The effect of conventional metal spinning parameters on the spun-part wall thickness variation

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Abstract: Conventional metal spinning technology is based on the sequential shaping of a circular sheet over a mandrel through the action of a roller that produces localised pressure to produce a hollow axisymmetric product. The wall thickness of the formed part in this process is, in general, considered to be nearly constant, but in fact, a non-uniform distribution of wall thickness is observed. The wall thickness variation is a major defect found in produced parts that can cause part failure and therefore the spinning process must be properly optimized. This paper deals with the analysis of the chosen conventional metal spinning parameters (tool path profile, mandrel speed and the tool feed rate) on the wall thickness variation of cylindrical shaped spun-parts made of DC01 low carbon steel, while a three-level full factorial design of experiment method (DoE) and ANOVA (Analysis of Variance) were used. The experimental results revealed that tool path profile and the tool feed affects the wall thickness variation in a significant way. The effect of the mandrel speed was not clearly observed.

Key words: conventional metal spinning, tool path profile, mandrel speed, tool feed, wall thickness, ANOVA

1. Introduction

Wall thickness variation is a major defect found in parts made from metal sheets that influences the intensity of part defects and possibly causes the cup failure [1]. The wall thickness of the formed part in conventional spinning is, in general, considered to be nearly constant [2]. But in fact, the wall thickness of conventionally spun cup is not uniform [3, 4]. Therefore, the spinning process must be carefully optimized in order to produce components with a minimal thickness variation [5].

The cup edge is much thicker than the original blank thickness; what is more, cup wall has two nearby necks. The first neck is at the cup bottom and the second one is at the cup wall. Cup wall fractures occur due to oversized blanks at the location of the second neck [6]. Conventional spinning process produces thinner cup wall with smaller roller feeds [3, 4], smaller roller nose radii [3, 4] and smaller radial clearances [3]. The inner profile of the final spun cup is larger than the mandrel profile due to springback. This difference gets wider with smaller roller nose radii, higher roller feeds, and higher conical roller angles. The final spun cup by conventional single roller doesn't closely fit to the forming mandrel. The cup is rather shaped with bulged form having a gap between the cup inner diameter and the mandrel. This gap is not uniform and increases with cup height with its minimum at the cup bottom [4].
In the work of Wang and Long [7] three key process parameters were selected: spindle speed, feed rate and type of material as the experimental input factors and the wall thickness, depth, and inside diameter variations of the spun cups was measured as the output factors. Authors concluded that the type of material has the most significant effects on the variations of thickness and depth of the spun parts, followed by the spindle speed and the feed ratio. In addition, thinner wall thickness is also obtained when a higher spindle speed is applied. It is shown that in this experiment a higher level of feed rate leads to thinner spun parts.

These experimental results are partially supported by the experimental results of Essa and Hartley [8], it was demonstrated that the mandrel rotational speed did not show any effect on the formability of spun part (average cup wall thickness, thickness variation and springback of the cylindrical cups). In order to obtain a more uniform thickness distribution, a low feed rate and a negative relative clearance should be used. High feed rates increase the contact area between the roller and workpiece that tends to decrease the applied stresses [4]. Therefore, the workpiece deformation decreases and thus, a high thickness variation is found.

Šugár et al. [5] analyzed the influence of mandrel speed feed ratio and tpp on the spun parts wall thickness distribution via a statistical analysis. Authors concluded that mandrel speed has minimal effect on the thinning of the component wall. These findings can be expressed as follow: mandrel speed has negligible influence on axial and radial force components, therefore radial and thickness strain is minimal.

On the other hand, Wong et al. [9] suggested that a low feed ratio would result in excessively thinning of the cup wall. This conclusion was supported by the work of Zhan et al. [10]. Šugár et al. [5] and Šugár et al. [11] explains this feature as follows: a lower feed ratio means that the tool acts on the workpiece over more revolutions, which in turn leads to higher shearing effects, an intensive flow of material to the open end of the part and an appreciable thinning of the wall. Material hearing between the roller and workpiece due to frictional effects may be the main reason of the sheet thinning. Wang and Long [7] adds that high feed ratios can help to maintain the original wall thickness unchanged but cracking failures may occur if a larger feed ratio is applied.

Design of the toolpath strongly influences the quality of the final part, and is especially important in conventional multi-pass spinning. Various toolpaths such as linear, concave, convex was studied. Careful choice and design of the toolpath leads to a high quality, wrinkle and crack-free product [12]. The tendency to buckle and cause wrinkles as well as cracking can be avoided by introducing the correct roller path [9].

Up to now, most investigations of roller path and passes in conventional spinning have focused on single pass or multi-pass with no more than 3 passes; mainly linear paths [13]. During multi-pass conventional spinning process, the number of spinning passes, the spacing between two consecutive passes and the shape of the part are determined by the roller trace [14].

Kang et al. [15] studied the deformation mechanism of a single-pass conventional spinning, where three types of roller trace have been applied: straight line, concave curve and convex curve. The thinning rate of the wall thickness should be well taken into account in the design of the roller path of the first pass, because the deformation in the first path plays a decisive part in the final wall thickness distribution of the workpiece. In the first pass, the deformation mode of the blank is quite different from that of other passes due to the great change of blank shape from plate to shell.

Wang and Long [16] carried out a FE analysis of the effects of roller paths (linear, concave, convex, and combined curve) on the variation of wall thickness and tool forces. The results show that the concave path produces highest tool forces among these four roller path profiles. Using the concave roller path tends to cause higher reductions of wall thickness of the spun part and using the convex roller path helps to maintain the original wall thickness unchanged. A greater curvature of the concave path would result in more thinning in wall thickness of the spun part.

Polyblank and Allwood [17] proposed a parameterized toolpath design based on a quadratic Bezier curve. They experimentally investigated how tool force, part geometry and various failure modes evolve with the varying of key features of the tool path. They also proposed a set of rules that are
useful for automatic toolpath generation, for instance: the maximum deformation in forwards pass (hence the maximum tool force) is limited by the acceptable thinning, and the appearance of wrinkles or foldback.

This paper deals with the experimental analysis of the cups wall thickness variation during the incremental material deformation process applying the conventional spinning technology, while the spun cups are produced of DC01 low carbon steel blanks. The influence of tool path profile, feed rate and mandrel speed on the spun cups wall thickness distribution was identified using the statistical analysis method.

2. Experimental setup

The input circular sheet metal blanks necessary for the production of the experimental samples were prepared by the AWJ cutting technology; the outer diameter \( D_0 \) of the blank is calculated to 142 mm, initial sheet thickness \( t_0 \) is 1 mm. The blanks, made of a low carbon steel DC01 (1.0330; chemical composition and the calculated basic mechanical properties, according to ISO 6892-1:2016 standard for uniaxial tensile tests, are specified in Table 1), were used for the production of the hollow cylindrical shaped spun cups; the inner diameter of the spun cup is 91±0.5 mm, the sidewall height is 33±1 mm and the sidewall thickness of 1±0.1 mm (see Figure 1).

| Element | C max | Mn max | P max | S max | Si max | Al max |
|---------|-------|--------|-------|-------|--------|--------|
| wt (%)  | 0.12  | 0.6    | 0.045 | 0.045 | 0.03   | 0.02   |

| Yield strength (MPa) | Tensile strength (MPa) | Elongation (%) |
|----------------------|-------------------------|----------------|
| 187 ± 11.2           | 321 ± 8.5               | 44 ± 1.6       |

| Degree of planar anisotropy \( \Delta r \) (-) |
|-----------------------------------------------|
| + 0.34                                        |

![Figure 1. Cylindrical-shaped spun parts](image)

Spun cups were produced under various combinations of CNC metal spinning process parameters according to the Table 2, using a 3-level full factorial Design of Experiment, where a tool path profile \( (tpp) \), mandrel speed \( (n) \) and the tool feed rate \( (f) \) were chosen as the input process parameters. Mandrel rotational speed varies from 400 to 1200 min\(^{-1}\), tool feed rate varies from 0.4 to 1.2 mm in a combination with three most applied tool path profiles: linear, convex and concave. Labeling of the tool path profiles is given with the respect to the initial metal blanks. The designed tool path profiles are depicted in Figure 2. For this purpose a DENN ZENN 80 CNC conventional metal spinning machine equipped with a Sinumeric Siemens 840D control unit was used during the whole experimental research. A multi-pass spinning was applied for incremental material deformation, using 16 forward (movement of the tool is towards the blank edge) tool passes in total, consisting of 15 forming passes and one calibration pass. 27 spun cups were produced in total according to the above defined DoE (one cup for each process parameters combination) at a room temperature. Production of spun cups was carried out with the application of liquid oil lubricant.
Table 2. Studied input metal spinning parameters

| Parameter               | Level 1 | Level 2 | Level 3 |
|-------------------------|---------|---------|---------|
| Tool-path profile \( tpp \) | Convex  | Linear  | Concave |
| Tool feed rate \( f \) (mm) | 0.4     | 0.8     | 1.2     |
| Mandrel speed \( n \) (min\(^{-1}\)) | 400     | 800     | 1200    |

![Fig 2. Studied tool path profiles: convex, linear and concave](image)

The dimensional parameters of the applied forming tool – roller are chosen as follows: diameter \( d_r \) of 100 mm, roller nose radius \( r_n \) of 8 mm and the angle between the axis of the roller and the axis of the blank is 35° (see Figure 3). The roller is produced of 90MnCrV8 tool steel (1.2842) which is heat-treated to 60±1 HRC (quenching and tempering processes); since this type of material is widely applied in production of blank metal forming tools.

![Fig 3. Setup of the conventional metal spinning process](image)

After the production of spun parts, according to the DoE method, it was possible to measure the sidewall thickness in three different directions of the component: 0°, 45° and 90° directions relative to the blank material rolling direction (as depicts Figure 4), because the effect of the blank material planar anisotropy is expected. What is more, thickness was measured in three zones on the spun cup sidewall: at a distance of 3mm (transition radius), 8 mm (wall) and 30 mm (open end of the cup) from the cup bottom.
The measured data revealed that the effect of the material planar anisotropy on the thickness variation is only minimal and therefore can be negligible; this means that the mean values of the sidewall thickness measured in three directions were taken into account for the final evaluation.

![Figure 4. Spun cup sidewall thickness measuring plan: a) measured directions, b) measured zones](image)

3. Results and discussion
After the implementation of the experimental measuring process it was possible to analyse the effect of the input process parameters on the thickness variation of the blank sheet during the deformation process. The measured thickness data are summarized in the Table 3 for the individual combinations of the studied parameters. The percentage thickness variation data, which is calculated relative to the initial thickness of the blank sheet (t₀ equals 1 mm), are specified in Table 4. It can be clearly seen that the measured thickness values are varying in the wide interval from 0.903 mm to 1.138 mm. The experimental results also show that the most massive thickness reduction is observed on the transition radius zone (t₁) and on the cup wall t₂ (for the concave tpp). On the open end of the spun part (t₃ zone), a thickening effect dominates over a thinning effect. Only a few thinning cases were observed in this zone.

| Mandrel speed (min⁻¹) | Tool feed rate (mm) | Convex tpp | Linear tpp | Concave tpp |
|-----------------------|--------------------|------------|------------|-------------|
|                       |                    | t₁ (mm)    | t₂ (mm)    | t₃ (mm)    | t₁ (mm)    | t₂ (mm)    | t₃ (mm)    |
|                       | 0.4                | 0.949      | 0.964      | 1.076      | 0.956      | 0.948      | 1.018      | 0.931      | 0.903      | 0.938      |
|                       | 0.8                | 0.970      | 0.991      | 1.106      | 0.973      | 0.975      | 1.103      | 0.941      | 0.917      | 1.004      |
|                       | 1.2                | 0.980      | 1.011      | 1.124      | 0.953      | 0.987      | 1.085      | 0.953      | 0.929      | 1.037      |
|                       | 0.4                | 0.958      | 0.975      | 1.062      | 0.956      | 0.950      | 1.045      | 0.932      | 0.909      | 0.945      |
|                       | 0.8                | 0.984      | 1.009      | 1.111      | 0.959      | 0.977      | 1.094      | 0.947      | 0.931      | 0.982      |
|                       | 1.2                | 0.975      | 1.015      | 1.138      | 0.976      | 0.988      | 1.122      | 0.962      | 0.946      | 1.028      |
|                       | 0.4                | 0.944      | 0.964      | 1.063      | 0.949      | 0.949      | 1.074      | 0.943      | 0.918      | 0.905      |
|                       | 0.8                | 0.962      | 0.990      | 1.085      | 0.963      | 0.977      | 1.089      | 0.972      | 0.952      | 1.035      |
|                       | 1.2                | 0.979      | 1.006      | 1.120      | 0.976      | 0.994      | 1.109      | 0.955      | 0.940      | 1.060      |

Thickness standard deviation values did not exceed the 0.010 mm value in any combination of input parameters.

The graphs in Figure 5 show the evolution of sidewall thickness in consideration of the tool feed and the applied tool path profile at a mandrel rotation speed of 800 min⁻¹. It is clear that the parameters of tool path profile as well as the size of its feed rate significantly affect the variation in the thickness of the spun-cups sidewall. These graphs also indicate that the higher the roller tool, the more significant sidewall thickness variation (thinning means the negative thickness variation or thickening-positive variation of thickness) occurs.
The relative rotational speed of 400 eases, but the thickness of the process is as follows:

- The thickness increasing is only minimal. Hence, this type of tool thickness in the open end of the component.

- The thickness reduction in the open end of the spun parts (11 zone, if sidewall thickening occurs, the thickness increasing is only minimal. Hence, this type of tool path profile appears to be the most improper from the originated thickness variation point of view. The convex tpp contributes to the minimal thickness reduction in the 11 zone, but with the increasing measured distance there is a thickening of the component sidewall observed; while the thickness acquires the maximal values at the open end of the component using this tpp type. Using the linear tpp, the thickness reduction in the 11 and 12 zones is approximately constant; however there is a slight increase in the sidewall thickness in the 13 zone.

- The influence of the of the tool feed size on the sidewall thickness in the individual measured zones is as follows: with the increasing feed values, the thickness reduction decreases, but the thickness of the sidewall increases towards to the open end of the spun parts. The reason is that the higher forming velocity causes a higher material strain rate, this result in a larger material work-hardening during the.

| Mandrel speed (min\(^{-1}\)) | Tool feed rate (mm) | Convex tpp $tv1$ (%) | Convex tpp $tv2$ (%) | Convex tpp $tv3$ (%) | Linear tpp $tv1$ (%) | Linear tpp $tv2$ (%) | Linear tpp $tv3$ (%) | Concave tpp $tv1$ (%) | Concave tpp $tv2$ (%) | Concave tpp $tv3$ (%) |
|-------------------------------|---------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| 400                           | 0.4                 | -5.1 - 3.6 + 7.6      | -4.4 - 5.2 + 1.8      | -6.9 - 9.7 - 6.2      | -4.4 - 5.2 + 1.8      | -6.9 - 9.7 - 6.2      | -4.4 - 5.2 + 1.8      | -6.9 - 9.7 - 6.2      | -4.4 - 5.2 + 1.8      | -6.9 - 9.7 - 6.2      |
|                               | 0.8                 | -3.0 - 0.9 + 10.6     | -2.7 - 2.5 + 10.3     | -5.9 - 8.3 + 0.4      | -2.7 - 2.5 + 10.3     | -5.9 - 8.3 + 0.4      | -2.7 - 2.5 + 10.3     | -5.9 - 8.3 + 0.4      | -2.7 - 2.5 + 10.3     | -5.9 - 8.3 + 0.4      |
|                               | 1.2                 | -2.0 + 1.1 + 12.4     | -4.7 - 1.3 + 8.5      | -4.7 - 7.1 + 3.7      | -4.7 - 1.3 + 8.5      | -4.7 - 7.1 + 3.7      | -4.7 - 1.3 + 8.5      | -4.7 - 7.1 + 3.7      | -4.7 - 1.3 + 8.5      | -4.7 - 7.1 + 3.7      |
| 800                           | 0.4                 | -4.2 - 2.5 + 6.2      | -4.4 - 5.0 + 4.5      | -6.8 - 9.1 - 5.5      | -4.4 - 5.0 + 4.5      | -6.8 - 9.1 - 5.5      | -4.4 - 5.0 + 4.5      | -6.8 - 9.1 - 5.5      | -4.4 - 5.0 + 4.5      | -6.8 - 9.1 - 5.5      |
|                               | 0.8                 | -1.6 + 0.9 + 11.1     | -4.1 - 2.3 + 9.4      | -5.3 - 6.9 - 1.8      | -4.1 - 2.3 + 9.4      | -5.3 - 6.9 - 1.8      | -4.1 - 2.3 + 9.4      | -5.3 - 6.9 - 1.8      | -4.1 - 2.3 + 9.4      | -5.3 - 6.9 - 1.8      |
|                               | 1.2                 | -2.5 + 1.5 + 13.8     | -2.4 - 1.2 + 12.2     | -3.8 - 5.4 + 2.8      | -2.4 - 1.2 + 12.2     | -3.8 - 5.4 + 2.8      | -2.4 - 1.2 + 12.2     | -3.8 - 5.4 + 2.8      | -2.4 - 1.2 + 12.2     | -3.8 - 5.4 + 2.8      |
| 1200                          | 0.4                 | -5.6 - 3.6 + 6.3      | -5.1 - 5.1 + 7.4      | -5.7 - 8.2 - 9.5      | -5.1 - 5.1 + 7.4      | -5.7 - 8.2 - 9.5      | -5.1 - 5.1 + 7.4      | -5.7 - 8.2 - 9.5      | -5.1 - 5.1 + 7.4      | -5.7 - 8.2 - 9.5      |
|                               | 0.8                 | -3.8 - 1.0 + 8.5      | -3.7 - 2.3 + 8.9      | -2.8 - 4.8 + 3.5      | -3.7 - 2.3 + 8.9      | -2.8 - 4.8 + 3.5      | -3.7 - 2.3 + 8.9      | -2.8 - 4.8 + 3.5      | -3.7 - 2.3 + 8.9      | -2.8 - 4.8 + 3.5      |
|                               | 1.2                 | -2.1 + 0.6 + 12.0     | -2.4 - 0.6 + 10.9     | -4.5 - 6.0 + 6.0      | -2.4 - 0.6 + 10.9     | -4.5 - 6.0 + 6.0      | -2.4 - 0.6 + 10.9     | -4.5 - 6.0 + 6.0      | -2.4 - 0.6 + 10.9     | -4.5 - 6.0 + 6.0      |

+ positive thickness variation (thickening),
- negative thickness variation (thinning).
deformation process. Mechanical properties of the deformed material are increasing, however, the formability of the material is worse and the thickness reduction is therefore reduced [8-10, 21].

Using a high feed rate leads to an increase in the compressive tangential stress and accordingly, compressive deformation and thickness strain increase. The final average thickness will therefore deviate away from the initial thickness [8].

**Figure 5.** Measured thickness variation for different tool feed rates (mandrel speed of 800 min⁻¹)

**Figure 6.** Measured thickness variation for different tool path profile parameter (mandrel speed of 800 min⁻¹)

Figure 6 shows the effect of the tool path profile parameter on the thickness values evolution for the mandrel rotational speed of 800 min⁻¹ and a given tool feed. For instance, for the tool feed \( f = 0.8 \) mm it can be clearly seen, that the thickness reduction is equal to 1.6% (application of convex tpp), 4.1% (application of linear tpp) and 5.3% by use of concave tpp in the t₁ measured zone. In the t₂ measured zone the thickness increasing of about 0.9% for the convex tpp was observed and thickness reduction of about 2.3% and 6.9% for the linear and concave tpp was spotted. The thickening effect is characteristic for the open end of the parts on t₃ measured zone. The thickness increase of about
11.1% and 9.4% is typical for application of convex and linear tpp respectively. Thickness reduction of 1.8% was recorded for the concave tpp in this zone. It is possible to notice at the same time that the most massive thickness variation is achieved using the concave tool path profile and vice versa, application of convex tpp helps to minimise the thickness variation. According to [16] using concave roller paths in spinning tend to cause higher reduction of the wall thickness of the spun part and using the convex roller path helps to maintain the original wall thickness unchanged. A greater curvature of the concave path would result in more thinning in wall thickness of the spun part.

In order to quantify the effects of the studied factors and 2-factor interactions on the thickness variation of the spun cups, the analysis of variance (ANOVA) using Minitab v.17 software was performed. The Fisher’s ratio (F-ratio), which is the ratio between the variance due to the effect of a factor and the variance due to an error term, was used to measure the significance of the factor at the desired significance level. If the F-value is greater than the tabulated F_{crit} value, the process parameter is considered as significant.

The ANOVA results (Table 5) revealed that the studied input parameters: tool path profile tpp and tool feed f can be considered as statistically significant in the zones of transition radius (t1- thinning) and extremely significant in the zone of the part open end (t3- thickening). The effect of the mandrel speed on thickness variation is only minimal in these zones, which is supported by other experimental researches [5, 8, 22]. This can be explained as follows: mandrel speed has the negligible effect on the axial and radial force components, therefore radial and thickness strain is minimal [23].

In the part wall zone (t2- thinning or thickening occurs) it was found that besides the tool path profile and tool feed rate, the mandrel speed and 2-factor interaction of tpp*n can be considered also as significant factors on the thickness variation.

| Table 5. ANOVA for studied sidewall thickness in three different zones |
|-----------------------------|-----------------------------|-----------------------------|
| Source | Thickness variation t1 | Thickness variation t2 | Thickness variation t3 |
|       | DF | F-ratio | p-value | DF | F-ratio | p-value | DF | F-ratio | p-value |
| tpp   | 2  | 7.18    | *0.016  | 2  | 289.12  | *0.000  | 2  | 52.03   | *0.000  |
| n     | 2  | 0.53    | 0.610   | 2  | 5.44    | *0.032  | 2  | 0.15    | 0.861   |
| f     | 2  | 9.90    | *0.007  | 2  | 98.10   | *0.000  | 2  | 25.07   | *0.000  |
| tpp*n | 4  | 0.90    | 0.508   | 4  | 4.22    | *0.040  | 4  | 0.57    | 0.694   |
| tpp*f | 4  | 0.31    | 0.861   | 4  | 1.41    | 0.313   | 4  | 1.26    | 0.361   |
| n*f   | 4  | 0.17    | 0.950   | 4  | 0.41    | 0.797   | 4  | 0.24    | 0.909   |
| Error | 8  | 8       | 8       | 8  | 8       | 8       |
| Total | 26 | 26      | 26      | 26 | 26      | 26      |

where: tpp - tool path profile, n - mandrel speed, f - tool feed rate, DF - degrees of freedom.
Tabulated F_{crit} at 95 % confidence level: F_{crit}(0.05; 2; 8) = 4.46; F_{crit}(0.05; 4; 8) = 3.84
R-sq(adj) = 86.63 % for t1; R-sq(adj) = 96.82 % for t2 and R-sq(adj) = 84.77 % for t3; replicates: 1
* statistically significant parameter

4. Conclusion
The following conclusions can be drawn according to the experimental results:
- Thickness evolution in the individual measured zones is significantly affected by the combination of input process parameters, while the massive thinning and thickening was observed.
- Tool path profile tpp and tool feed rate f can be considered as statistically significant parameters among the all studied process parameters and their 2-factor interactions. The effect of the mandrel speed is only minimal.
- From the minimal thickness reduction point of view it is recommended to apply the convex tool path profile, however this tpp leads to the most massive thickness increase on the open end zone. Contrariwise, the concave tool path profile causes the biggest reduction on first two measured zones,
what also predicted the potential zones of the generated cracking of the material. However, the thickening feature on the open end is minimal.

- It was found that higher tool feed values contribute to the lesser thickness reduction, but on the other hand to a thickness increase on the open end zone of the formed parts. This can be explained as follows: if lower tool feed is applied, the material deformation takes a longer time, which results in a considerable thinning of the spun part wall; hence the wall heights values are higher.
- Authors recommend the application of higher mandrel rotational speeds during the deformation process. There are two reasons for this: one is an increased magnitude of spinning force due to the high deformation rate; the other is that the deformation energy required per revolution is likely to decrease because the feed rate is inversely proportional to the spindle speed (mm/rev) [24].

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