Int J Mater Form (2016) 9:9–19
DOI 10.1007/s12289-014-1195-6

ORIGINAL RESEARCH

Variation of components by automated driving

A knowledge-based approach for geometric variance

Daniel Opritescu · Wolfram Volk

Received: 7 March 2014 / Accepted: 23 September 2014 / Published online: 11 October 2014
© Springer-Verlag France 2014

Abstract Driving as an incremental forming method can be carried out on driving machines. The copied driving process has been developed based on this manual manufacturing method. The process allows the reproduction of identical components using manual manipulations performed by the worker on the driving machine, the so-called manufacturing strategies. For this, the manufacturing strategy is tracked during the manual driving process and can thus be repeated accurately by robot handling to ensure reproducibility. Since manufacturing strategies can be made available for hand-crafted components, in this paper, for a sample component we demonstrate how this process information can be utilised to derive geometric variations of the sheet metal part in the sense of scaling. For this purpose, the necessary procedures are presented which apply an existing component geometry and the associated manufacturing strategy. An analytical characterisation of the manufacturing strategy and a functional description of the relation between sheet blank geometry before deformation and manufacturing strategy are deduced. This allows control of process parameters to vary the strategy and hence enables a variation of component geometry that is finally subject to validation and verification.

Keywords Incremental sheet forming · Flexible manufacturing system (FMS) · Knowledge-based system · Tool path

D. Opritescu (✉) · W. Volk
Institute of Metal Forming and Casting (utg),
Technische Universität München,
Garching, Germany
e-mail: daniel.opritescu@utg.de

Introduction

The challenges of the market for sheet metal parts demand more and more individuality and customer specific products [1]. Facing these requirements incremental sheet forming opens up new possibilities in the field of sheet metal working. Usually, two point incremental forming (TPIF) and single point incremental forming (SPIF) are of special interest, as they enable the production of asymmetric sheet metal shapes. Both processes use a simple smooth-ended forming tool with a diameter far smaller than the dimension of the part being produced. It is moved along contours which follow the final geometry that is described in CAD and CAM software. The term SPIF is used when the counterpart of the sheet is supported by a faceplate or a counter tool, whereas TPIF is used when a full or partial die supports the sheet blank during the process. A comprehensive overview of these incremental forming technologies is given in [2]. While this contribution adresses the feasibility and the fundamentals of the processes, in [3] an extensive recapitulation of incremental sheet forming in general is given, focusing on technological developments by reviewing and listing patents.

There is a lot of research done on the promising forming processes TPIF and SPIF to comply with industrial quality requirements. For this reason, fundamental material formability issues have been studied and correlations to mechanical properties analysed, e.g. [4]. In [5], deformation mechanisms, as well as different materials, are studied so as to promote the understanding of the process. A further analysis of the forces during the forming process, taking into account different process parameters, is performed in [6] and can be used for supporting part failure prediction. Theoretical models can also be found in the literature. In [7], for instance, an analysis focused on the extreme modes of deformation which appear during the process is established. In [8], the authors present an approach to accurately define forming limits for SPIF, assisting the designer in understanding and determining in what case SPIF is a viable process for production of a specific component shape.

Various promising methods for trying to resolve dimensional and shape errors are recapitulated in [9], e.g. flexible support and the use of adapted trajectories. Most improvements have been achieved by studying the tool path strategies in detail. While [10, 11] introduce concepts for tool path generation and control on the basis of on-line data detection during the running CNC program for SPIF, in [12] the authors focus on TPIF. The surface quality and geometric accuracy of the scrutinised component is enhanced by analysing the sheet behaviour as a function of different tool path strategies. Furthermore, multi-stage strategies are presented in order to overcome geometric restrictions and limitations in incremental forming [13–15]. These concepts are based on sequential manufacturing of intermediate components exceeding conventional single-step forming limits. Modifications of these methods are documented in the literature which aim to prevent stepped features and thus successfully achieve a smoother component base [16].

Often, tools like finite element analysis are applied for compensation of tool paths. Recent approaches deal with implicit iterative algorithms, combined with multiple domain methods, in order to reduce overall computing [17]. However, computation time is still a major restriction to the implementation of finite elements in the field of incremental sheet forming.

Ongoing research activities turn attention to the implementation of feature-based methods. Here, the workpiece is split into a configuration of simple geometric shapes for which optimal tool paths are generated and finally composed to a single pass strategy [18]. This approach is further improved by utilising multivariate adaptive regression splines, as introduced in [19], as a fast and robust error prediction tool. Therewith, error response surfaces are generated for individual features and feature combinations, bringing down the accuracy for the majority of the considered test cases to less than 0.4 mm of average absolute deviations [20].

Though significant imrovements have been reached, there are still strong bounds on the processes with respect to part accuracy and limitations on the geometric bandwidth of the component shape in general. These are the reasons why TPIF and SPIF have been rarely applied in practice up to now.

In this paper, we consider a special kind of driving process which facilitates a different technical realisation of an incremental sheet forming process and could help overcome the limitations of TPIF and SPIF (Fig. 1). Of course, the process itself has limitations concerning the size of the parts

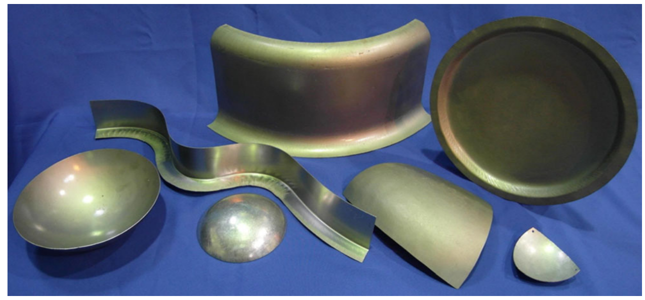

Fig. 1 Small excerpt of the range of component shapes producable utilising the investigated driving process

and their accessibility during the process. Furthermore, the level of detail is limited by the tool dimensions.

For the process, only low-priced universal tool sets, consisting of pairs of top and bottom tools, are needed. The final geometry is incrementally achieved in a large number of steps, and strokes respectively. The main tools utilised for that kind of driving process type can perform stretching or shrinking in local forming areas of the sheet metal part. A schematic draft of the stretching and shrinking tool sets is shown in Fig. 2.

The sheet metal part is only fixed between the tool components while punching. By translation of the vertical force of strokes into a horizontal direction, a local stretching or shrinking of the material is achieved. In contrast to TPIF or SPIF, the blank edge is not steadily clamped during the process. Instead, the sheet moves. That increases the degrees of freedom and makes tool path generation a great challenge and the critical issue. Unfortunately, applying tool path generation techniques, as for TPIF or SPIF, is not possible for this process as tool path and component shape are

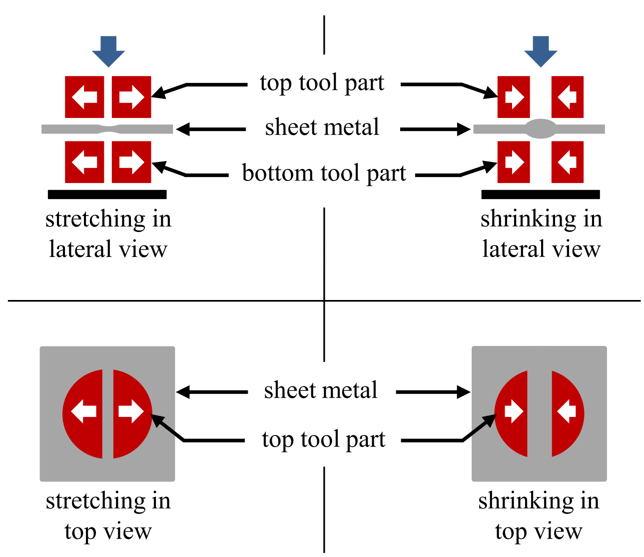

Fig. 2 Principle of tool sets for the driving process enabling local material stretching and shrinking

not related and thus the strategies cannot be derived directly from CAD data. Currently, strategies for part production utilising this process are still knowledge-based and strongly dependent on the worker's experience. However, users are struggling with high manual effort and poor reproducibility. Thus, automation is obligatory for making this process an economically justifiable application.

The first steps towards automation focused on simulation to enable numerically-controlled driving [21]. As it is a strongly interactive, manual process, and due to the process influencing factors, traditional approaches for automating the process failed. Reasons are, for example, changing mechanical properties during the process, tribology, wear, work hardening and the high number of forming steps. In particular for 2D-geometries, cognitive methods were adopted effectively to make at least worker assistance or partial automation possible [22]. However, for 3D-components, there was less success, as the cognitive concepts for 2D-problems cannot easily be adopted to 3D-problems.

An initial achievement, and first effective result, for driving 3D-components was the development of the concept of copied driving. This process tracks the manual manufacturing process performed by the worker and converts that recorded information to a series of coordinates which serve as control data for a handling robot that can completely reproduce the manually-executed driving process [23]. Due to the manual tracking step, the copied driving process is suitable for small batch, but not for individual and prototypic production. For a further increase of the automation degree, it is proposed to derive the manufacturing strategies for new sheet metal parts from known strategies.

Problem formulation and conceptual design

As driving in general is a complex forming process, it is very difficult to directly model the complete process. Furthermore, the utilised process has the advantage that material can locally be stretched and shrunk, as a unique feature. However, this comes with the drawback that, in general, tool path strategies have no relation to the component geometry. This, on the one hand, originates from the characteristic of the process, as the sheet metal, for example, is not clamped at all. On the other hand, the orientation of the tool while punching on the component is of importance, as strokes at the same position, but with different orientation, have diverging influence. Thus, the objective is to provide a model-free idea based on the copied driving process that allows fully automated manufacturing of variants of known components. For this, the manufacturing strategies, the tracked positions and orientations of the sheet metal part during the manual driving process are available and can be recalculated to stroke positions with specific tool orientation on the sheet metal part. These will be utilised in order to increase the geometric spectrum and consequently qualify the driving process for industrial production applications in small batch series.

The appropriate flow chart for reaching this aim is depicted in Fig. 3. A desired sample geometry is given as input and has to be crafted manually. Thus, at least one appropriate manufacturing strategy for the component geometry is available. In a second step, the strategy is analysed and parametrically recreated. The generated strategy is used to clone the sample metal part and, in addition, to produce different geometric variants of the sample component by parameter variance. Finally, a parameter interpolation concept enables the application to produce a wide bandwidth of miscellaneous geometric variants of the sample component.

As we assume to have a strategy for a sample sheet metal part, we will not consider the input (1) and the manufacture step (2) within this paper. However, we will give a short

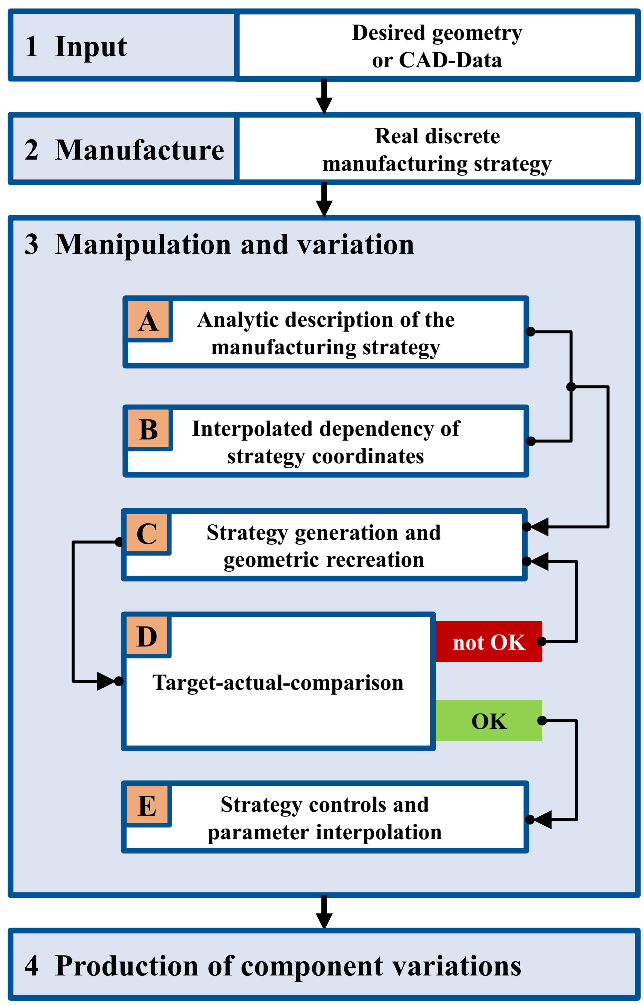

Fig. 3 Process chart for the concept of geometric variance of sheet metal components

definition of the sample geometry used for our research before focusing on the manipulation and variation module (3) with its specific sub-modules. We will start with the analytic description of the manufacturing strategy (A) and then continue with the interpolated dependency of strategy coordinates (B). After this, we shift order and introduce the strategy control and parameter interpolation (E), as this is necessary for the understanding of the complete process. Subsequently, the strategy generation and geometric recreation sub-module (C) will be addressed. Sub-module (D) is not considered in particular, as it is about measuring and digitising the component geometry, which is comprehensively specified in literature and the required measuring systems are commercially available. However, relevant investigations for this project, e.g. optical measurement of the sheet metal parts and the analysis of error tolerances, are integrated in the section dealing with sub-module (C). To complete the investigations, the production of component variants (4) is considered by a discussion of limits and restrictions on the application. As a conclusion, an outlook for further enhancements is appended to the summary.

Thus, the main objective is the analysis and development of concepts and techniques for knowledge-based manipulation of the manufacturing strategies faciliating geometric variants of sheet metal parts. For this purpose, the focus of this paper is to deduce a concept for the variance of a sample element. Thereby, variations in the sense of scaling are investigated which can be easily applied to shearing and curvature modification, too.

Strategy manipulation and geometric variation

In the following, a concept for varying sheet metal component geometries based on the copied driving process is presented. After defining a sample component, its manufacturing strategy is analysed in detail. This will lead to an analytical description of the strategy and subsequently to a method enabling control of the process parameters, allowing geometric modification of the sample sheet metal part.

Definition of a sample component

For further investigation, we will refer to the sample sheet metal component depicted in Fig. 4. The part can be divided into simple geometric features: one plane sector (1), two cylindric sectors (2) and one spheric sector (3). The blank is made out of a quadratic sheet metal with a lateral length of 135 mm, with one corner radiused by 67.5 mm. For the investigations, deep-drawing steel DC04 of 0.8 mm thickness is used.

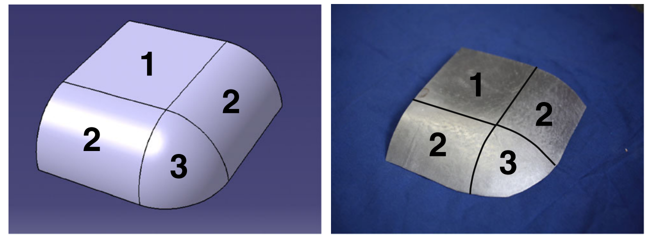

Fig. 4 Sample component: virtual (*left*) and real sheet metal part (*right*)

In order to obtain the specific geometry of the sample component, the sheet blank has to be formed by driving, applying an appropriate manufacturing strategy. For easy visualisation and understanding, the positioning coordinates for the robot are transformed to the sheet metal part coordinate system. A manufacturing strategy idea for the sample component is shown in Fig. 5 that depicts one possible path along which a worker or a handling robot has to perform strokes on the sheet blank before deformation. For the sample component the shrinking tool set with local deformation in parallel direction to the shown tool path trajectory has been applied.

Of course, there are more possible paths for generating the same output, but we have restricted ourselves to the given path and have only used this one for further analysis. It should be noted that this specific tool path proposal is based on the knowledge and experience of the worker as, up to now, there has been no way of tool path estimation for the applied type of driving process. In addition, in this research

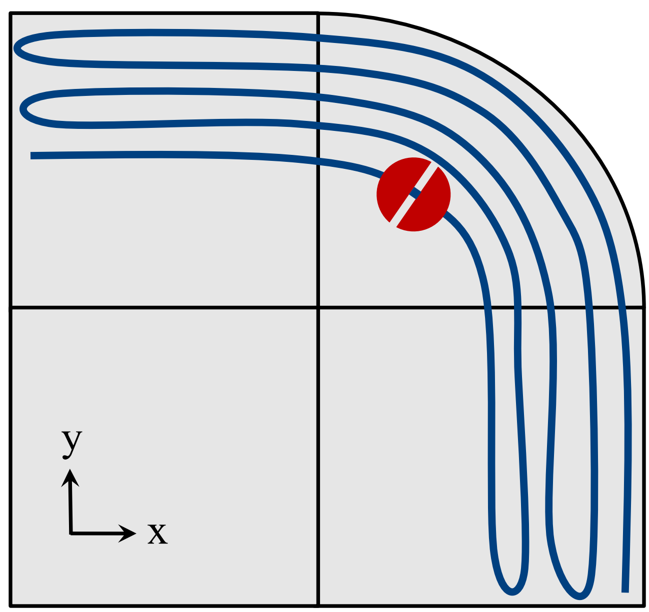

Fig. 5 Possible manufacturing strategy for the sample component; trajectory on the sheet metal part marks the tool path along which strokes have to be performed on the sheet blank before deformation; the local deformation is applied in parallel direction to the tool path trajectory

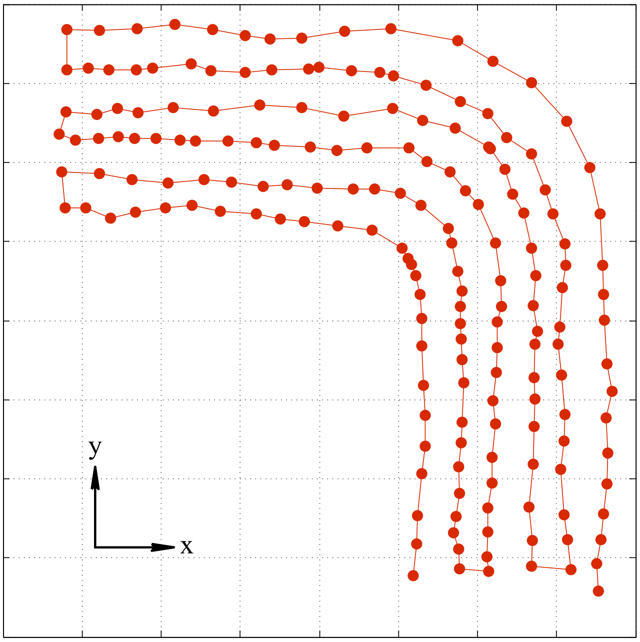

Fig. 6 Utilised strategy for crafting the sample component in 2D-projection in sheet metal part coordinate system; dots indicate stroke positions correlating to strokes on the component with the tool set; it should be noted that typically tool path and component shape are not related for this driving process

we keep the intensity of strokes constant at the level that was used for the manual manufacturing process. However, this is no limitation as the level of stroke intensity can be balanced by the number of strokes.

Figure. 6 shows the utilised real tool path strategy for crafting the sample component in 2D-projection. Every point denotes the explicit stroke performed by the driving tool on that position in the sheet metal part coordinate system.

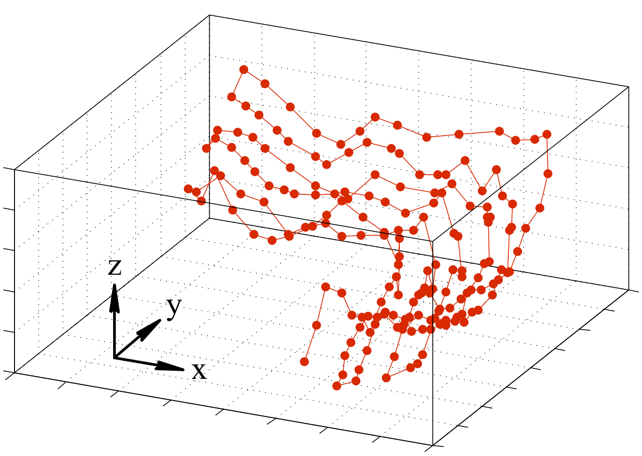

Fig. 7 Utilised strategy for crafting the sample component in 3D-visualisation in sheet metal part coordinate system; dots indicate stroke positions correlating to strokes on the component with the tool set; in general, for this special type of driving process, there is no relation between tool path and component shape and tool path strategies cannot be derived from CAD data

In Fig. 7, the manufacturing strategy for the component is depicted in 3D-visualisation. It is obvious that the strategy is not planar; this is caused by the fact that the unclamped sheet metal is formed during the driving process and thus the strokes have to be positioned appropriately in the sheet metal part coordinate system. Even with knowledge about the 3D-visualisation of the strategy, it is, in general, not possible to presume the component shape for this driving process.

Unfortunately, this manufacturing strategy is only applicable for this specific part and dimensioning. In practice, frequently parts of the same geometric characteristics are required, but in different dimensions or variations.

Analytic description of the manufacturing strategy

Plain manipulations of the strategy corresponding to linear transformations have already been considered in [24], but, as they do not take the number and density of strokes, as well as the character of the stroke curves on the metal sheets into account there is no possibility of process parameter control. Hence it was apparent that such approaches are very restricted in the scope of variation. The bandwidth of applicable scaling factors or shearing angles is very limited as the geometric deviation strongly increases and, in fact, is not acceptable for industrial applications in general. We significantly improve on this. Hence, the enhancement of this method to a concept applicable in practice for automated component variation is the main contribution of this research.

Thus we again focus on the strategy for the sample component in 2D-projection (Fig. 6). In a first step, we want to recreate the strategy by some analytical description. To a certain degree, the 2D-tool path is similar to quadrants of different radii, but these quadrants are slightly deformed. Such a deformation of quadrants could be realised numerically. One way of approximating the deformed quadrants of the real tool path strategy, is the overlay of quadrants with appropriate normal distributions. This method enables a flexible tool path generation as is shown in Fig. 8.

For a numerically-generated 2D-strategy approximation, we generate analytically two quadrants with start and end points nearly matching the starting points of the innermost and the outermost deformed quadrants of the real tool path strategy (Fig. 9a). These two generated quadrants are adjusted to the two real ones by overlay with appropriate normal distributions (Fig. 9b). These two numerically-generated paths, and the parameters of the distribution functions, can be interpolated in such a way as to enable an insert of an arbitrary number of generated

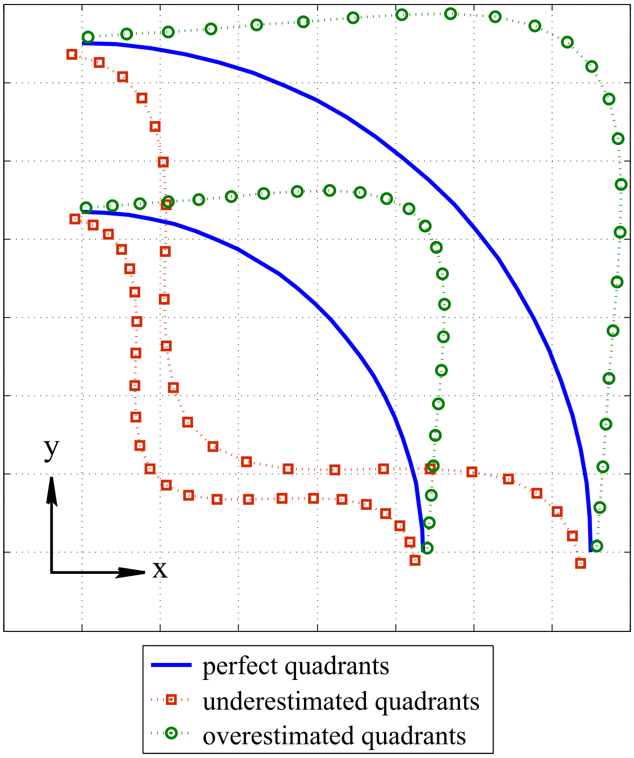

Fig. 8 Perfect quadrants and their underestimated and overestimated deformation by overlay with normal distribution functions

deformed quadrants $q = number\ of\ quadrants$ between the innermost and the outermost one (Fig. 9c).

Furthermore, $s = number\ of\ strokes\ per\ quadrant$ can be controlled by the user. Some examples of generated analytical manufacturing strategies for the sample component with varying stroke densities are depicted in Figs. 10a–f.

Of course, further possibilities of numerical processing are available, e.g. defining splines that approximate the real quadrants well. In fact, this would make the variation of the stroke density on the sheet much more sophisticated. At least new parameters for the tool path generation would be brought in. Hence, the recognition of specific features helps simplifying the path modelling step and facilitates keeping the parameters to a minimum.

Interpolated dependency of strategy coordinates

The strategy in 2D-projection, deduced in Section Analytic description of the manufacturing strategy, is not directly applicable as it is generated with restriction to 2D space. Thus, the third coordinate for positioning and also the three coordinates determining the orientation (the Euler angles) are missing, but are needed for a complete tool path strategy.

Therefore, in a second step, we deduce an interrelationship for the missing z coordinate for positioning and for the Euler angles α, β and γ. Such a relation can be established by interpolating the z coordinates of the real manufacturing strategy as a function of the x and y coordinates. In Fig. 11, the described dependency between the z coordinate and the x and y coordinates is displayed as in surface design. Analogous, the procedure can be adopted for the Euler angles.

This procedure is correct assuming that q and s do not affect the intermediate shape of the part, which is obviously not a valid assumption. As the dependency is based on the x and y coordinates for the manufacturing strategy of the sample component, strong variations of q and s yield to increasing errors in the interpolation approach. Although corresponding process boundaries cannot be determined, increasing the variation bandwidth could be achieved by introducing a flexible gripper system, whose flexibility would be able to abate such interpolation errors. For the investigations on the presented sample component these errors were rather negligible.

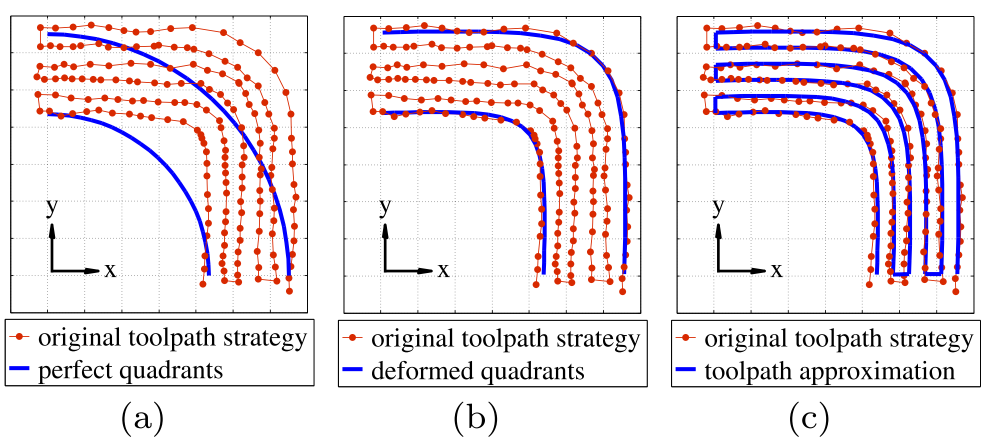

Fig. 9 Numerical generation of tool path strategy in 2D

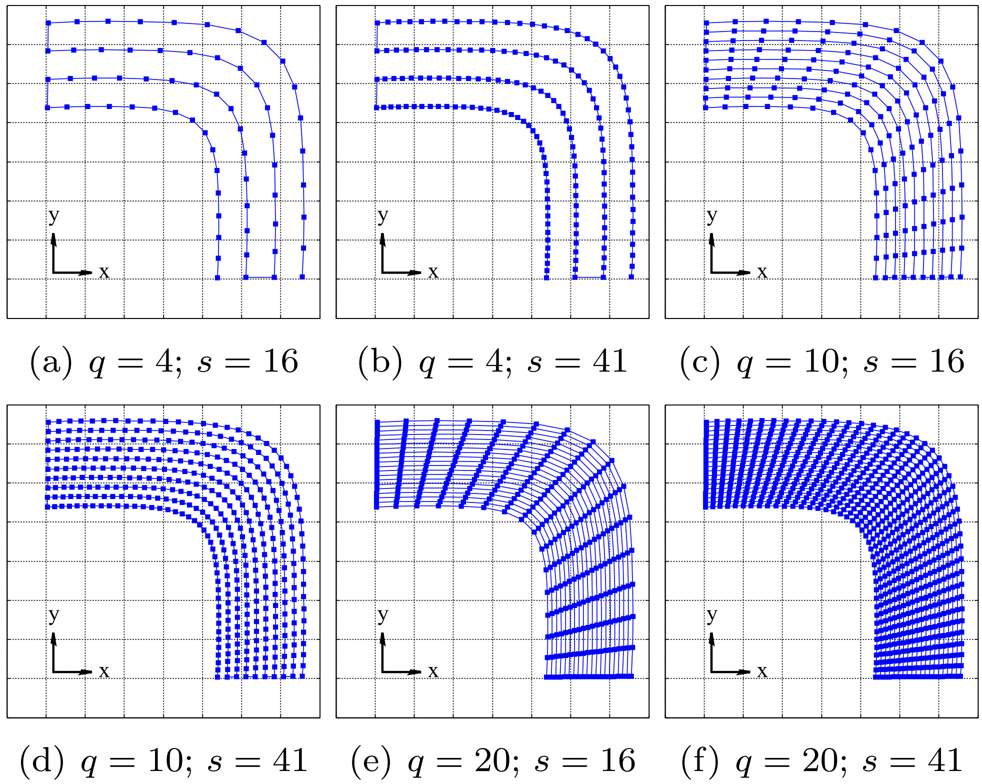

Fig. 10 Tool paths with different stroke densities for varying strategy parameters $q =$ *number of quadrants* and $s =$ *number of strokes per quadrant*

After all this, we are able to determine the missing coordinates completing the generated manufacturing strategy in 2D-projection to an applicable tool path strategy. An example of the step is shown in Fig. 12 for determining the z coordinates. This can be interpreted as the projection of the generated 2D-strategy onto the 3D interpolation surface which describes the analytic interrelationship of the x, y and z coordinates.

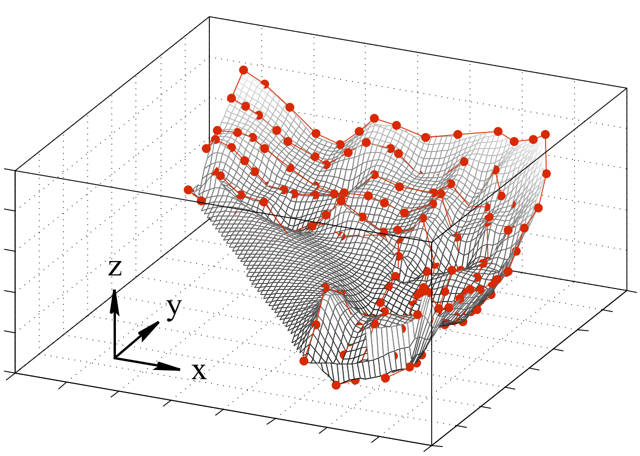

Fig. 11 Interpolated dependency of x, y and z coordinates for the original strategy of the sample component in sheet metal part coordinate system as in surface design; dots indicate stroke positions correlating to strokes on the component with the tool set; interpolation surface between the stroke positions visualises the deduced interrelation

Resuming, we have the analytical description of the real manufacturing strategy with deformed quadrants, and the interpolated analytic interrelation of the coordinates, which enable us to insert strokes at arbitrary positions on the sheet metal part. Compiling that allows the control of the strategy parameters q = *number of quadrants* and s = *number of strokes per quadrant* and thus the distribution of strokes on the sheet metal part. Consequently, we have eliminated the insuffiency plain manipulations of manufacturing strategies as presented in [24] imply.

Strategy control and parameter interpolation

In order to be able to vary the sheet metal component in the sense of scaling, we have to bring together the rudiments affiliated within this paper up to now.

First of all, we have to reproduce the sample part within given tolerances by a generated strategy. If we are able to successfully recreate the component this way, we can replace it by the new one wrought with the generated strategy. Further on, such recreated components will be referred to as component clones. Furthermore, we are cloning variants of the sample component for varying scaling factors in the same way. For this, we utilise digitally transformed representations of the sample component for a deviation analysis. This, of course, needs some process parameter variation and manufacturing steps in the

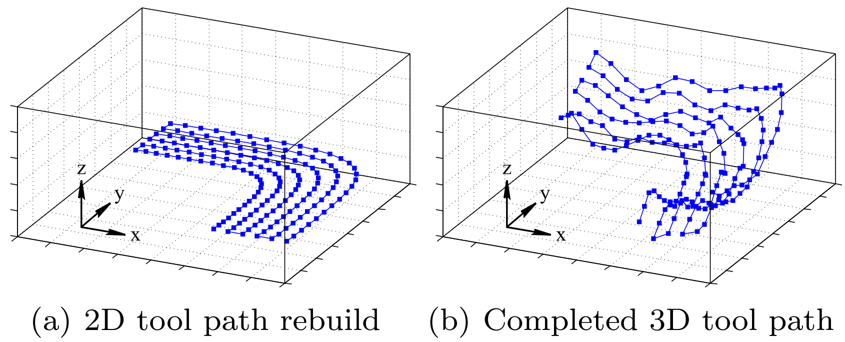

Fig. 12 Derivation of applicable manufacturing strategies: missing z coordinates for the manufacturing strategies can be determined by projection of the generated 2D-strategy rebuild onto the interpolation surface which describes the analytic interrelation of the x, y and z coordinates

sense of crafting the component and carrying out the corresponding error analysis. However, as there are only the two essential process parameters, q and s, concerning the manufacturing strategy, the search for a proper generated strategy in the 2D parameter space turns out to be straightforward.

Having determined manufacturing strategies, and thus the parameter configurations for the specific scaling factors of the sample sheet metal part, we can utilise that knowledge as supporting points for a parameter interpolation. Once the interpolation is performed, the user is able to generate manufacturing strategies for arbitrary scaled variants of the sheet metal part for the used deep-drawing steel of the given thickness. The principle of the parameter interpolation is schematically drafted in Fig. 13.

Furthermore, there is no need of deviation correction strategies as the supporting points ensure an accurate production process. If needed, more supporting points would have to be generated.

Strategy generation and geometric recreation

The concepts of manipulating the manufacturing strategy for the sample component introduced so far are of a theoretic nature and have to be validated and verified within the meaning of practice relevance. On the one hand, it

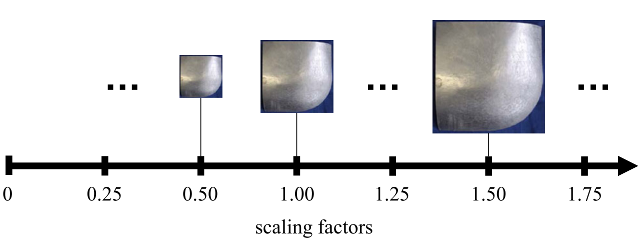

Fig. 13 Process parameter interpolation principle: after reproducing variants of the sample component, the process parameters used for recreation are utilised as supporting points for an interpolation; parameter interpolation enables generating strategies for arbitrary scaling factors

has to be checked if the new parametric strategy description is able to produce an identical component in the sense of geometric features by some parameter setting. On the other hand, the generation of interpolation supporting points and thus the ability to produce component variations by such generated strategies also has to be shown.

It is necessary to reproduce the sample component before starting the search for adequate parameter configurations. In addition, we have to establish a measure for deviations. Furthermore, reasonable tolerances within deviations can be accepted have to be defined. Finding and taking all the influencing parameters into account is all but impossible, thus we focus on the main contribution.

First, we accomplished a deviation analysis of the sample part in original size for the copied driving process. For this, 25 clones wrought with the original strategy have been compared to the original component. For the measurement of the sheet metal part geometry, and the comparison of the parts, an optical system has been employed which detects the distance between the point clouds representing the sheet metal parts. For the registration a best fit strategy has been employed, whereby the convex sides of the components were used for comparison.

The digitised components were represented by data point clouds of about 8500 to 9000 points each for original size parts. The size of the point clouds representing the sheet metal part geometries strongly depends on the surface dimensions of the components and behaves quite linear in that quantity. Hence, for components scaled by a factor of 2.00, the point cloud set extends to an amount of about 34000 to 36000 points, as the surface is approximately four times bigger. An example of such a comparison between two digitised components is given in Fig. 14 in false colour rendering for original size sheet metal parts.

Figure. 15 depicts the evaluation of the deviation analysis and shows the maximal, minimal and average distance between the digitised parts, as well as the standard deviation. The repeatability appears quite poor but some influencing factors have to be considered: the positioning

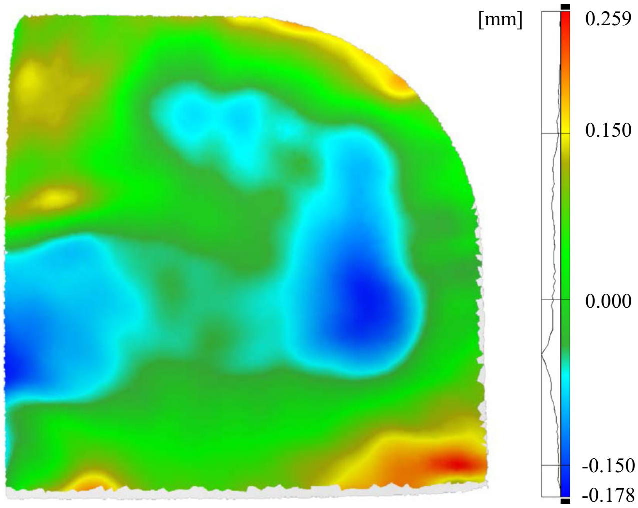

Fig. 14 Deviation analysis of sheet metal components depicting the distance between the two geometries after an appropriate matching has been performed

accuracy of the handling robot (specified with ± 0.06 mm), the impact of tribological effects during the process and the uncertainty of measurement results (coating variation, positioning on the measurement device). Taking all these into account, and defining the standard deviation as the measure for component deviation, a recreation of the sample element with a standard deviation of 0.4 mm succeeded. Thus, the introduced approach for strategy generation is adequate for cloning the sample part.

Further clones for different scaling factors have been wrought successfully with generated strategies, to ensure a sensible process parameter interpolation. Hence interpolation values have been created for scaling factors [0.80, 0.90, 1.00, 1.25, 1.50, 1.75, 2.00]. The associated real components are displayed in Fig. 16.

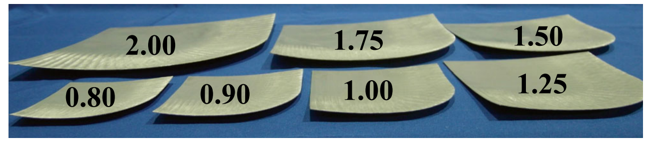

Fig. 16 Real sample component variants of different scaling factors as products of the supporting point generation for the process parameter interpolation

Actually for scaling factor 2.00, a standard deviation of 0.89 mm has been achieved which appears feasible, as the accuracy of the copied driving process gets worse for an increasing component size. This could be assessed in advance by a deviation analysis for 25 scaled components (scaling factor 2.00) to show how the dimension of the sheet metal part influences the deviations. For the manufacturing process the parameter setting $[q, s] = [16, 45]$ has been used. Since for a scaling factor of 2.00 the surface of the sheet blank quadruples, this setting had been choosen because it amounts to 720 strokes on the sheet, what is about four times the stroke number performed for the sample component production (179 strokes). The results are assembled in Fig. 17.

In total, this shows that the presented strategy generation approach is also feasible for interpolation supporting points generation. Even if it seems straightforward, for clarity it should be mentioned that the concept enables variance

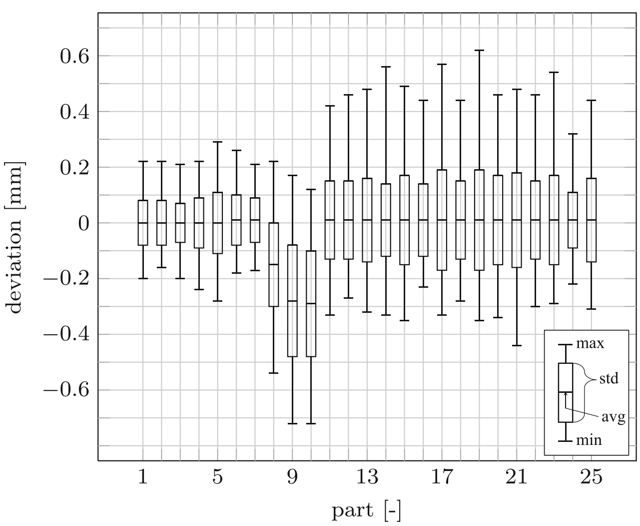

Fig. 15 Deviation analysis for the original sample component size (scaling factor 1.00) as produced by copied driving; besides the illustration of maximal (max), minimal (min) and average distance (avg) between the parts, the standard deviation (std) is also displayed

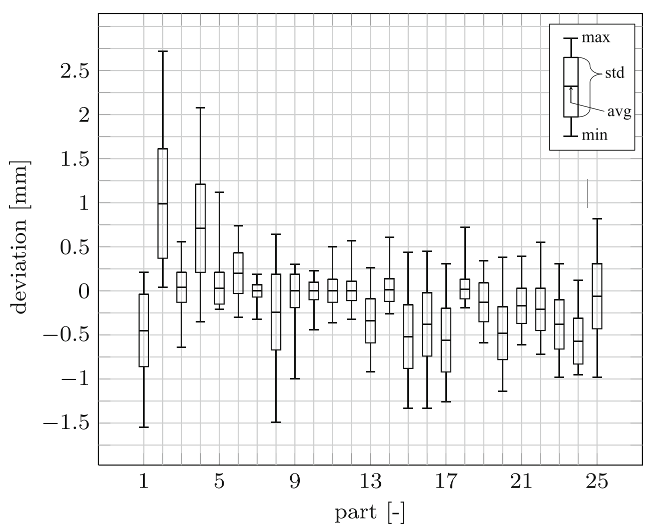

Fig. 17 Deviation analysis for the scaled sample component (scaling factor 2.00) as produced by copied driving; besides the illustration of maximal (max), minimal (min) and average distance (avg) between the parts, the standard deviation (std) is also displayed

even for big scaling factors, as the interpolation ensures high geometric conformance.

Limits and restrictions of the concept

The developed scaling concept for the sample component could be adopted for composition of different component variants, e.g. shearing or curvature variation as suggested in [24]. While additional mandatory parameters enlarge the dimension of the parameter space, the interpolation approach remains unaffected. Appropriate clones for adequate supporting points would have to be wrought. However, such variations make further data analysis and experimental input necessary, e.g. adjusted stroke densities on the deformed quadrants on the sheet.

Furthermore, for the generation of a scaled part tool path, a series of parts need to be manufactured to determine appropriate parameter settings. On the one hand, one will claim that small series or one of a kind production is rather remote from this approach. On the other hand, once the parameter settings are determined, the concept offers the possibility to produce parts of arbitrary scaling factors by interpolation, what is a strong improvement on [24] and on the state-of-the-art for the investigated driving process type in general.

In terms of scaling, the spectrum of variance is limited by real conditions. On the one hand, the finite dimension of the driving tool set allows scaling-down only to a fix factor, but this could be overcome to a certain degree by establishing and applying smaller tool sets. On the other hand, an arbitrary scaling-up is restricted by the dimension of the gripper system and the appearing vibrations. Moreover, for large sheet metal parts, we observe flection caused by the operating weight. To overcome these limitations, the desired component shape can be partitioned in advance and the segments would have to be produced individually.

Finally, the developed method is dependent on the tool and on the material used. However, utilising the approach concepts for diverse tools and materials can easily be derived. If the tool does not change, the quest of finding an analytical description for the manufacturing strategy can be omitted and only supporting points have to be generated. In contrast, if the tool or the component geometry changes, one has to put effort into finding an analytical description of the manufacturing strategy which is quite complex.

A possible simplification of this process is the adoption of probability calculus and statistics for the analytical description of manufacturing strategies. For the discrete stroke positions of manufacturing strategies, probability density functions can be derived by a kernel density estimation. Thus, continuous analogues for the discrete tool paths would be available. This nonparametric technique enables an automated handling of arbitrary manufacturing strategies and does not require any systematic tool path engineering by the user in advance. The discretisation of the density functions back to discrete stroke positions can be used for the variable generation of manufacturing strategies. Hence, a predefined number of strokes is distributed on the sheet blank according to the derived probability density function. Thereby, a detailed analysis is needed on how to retain the stroke order. All in all, this enables an automated performance of the search for analytical descriptions of discrete tool paths. Neither a recognition of geometric features within the real tool path nor a modelling step is any longer needed.

Summary and outlook

A prospective approach for automating the driving process is based on the copied driving concept. It is proposed to use known manufacturing strategies for producing new sheet metal parts or rather modifications of known component geometries. To achieve this ambition, some preliminary problems have to be solved.

In this paper, we presented an extension and application of the copied driving concept. We have introduced a sample component and derived a method for enabling efficient geometric variance in the sense of scaling. This had not been possible up to now and is a strong improvement on the state-of-the-art of this special process type.

In this context, an analytical description of the real manufacturing strategy and an interrelationship for the strategy coordinates have been derived. Thus, recreating the sample component within reasonably defined tolerances and producing supporting points for a process parameter interpolation using generated strategies was possible. This faciliates production of a wide range of component variants.

In particular, the obligatory analytical replication of manual manufacturing strategies is, in general, exceedingly complex. In addition, for every sheet metal part geometry, an appropriate analysis has to be performed explicitly. One possibility for simplifying this process is the adoption of approaches of probability calculus and statistics for the analytical description of manufacturing strategies. These will be of central interest for further investigation.

Such an analytic depiction of manufacturing strategies enables automated strategy description and, furthermore, simple control of process parameters. Thus, a comprehensive application and a significant increase of the degree of automation could be achieved, that further qualifies the process for the commercial production of sheet metal parts.

We extend our sincere thanks to the European Research Association for Sheet Metal Working and the German Federation of Industrial Research Associations financing our investigations as part of the program for the furthering of the Industrial Collective Research by the Federal Ministry of Economics and Technology.

References

1. Tseng M, Piller FT (2003) The customer centric enterprise. Advances in mass customization and personalization. Springer, Berlin
2. Jeswiet J, Micari F, Hirt G, Bramley A, Duflou JR, Allwood J (2005) Asymmetric single point incremental forming of sheet metal. CIRP Ann Manuf Technol 54:623–649
3. Emmens WC, Sebastiani G, van den Boogaard AH (2010) The technology of incremental sheet forming - A brief review of the history. J Mater Process Technol 210:981–997
4. Fratini L, Ambrogio G, Di Lorenzo R, Filice L, Micari F (2004) Influence of mechanical properties of the sheet material on formability in single point incremental forming. CIRP Ann Manuf Technol 53:207–210
5. Allwood J, Houghton N, Jackson K (2005) The design of an incremental sheet forming machine. Adv Mater Res 5:471–478
6. Duflou JR, Tunckol Y, Szekeres A, Vanherck P (2007) Experimental study on force measurements for single point incremental forming. J Mater Process Technol 189:65–72
7. Martins PAF, Bay N, Skjoedt M, Silva MB (2008) Theory of single point incremental forming. CIRP Ann Manuf Technol 57:253–256
8. Ham M, Jeswiet J (2007) Forming limit curves in single point incremental forming. CIRP Ann Manuf Technol 56:277–280
9. Micari F, Ambrogio G, Filice L (2007) Shape and dimensional accuracy in single point incremental forming: state of the art and future trends. J Mater Process Technol 191:390–395
10. Rauch M, Hascoet JY, Hamann JC, Plennel Y (2008) A new approach for tool path programming in incremental sheet forming. Int J Mater Form 1:11911194
11. Rauch M, Hascoet JY, Hamann JC, Plennel Y (2009) Tool path programming optimization for incremental sheet forming applications. CAD 41:877885
12. Attanasio A, Ceretti E, Giardini C, Mazzoni L (2008) Asymmetric two points incremental forming: improving surface quality and geometric accuracy by tool path optimization. J Mater Process Technol 197:5967
13. Duflou JR, Verbert J, Belkassem B, Gu J, Sol H, Henrard C, Habraken AM (2008) Process window enhancement for single point incremental forming through multi-step toolpaths. CIRP Ann Manuf Technol 57:253–256
14. Skjoed tM, Bay N, Endelt B, Ingarao G (2008) Multi stage strategies for single point incremental forming of a cup. Int J Mater Form 1:11991202
15. Verbert J, Belkassem B, Henrard C, Habraken AM, Gu J, Sol H, Lauwers B, Duflou JR (2008) Multi-Step toolpath approach to overcome forming limitations in single point incremental forming. Int J Mater Form 1:12031206
16. Malhotra R, Bhattacharya A, Kumar A, Reddy NV, Cao J (2011) A new methodology for multi-pass single point incremental forming with mixed toolpaths. CIRP Ann Manuf Technol 60:323–326
17. Hadoush A, van den Boogaard AH (2012) Efficient implicit simulation of incremental sheet forming. Int J Numer Method Eng 90:597–612
18. Verbert J, Duflou JR, Lauwers B (2007) Feature based approach for increasing the accuracy of the SPIF process. Key Eng Mater 344:527–534
19. Friedman JH (1991) Multivariate adaptive regression splines. Ann Stat 19:1–67
20. Behera AK, Verbert J, Lauwers B, Duflou JR (2013) Tool path compensation strategies for single point incremental sheet forming using multivariate adaptive regression splines. CAD 45: 575–590
21. Hoffmann H, Hautmann R, Petry R (2005) Studies for the development of a simulation basis for numerically controlled driving of sheet metal. Adv Mater Res 5:517–524
22. Scherer D, Yang Z, Hoffmann H (2010) Driving a flexible manufacturing method for individualized sheet metal products. Int J Mater Form 3:955–958
23. Hoffmann H, Yang Z, Scherer D, Klinker G, Echtler F (2010) Entwicklung automatisierter Fertigungsstrategien für das Kopiertreiben (In German). European Research Association for Sheet Metal Working, Hannover
24. Opritescu D, Sachnik P, Yang Z, Golle R, Volk W, Hoffmann H, Schmiedl F, Ritter M, Gritzmann P (2012) Automated Driving by standardizing and scaling the manufacturing strategy. Procedia CIRP 3:138–143