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Influence of toolpath strategies on the final accuracy and thickness distributions in multi-stage incremental forming

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Abstract. This study focuses on finding a toolpath strategy for accurately forming geometric details on a preshaped sheet metal part by incremental forming in multiple steps. The final thickness distributions and geometrical accuracy are analyzed for spiraling and dedicated feature toolpath strategies. The results are compared to forming the full part (base shape with details) in a conventional single stage manner. Forming the part in multiple steps did improve the accuracy of the part, by decreasing the underforming of the base shape compared to single stage forming. The observed overforming was highly influenced by the location of the detail. In terms of thickness distributions, the toolpath strategy highly influenced the location of the minimal thickness inside each detail. Here, the dedicated feature toolpath proved to be effective for achieving a more uniform thickness distribution.

Introduction

Incremental sheet forming (ISF) is a versatile and innovative manufacturing process that enables the production of complex 3D shapes through the gradual deformation of sheet metal. Unlike traditional forming methods that use dies or molds to shape entire components in one pass, ISF employs a more localized approach by incrementally deforming the material in each pass of a generic tool. This process offers several advantages, including reduced tooling costs and increased flexibility in design. In Single Point Incremental Forming (SPIF), a single tool, mostly hemispherical in shape, moves along a toolpath and thereby locally deforms the sheet [1].

One of the advantages of SPIF lies in its flexibility to form complex shapes. However, this flexibility also introduces challenges in controlling unwanted deformations, primarily due to the absence of sheet support. Proposed solutions for mitigating these unwanted deformations include compensation methods that adjust the Computer Aided Design (CAD) model of the desired shape, or adapting the toolpath [1]. Many studies show the influence of the toolpath strategy on the final feasibility and geometric accuracy [2,3]. Typically used toolpath strategies are spiral or contour toolpaths, with spirals offering superior surface finish, but also posing challenges in implementation on more complex geometries [1]. Another important toolpath parameter is the stepdown, where a higher value results in a reduced surface quality, but a too low stepdown might result in early failure due to fatigue or cyclic loading [1]. Additional strategies to enhance geometric accuracy include inclination of the plane for the toolpath [4,5], separation of features [6] and multi-stage forming [7,8,9]. For the feature separation, Lu et al. [6] suggested identifying regions based on edges such that the toolpath can be adapted properly and the geometric accuracy improved. Here, the features are considered as different areas divided from each other by edges.

This paper delves into the adaptation of toolpaths in combination with multi-stage forming, focusing on complex shapes that comprise a base shape with intricate details superimposed, or on enhancing preformed parts with additional details. Particularly this last category is promising, since hybrid techniques, that combine ISF with mass sheet forming methods, might improve efficiency and can be a good solution for customized parts that have a common base shape. Here,

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traditional techniques can be used for producing the base shape in mass and personalized details can be added later using ISF. One example of such hybrid forming is the combination of stretch forming with SPIF, where the stretch forming can be used to avoid noncompliance with process limits by producing a preshape with more uniform thickness distributions on which SPIF can be applied in a later stage [10]. By combining the strengths of both conventional and incremental forming, manufacturers can meet the growing demand for customized, high-detail components across diverse industries.

This paper dives further into identifying an appropriate toolpath strategy for details when a preformed base shape is available, offering insights into optimizing the incremental forming process.

Experiments and Methods

Using a single stage strategy in Single Point Incremental Forming has limitations in terms of geometric accuracy and the ability to produce complex shapes consisting of intricate details. This study focuses on applying details on an already preformed part, thereby comparing multi-stage forming strategies with conventional single stage forming of the full detailed part in only one step. Two different toolpath strategies are applied to form the details on top of an already formed base shape. This exploration includes both regular spiral toolpaths and specialized feature toolpaths, the last one proposed by Carette et al. [11], for the individual details. Subsequently, all resulting parts are compared in terms of geometric accuracy and final thickness distributions for optimizing the incremental forming process.

The experiments are conducted on 225x225 mm sheets of pure commercial Zinc with a thickness of 1.5 mm on a Maho600 CNC machine. The shape to be considered consists of a hemispherical base shape with multiple spherical details, at different locations on the base shape (see Fig. 1). The locations are chosen by dividing the base shape in three areas: zone 1 close to the backing plate (details A, D and F), zone 3 at the top (detail C) and zone 2 in the middle between zones 1 and 3 (details B and E). The midpoints of the spheres are located in these zones, which have the same meridional distance *s* from each other and from the backing plate, measured along the hemispherical surface. The spherical details have diameters of 20, 30 or 40 mm, and are inserted such that their maximal angle with the blank (the *xy*-plane) is 90 degrees. The sheet is clamped along its circumference with a circular backing plate of 180 mm diameter.

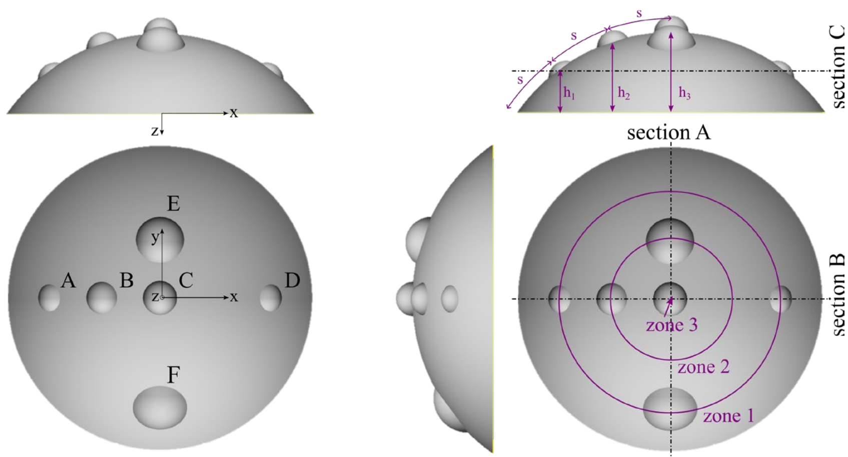


Figure 1: Geometric shape used for the experimental campaign: a spherical base shape with multiple spherical details.

After lubricating the sheet with Nuto 46 oil, toolpaths are applied with a 10 mm diameter tool at a feedrate of 2000 mm/min, following either spiral or feature toolpaths for the details with a scallop width of 1 mm. The base shape is formed with a spiral toolpath with the same scallop width. Both the spiral and feature toolpaths perform a spiraling type of movement, with the difference that for the conventional spiral toolpath these are oriented parallel to the blank (the *xy*-plane), whereas the feature toolpath starts by following the edges of the part (see Fig. 2). For this shape, the feature toolpaths of the spherical details correspond to tilted spiral toolpaths. The details are formed in the following sequence: A-D-B-C-F-E. The single stage forming is done with a contour toolpath, since the spiral toolpath cannot form details if they are deeper than the base shape. In that case, when taking a *z*-slice, multiple sections can be extracted and the spiral toolpath cannot be formed anymore.

In between each step and after production, the sheet is measured on a Coord3 MC16 CMM with LC60Dx Laser Line Scanner to obtain the geometric accuracy and thickness distributions.

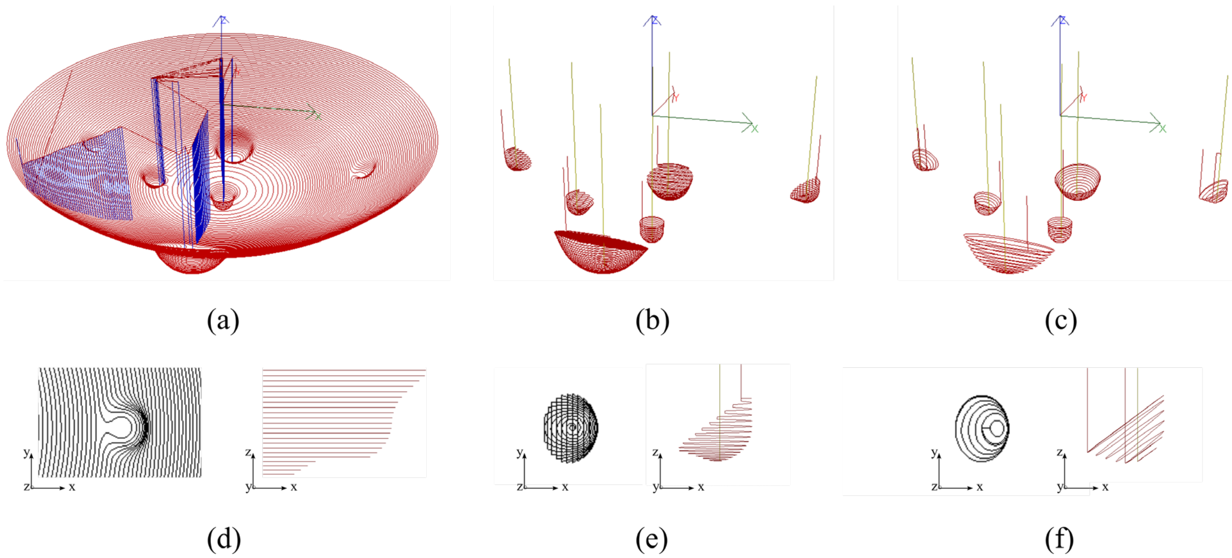


Figure 2: (a) Contour toolpath to form the part in one step and (b) spiral and (c) feature toolpaths for forming details A-F in multiple stages (see Fig. 1). Closeups of the (d) contour, (e) spiral and (f) feature toolpath for detail D.

Results and Discussion

Geometric Accuracy. Fig. 3 shows that forming the details on top of a preshaped part (multi-stage forming with spiral or contour toolpaths for the details, Fig. 3.b and c) significantly affects the geometric accuracy compared to forming the full shape with details in only one step. In Fig. 3.a, it is clear that the underforming (orange areas) of the base shape close to the backing plate is much higher in single stage than when the details are formed in a later stage. Table 1 confirms these observations, with a maximal underforming of the base shape reducing from 1.65 mm in the single stage case to less than 1 mm when applying the details separately. The underformed areas in the single stage case are located within the *xy*-plane of a toolpath contour, surrounding the formed details. In each single stage contour, the toolpath extends outwards while shaping the details, as can be seen in the toolpath in Fig. 2.d. Close to the backing plate, the three details A, D and F influence the base shape significantly. This is due to the outward tool movement, resulting in a flattening of the already formed areas in the base shape. Consequently, this phenomenon leads to an underforming of the part. This effect might be less outspoken in the details further away from the backing plate (details B, C and E in zones 2 and 3) due to a higher geometrical stiffness of the already formed areas.

The highest geometrical deviations occur due to overforming at the edges between the base shape and the details (blue areas in Fig. 3). Table 2 shows that the overforming is maximal at the edge of detail C, located at the top of the hemispherical base, with a geometrical deviation of 4.09

mm in single stage forming. Here, multi-stage forming significantly decreases this maximal deviation to 3.46 mm when using spiral toolpaths and 2.89 mm for feature toolpaths.

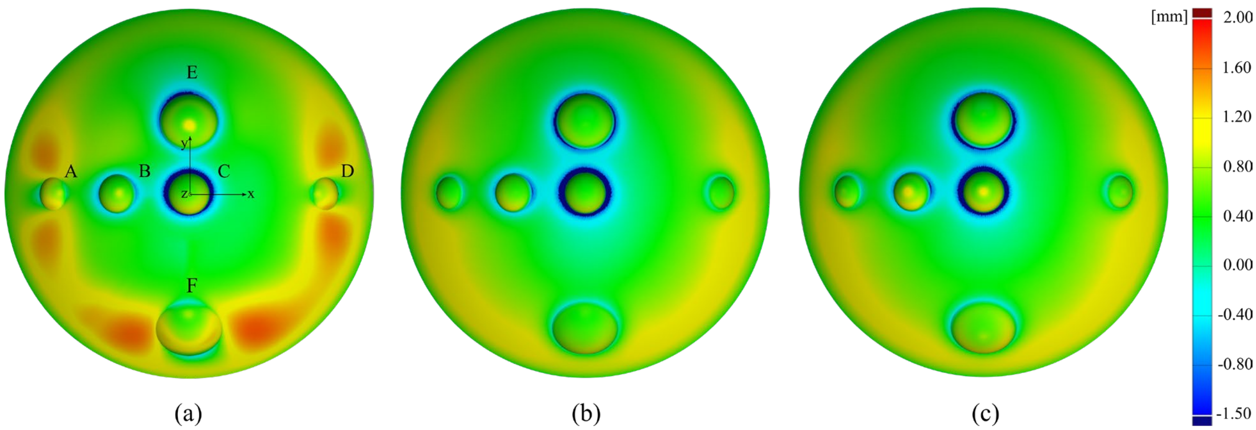


Figure 3: Geometrical accuracy for (a) the contour single stage strategy, (b) the spiral multi-stage strategy and (c) the feature multi-stage strategy. Negative values indicate overforming, positive underforming.

Table 1: Geometric deviations for each strategy, presenting the maximal underforming (positive values in Fig. 3).

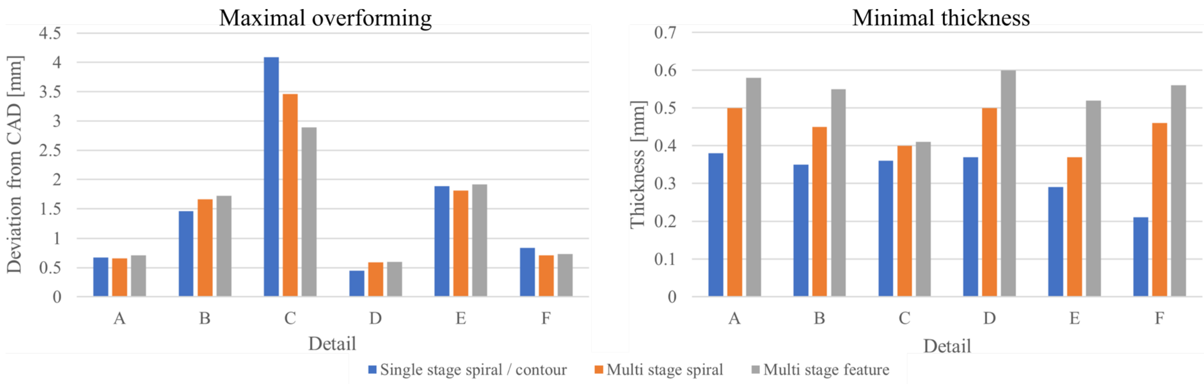
Maximal *under*forming [mm]				
Detail	Detail position	Single stage spiral / contour	Multi-stage spiral	Multi-stage feature
base shape	NA	*1.65*	*0.97*	*0.99*
A	1	1.08	0.49	0.66
B	2	0.68	0.70	0.95
C	3	0.73	0.62	0.85
D	1	1.24	0.53	0.57
E	2	0.90	0.41	0.51
F	1	1.13	0.64	0.79

Table 2: Geometric deviations for each strategy, presenting the maximal overforming (negative values in Fig. 3). The location of this maximal overforming is always at the transition between the detail and the base shape.

Maximal *over*forming [mm]				
Detail	Detail position	Single stage spiral / contour	Multi-stage spiral	Multi-stage feature
A	1	0.67	0.66	0.71
B	2	1.46	1.66	1.72
C	3	*4.09*	*3.46*	*2.89*
D	1	0.45	0.59	0.60
E	2	1.89	1.81	1.92
F	1	0.84	0.71	0.73

Fig. 4.a visualizes the maximal overforming of each detail, as shown in Table 2. Interesting to observe here are consistent patterns that can be connected to the location of the detail. As can be

seen in this graph, the details closest to the backing plate (A, D and F) show the least overforming at their edges with the base shape. This maximal overforming seems very consistent, even though the detail size and proximity to neighboring features are not the same. Details in zone 2 (B and E, see Fig. 1) also show similar overforming, higher than the overforming in zone 1, close to the backing plate. Detail C, the one in the center of the spherical base, shows the highest overforming for all different strategies. Here, the influence of the strategy is more clear than for the other details, with higher deviations from the desired CAD model for the single stage strategy, and the best performance for the multi-stage feature toolpath.



(a) (b)

Figure 4: Comparison between the different strategies of all details for (a) the maximal overforming from Table 2 and (b) the minimal thickness from Table 3.

A sectional view of the geometric accuracy at different locations is shown in Fig. 5. Here, the overforming at the edge between the detail and the base shape is even more clear. The section at Z=h_1 shows the underforming of the base shape within the *xy*-plane of a toolpath contour. Interesting to note here is that the underforming is much higher for single stage forming, but the curvature at the edge of the detail is more outspoken in a section parallel to the blank.

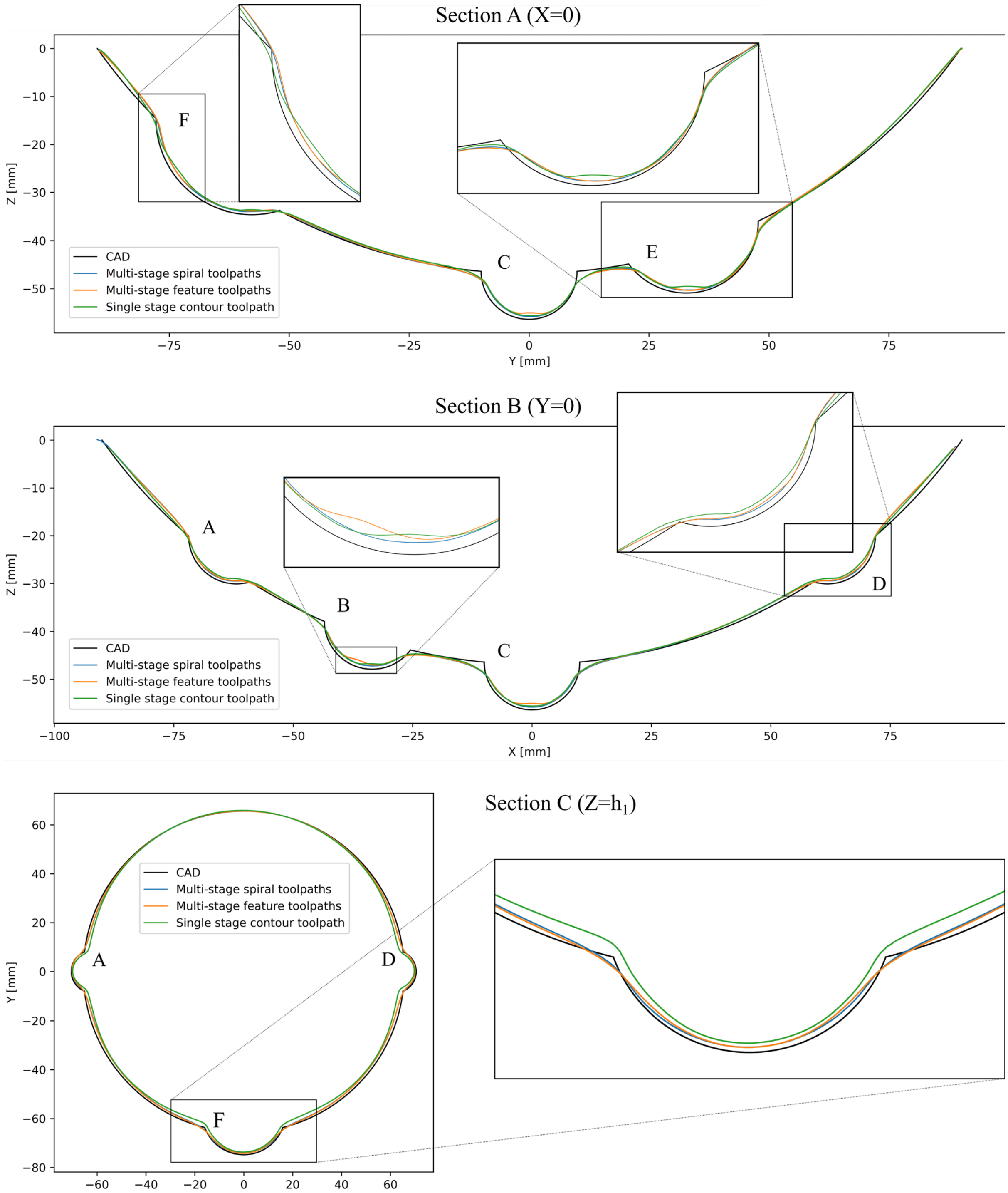


Figure 5: Comparison of the measured shape and desired shape for all strategies at section A, B and C in Fig. 1.

Thickness distributions. Fig. 6 illustrates that the thickness distributions vary significantly among the three strategies. Table 3 also reveals that the minimal thickness after forming is considerably lower in the single stage case compared to multi-stage forming. Depending on the toolpath strategy, the location of minimal thickness within each detail also differs. Multi-stage spiral and single stage contour toolpaths yield lower thicknesses in areas with higher wall angles, while feature toolpaths avoid such local thinning by tilting the toolpath, thereby decreasing the maximal wall angles compared to the forming direction. Table 3 highlights the influence of the strategy on the thickness distributions. Although, in theory, none of the details should be feasible according to the sine rule, in practice the angles do not reach 90 degrees due to unwanted overforming at the edges (see Fig. 5). For the detail located at the top of the base shape (detail C), no significant difference in thickness distributions across the three strategies can be observed. This is logical, since the three strategies have a very similar toolpath for this part of the shape. Fig. 4.b also shows a comparison of the minimal thickness of each detail for all different strategies. Here, it is also clear that the multi-stage strategies significantly increase the minimal thickness for almost all details, with the feature toolpath showing the best performance.

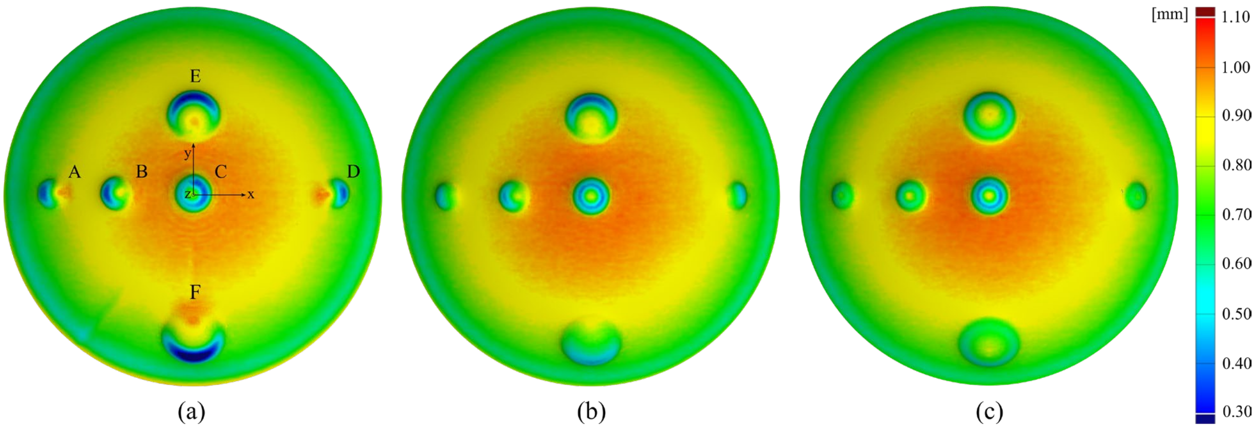


Figure 6: Thickness distributions of (a) the contour single stage strategy, (b) the spiral multi-stage strategy and (c) the feature multi-stage strategy.

Table 3: Minimal thickness for each strategy.

Minimal thickness [mm]			
Detail	Single stage spiral / contour	Multi-stage spiral	Multi-stage feature
A	0.38	0.50	0.58
B	0.35	0.45	0.55
C	0.36	0.40	*0.41*
D	0.37	0.50	0.60
E	0.29	*0.37*	0.52
F	*0.21*	0.46	0.56

Conclusion

This study investigated toolpath strategies in combination with multi-stage forming for improving the geometric accuracy and thickness distributions of complex shapes consisting of a base shape with one or more details. The following conclusions can be made:

- Both a spiral and a feature toolpath decreased the deviations for the proposed shape. The maximal overforming at the edges of the details showed to be connected to the location of the detail, where details further from the backing plate showed larger overforming. The single step contour toolpath resulted in higher deviations in the base shape compared to the multi-stage toolpaths, with much higher underforming in the *xy*-plane around the details close to the backing plate.
- The thickness distributions were significantly influenced by the toolpath strategy. Both of the proposed multi-stage strategies resulted in a higher minimal thickness compared to single stage forming with a contour toolpath. The multi-stage feature toolpath showed to be the best choice in terms of thickness distributions when forming details on steeper walls,

where the feature toolpath inclination decreased the wall angles compared to the forming direction.

These results show that the choice of the toolpath strategy plays an important role in complex parts with details. The study gives more insight in adding details to preshaped parts, which is a promising direction for applying ISF as a hybrid process in industry. The findings show that multi-stage forming is promising for forming the proposed details. However, a tailored approach, depending on the formed shape and location of the details, might be needed.

Future research may explore a broader range of parts, both for the base shape and for the shape and placement of the details. Applying the found strategies on real-life examples can then be enhanced by automatic separation of the detail from the base shape, such that the base and detail toolpaths can be quickly subtracted and merged with each other. Subtracting the detail can be done by detection of the edges, for example based on the feature detection proposed by Behera et al. [9].

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References

[1] J. R. Duflou, A. M. Habraken, J. Cao, R. Malhotra, M. Bambach, D. Adams, H. Vanhove, A. Mohammadi, J. Jeswiet, Single point incremental forming: state-of-the-art and prospects, International Journal of Material Forming. Vol. 11, no. 6 (2018) 743–773. https://doi.org/10.1007/s12289-017-1387-y

[2] J. M. Allwood, O. Music, A. Raithathna, S.R. Duncan, Closed-loop feedback control of product properties in flexible metal forming processes with mobile tools, CIRP Annals. Vol. 58, no. 1 (2009) 287–290. https://doi.org/10.1016/J.CIRP.2009.03.065

[3] L. Ben Said, The incremental sheet forming; technology, modeling and formability: A brief review, Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering. Vol. 236, no. 6 (2022) 2729–2755. https://doi.org/10.1177/09544089221093306

[4] H. Vanhove, J. Gu, H. Sol, J. R. Dulfou, Process Window Extension for Incremental Forming through Optimal Work Plane Rotation. In the 10th anniversary of the International Conference on Technology of Plasticity, Aachen, Germany on September 25th-30th, 2011.

[5] S. Tanaka, Incremental sheet forming with direction control of path planes, ICTP2011. Vol. 53, no. 619 (2011) 503–507.

[6] B. Lu, J. Chen, H. Ou, J. Cao, Feature-based tool path generation approach for incremental sheet forming process, J Mater Process Technol. Vol. 213, no. 7 (2013) 1221–1233. https://doi.org/10.1016/j.jmatprotec.2013.01.023

[7] Z. Yan, H. Hassanin, M. A. El-Sayed, H. M. Eldessouky, J. R. P. Djuansjah, N. A. Alsaleh, K. Essa, M. A. Ahmadein, Multistage Tool Path Optimisation of Single-Point Incremental Forming Process, Materials 2021. Vol. 14, no. 22 (2021) 6794. https://doi.org/10.3390/MA14226794

[8] K. S. Jung, J. H. Yu, W. J. Chung, C. W. Lee, Tool Path Design of the Counter Single Point Incremental Forming Process to Decrease Shape Error, Materials 2020. Vol. 13, no. 21 (2020) 4719. https://doi.org/10.3390/MA13214719

[9] A. K. Behera, B. Lauwers, J. R. Duflou, Tool path generation framework for accurate manufacture of complex 3D sheet metal parts using single point incremental forming, Comput Ind. Vol. 65, no. 4 (2014) 563–584. https://doi.org/10.1016/J.COMPIND.2014.01.002

[10] R. Jagtap, S. Kumar, An experimental investigation on thinning and formability in hybrid incremental sheet forming process, Procedia Manuf. Vol. 30 (2019) 71–76. https://doi.org/10.1016/j.promfg.2019.02.011

[11] Y. Carette, H. Vanhove, J.R. Duflou, Multi-step incremental forming using local feature based toolpaths, Procedia Manuf. Vol. 29 (2019) 28–35. https://doi.org/10.1016/J.PROMFG.2019.02.102