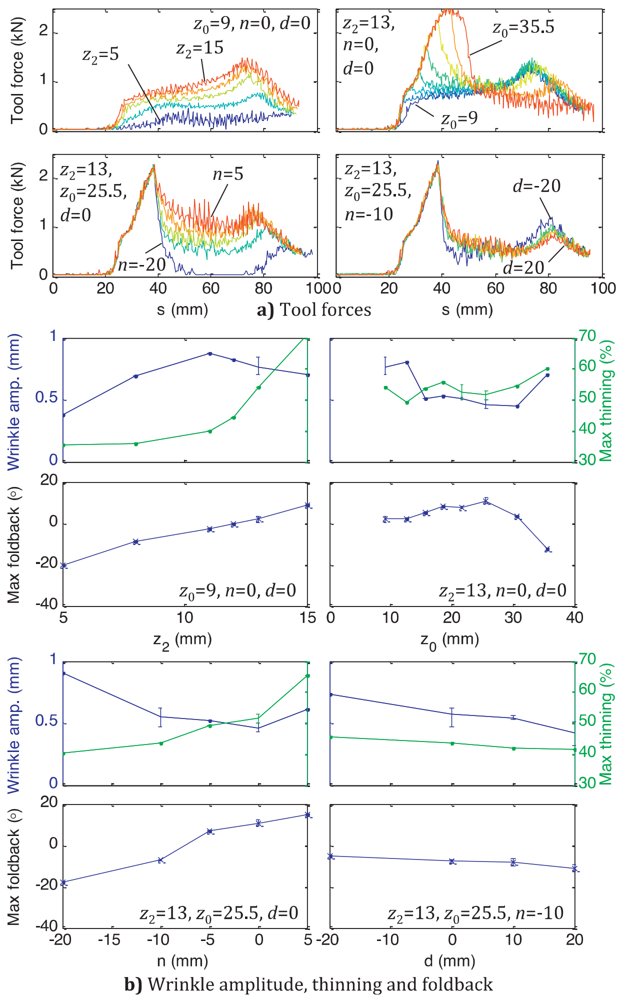

Fig. 4. Forward pass trials with 45° cone.

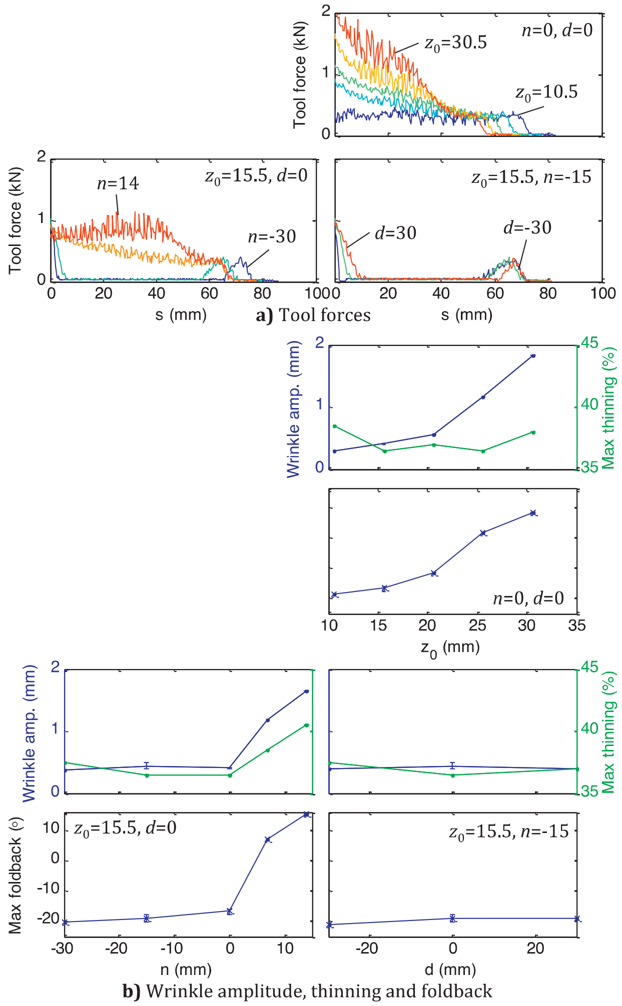

Fig. 5. Backward pass trials with 45° cone.

reduction to the perimeter. The tendency to wrinkle in both cases increases with z_2 but decreases as the tool path becomes more concave. However, the same concavity particularly when coupled with higher values of z_2 leads to an increase in maximum thinning. The tendency towards foldback, which when sufficiently pronounced causes difficulty for later passes, is always present with a flat workpiece, and returns later in the process for large deformations with concave toolpaths. Contrasting the forwards and backwards passes in Figs. 4 and 5, the force distribution for the backwards pass is quite different – being negligible as the pass begins, then rising linearly towards the mandrel. The backwards pass avoids thinning, but an overambitious deformation, particularly if with a concave path, leads to a strong tendency towards wrinkling and foldback.

4. Discussion

The results of Figs. 3–5 provide rich opportunities for further interpretation, and have been provided in full to allow detailed comparison with future studies aiming at the same goal. Three tentative insights are drawn from the results here.

4.1. Force control of the tool path

Several observations in Section 3 related the maximum thinning to increases in the tool force distribution. There was no correlation between maximum thinning and maximum force, but Fig. 6 instead shows that the maximum thinning was strongly correlated with the mean force. This suggests that failure by tearing could be countered by strategies to reduce the average force.

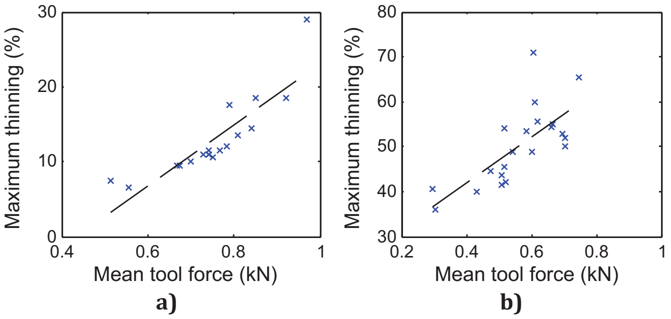

Fig. 6. Thinning and average force on the forward pass.

4.2. Evolution of workpiece geometry

The tendency towards wrinkling during the forward pass was dependent on the way that the workpiece changed shape during the pass. In tool passes that led to low wrinkle amplitude, the outer edge of the workpiece remains flat, pointing radially outwards. However, in those with higher wrinkle amplitude, the outer edge of the workpiece was bent forward. These observations were consistent across all the experiments performed. This suggests that, if wrinkling becomes a concern, the toolpath should be modified to force the edge of the workpiece to be radial to the axis of rotation. In the trials with the cone, the behaviour was slightly different: the tendency to wrinkle was reduced when the material not yet in contact with the mandrel maintained the 45° cone shape, such that after each pass, the size of the remaining cone has reduced but its angle has not changed. This, again, was consistently observed across all of the experiments. These two observations suggest that, in addition to the force control proposed above, a geometrical strategy could also be developed, based on limiting the rotation of the tangent to the outer perimeter.

4.3. Rules for toolpath design

At first sight, the results of Section 3 suggests that in order to reduce both tool forces and maximum thinning, toolpath designers (manual or automatic) should reduce the aggressiveness of the toolpath by reducing z_0 and z_2. However, this leads to reduced geometry change, so more passes would be needed in order to produce the same deformation. Nevertheless, the results are consistent with Kawai and Hayama [12] who suggest that a greater number of less aggressive passes reduces thinning in the final product.

The results show that toolpath design in spinning involves finding a balance between the need for deformation and the avoidance of failure by wrinkling, thinning or foldback. Craft find this balance by experience, but the results of these trials, allow a tentative proposal for a set of rules that might form the basis of a future automatic toolpath design without requiring the unacceptable delay that would be caused by optimising paths in a numerical model of the process.

1. Forwards passes should aim to maintain a constant value of tool force early in the pass tapering over the last 25% of travel to zero at the perimeter.
2. If a target value of the constant force is known, z_0 should be chosen to approach the value, and the rest of the pass may be determined by the required force profile.
3. Early in the process, the perimeter of the workpiece should remain perpendicular to the axis of rotation. Once a stiff shape, such as the 45° cone used here, has been established, the passes should aim to maintain this shape, as pass by pass more material is formed onto the mandrel.
4. The maximum deformation in a forwards pass (hence the maximum tool force) is limited by the acceptable thinning, and the appearance of wrinkles or foldback.
5. Wrinkling can be reduced if a more concave tool path is used, provided this avoids the tendency to foldback.
6. Once the spun part has deformed sufficiently from its initial plane to have intrinsic stiffness, backwards passes can be used to increase the rate of shape change without the risk of thinning. The tool-force on the backwards pass should be near to zero for approximately the first three quarters of the inwards pass, and then increase linearly as the tool approaches towards the mandrel.

These tentative rules could be validated in future, both by interviews with skilled craft workers, and in automatic trials. At least some extensions are likely, as craft workers appear to have particular procedures for reacting to the early appearance of foldback or wrinkling. The trials in this paper have also been limited to one workpiece material and geometry, and to a single feed ratio (the ratio of tool speed to workpiece rotational speed) so a wider range of production would be required in any serious validation, including the need to "non-dimensionalise" the proposed rules to account for different workpiece materials, thicknesses, spinning ratios and product geometries.

A further limitation of this work is that it aims to optimise each toolpass individually. In order to optimise the whole toolpath, the effect of each toolpass on the outcome of the whole process should be considered. In particular, in order to understand the backward pass properly, it should be considered along with the next forward pass in order to answer the question: does the backward pass reduce the tendency towards wrinkling or thinning in the subsequent forward pass? The focus of this paper has been to example how key features of the tool path design influence the tendency to three critical workpiece failures – wrinkling, thinning and foldback. Once these tendencies can be avoided reliably, it will become possible to extend the optimisation of the process to seek the fastest means of producing parts to a specified quality level.

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