Material Forming - ESAFORM 2023 Materials Research Forum LLC
Materials Research Proceedings 28 (2023) 943-950 https://doi.org/10.21741/9781644902479-103

Approaches for load path design for stretch forming based on part surface geometry

REITMAIER Lisa-Marie[1,a *], BAILLY David[1,b] and HIRT Gerhard[1,c]

[1]Institute of Metal Forming, RWTH Aachen University Intzestraße 10, 52072 Aachen, Germany

[a]lisa-marie.reitmaier@ibf.rwth-aachen.de, [b]david.bailly@ibf.rwth-aachen.de, [c]gerhard.hirt@ibf.rwth-aachen.de

Keywords: Stretch Forming, Sheet Metal, Loading Trajectory, Load Path, CAE Methods

Abstract. Stretch forming enables manufacturing large, slightly curved sheet metal parts. If the curvature is multi-directional and complex, parts often cannot be stretch-formed successfully, due to local or inhomogeneous straining that leads to early material failure, buckling or springback. To control strain distribution, the flexibility of load application needs to be improved. This can be achieved through loading at discrete points based on defined cross-sections of part geometries. However this can be applied only by multi grippers, requiring complex plant technology and control. New parameterized approaches for load path generation based on the part surface geometry for single rigid grippers have been developed to improve the flexibility of load paths. The approaches can be mainly distinguished between Surface Transformation method (ST), which transforms a surface into a curve as the base for tangential path creation and the Tool Path Fitting method (TPF). In TPF, paths are created for several cross-sections, similar to the application for multi grippers, and then compiled into one path. In this paper, the load path approaches have been applied and numerically investigated for parts with positively curved translation surfaces. Results of FE simulation of the stretch forming process show the applicability, potential and limitations of the load path design approaches.

Introduction

Stretch forming is an established industrial process for forming automobile body panels such as doors or roofs and aircraft parts [1]. In general, the process is suitable to manufacture large and slightly curved components for various applications. The stretch forming process typically involves a rectangular sheet metal blank clamped at either two opposite sides, less often at all four sides, formed by a relative movement between the grippers and the die. Within the forming process, the grippers either move in only vertical direction (conventional stretch forming) or in both vertical and horizontal directions simultaneously (tangential stretch forming) so that the load is acting tangentially to the die contour. In general, components produced via tangential stretch forming achieve higher geometrical accuracy [1].

A tangential load path is generated based on a representative curve of the part geometry. In the case of a unidimensional-curved component, the curve equals the cross-sectional part contour. For bi-dimensional and more complex curved components, the cross-section varies in transverse direction. In this case, the creation of stretch forming load path is mainly experience based. To apply loading with respect to the overall part surface and to overcome existing process limits, loading at discrete points along transverse curvature according to the longitudinal cross-sectional profiles has been investigated [2,3]. The flexible loading with respect to the complete part geometry surface improves uniform deformation of the sheet metal and contributes to overcome existing process limits for complex shaped parts in stretch forming. To realize these load profiles, multi grippers with separate modules, complex machinery and process control are required. In order to waive such complex technology systems and work with existing rigid gripping modules, Schmitz et al. [4] used a conventional stretch forming operation and presented a method to

Materials Research Proceedings 28 (2023) 943-950 https://doi.org/10.21741/9781644902479-103

manipulate the strain distribution by selective weakening of the blank with specific hole pattern to homogenize the strain over the part surface. This method involves an optimization algorithm and requires an additional preceding step of laser cutting. In order to avoid complex machinery and additional process steps, alternative parameterized load path design approaches with respect to the overall part surface geometry have been investigated and are presented in this paper.

Approach and Procedure

In this study, different load path design approaches for rigid gripper application based on the surface geometry of bi-dimensional curved components are developed. The approaches can be mainly distinguished between Surface Transformation method (ST), which transforms a surface into a curve as the base for tangential path creation and the Tool Path Fitting method (TPF). In TPF, paths are created for several cross-sections, similar to the application for multi grippers, and then compiled into one path. The part surfaces considered in this work are translation surfaces with positive Gaussian curvature. A translation surface is defined by two curves and is obtained by moving a generator curve, which remains parallel to its initial position, along a guide curve. In this study, the part surfaces and the corresponding stretch forming load paths are created via a developed Python script. Within the scope of this work, the different load path approaches are presented for two different exemplary part geometries. The results are generated through numerical process simulations in LS-Dyna with help of validated stretch forming FE-Models. The criteria for analyzing the different load path approaches are the achieved part geometry and strain distribution.

Material and Methods

Material. The sheet material is 1.4404 austenitic stainless steel in 0.8 mm thickness. The material data is determined via tensile test with samples taken in rolling direction of the sheet. A yield strength of $R_{p0,2}$=279,197 MPa, ultimate tensile strength of R_m =620.043 MPa and ultimate strain A_g=47.697 % were identified.

FE-Model. In order to analyze and compare the forming results after applying different load paths, a FE-Model is established in LS-PrePost 4.3 and the simulations are performed with the explicit solver of LS-Dyna R.11.1.0. The sheet metal blank is 750 x 500 mm in size and discretized with Belytschko-Tsay shell elements with 4 mm. The load is applied on the edge nodes of the short opposite sides of the blank. The sheet is modelled as an elastoplastic deformable body whereas the die is modeled as a rigid body. The die geometry as well as the desired part geometry is limited to bi-dimensional curved translation surfaces with only positive Gaussian curvature. Two-sided stretch forming is conducted.

General approach for load paths determination. To create a conventional load path with only vertical movement, the highest and lowest point of a surface and the final tangential angle α need to be identified (Fig. 1, left). Pre-stretching or post-stretching can be added and involve horizontal movement. A tangential load path (Fig. 1, right) is based on either a cross-sectional curve of the part geometry, or a representative curve that is usually generated based on experience. The path represents an involute of this curve, which can be pictured as wrapping of the sheet metal on the die surface. The involute is defined by the curve and the edge or rather endpoint of the sheet metal. To ensure tensile loads throughout the process a stretching rate of 0.1 % per forming step is applied.

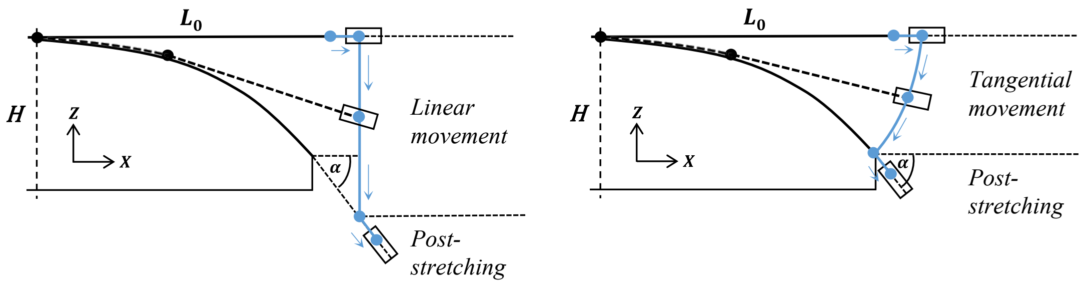

Fig. 1. Schematic drawing of load path determination for a conventional path (left) and a tangential path (right) with an optional pre- or/and post-stretching movement.

Approaches for Load Path Design

The presented approaches for load path design are based on the general approach for tangential stretch forming as stated in the previous section. Therefore, to generate a load path, a defined curve is needed. The Surface Transformation method (ST) transforms a surface into one representative curve as the base for path creation. For the Toolpath Fitting method (TPF), several load paths are created for several cross sections, comparable to the path creation for multi grippers. However, instead of moving multi grippers accordingly, the different paths are compiled into one load path for the rigid single gripper based on different criteria.

Surface Transformation method (ST). In order to transform a multi-curved surface into a single representative curve, all of the surface points are projected onto a plane (cf. Fig. 2). Then, by means of different criteria, a curve is derived from the point cloud. For the first approach, the curve is created based on the lowest points of the surface. Since the first contact point of the sheet metal is always the highest point of a part geometry, respectively the highest point of the lower die, the generated path needs to be corrected by extending the path at the process begin to the same height as the highest point of the part surface geometry.

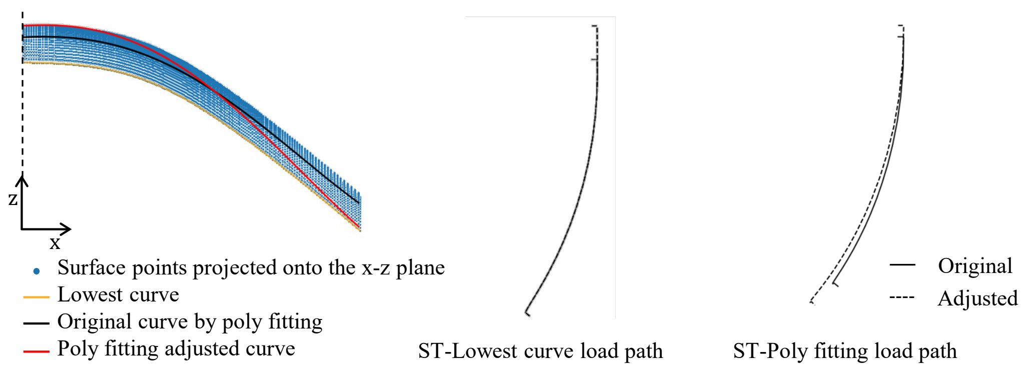

Fig. 2. Projection of coordinate points of a three-dimensional part surface geometry on x-z plane and created representative curves (left) and resulting load paths based on the representative curves (right) generated from two different ST-methods.

In the special case of translation surfaces with only positive Gaussian curvature, the determined lowest curve of the points equals the longitudinal edge curve of the surface. Another load path is based on a curve, which is derived by polynomial fitting through all surface points. The degree of polynomial was set to four. The curve is adapted accordingly in order to include the highest and lowest point of the surface and then the load path is determined based on this curve. Beside the highest point, the lowest point needs to be included to be able to fully form the desired part geometry.

Coming to the next Surface Transformation method (Fig.3), the surface is cut in transverse direction (y-direction) by several planes. For every transverse cross-section, the points on the curve (black dotted curve) are fitted into a line (red dotted line). All the lines are projected to x-z plane resulting in one red point per cross-section curve. If a sufficient number of transverse cuts are performed, an averaged curve (connecting the red points in the right figure) can be determined. The highest and the lowest point are integrated in the curve as for the poly fitting method.

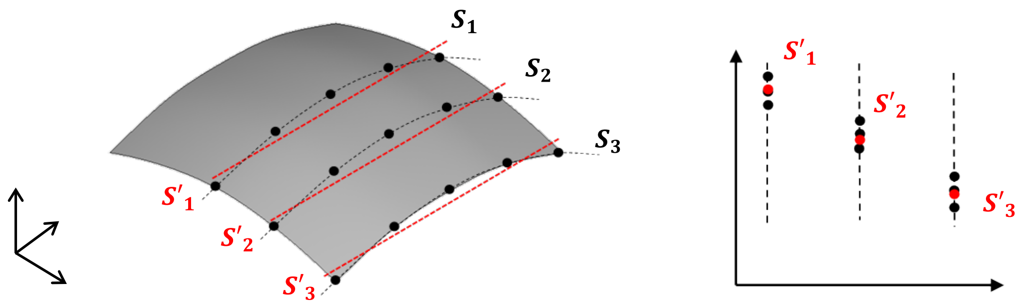

Fig. 3. Simplified sketch of the curve determination by transverse fitting type of Surface Transformation method.

Tool Path Fitting method (TPF). This method (Fig. 4) is based on the generation of load paths determined for each longitudinal cross-sectional curve (black dotted line) of the surface geometry. Within this work, the TPF-method is based on 20 cross-sections. Every load path has the same defined number of steps. So, subsequently for every step, one of the coordinate points of the load paths ($J_{j,\,Ri}$) is picked or fitted into one point. In the first approach, the position that causes the most stretching in the corresponding load step is picked (J_j). In the other approach, this is done by least squares method to find the mean point (T_j).

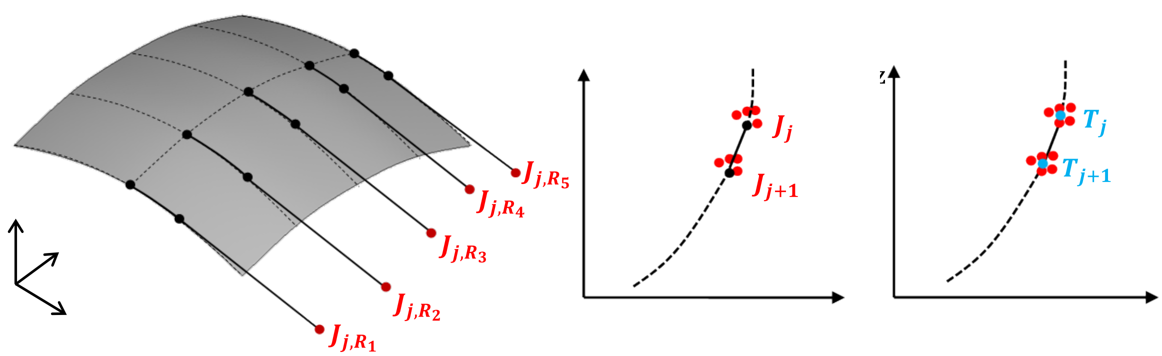

Fig. 4. Simplified sketch of the path determination by Tool Path Fitting method for the lowest point (left) and the mean point (right).

The developed approaches for load path design are summarized in Table 1. The results from the numerical study are presented in the next section.

Table 1. Summary overview of the developed approaches.

Surface Transformation method (ST)	Tool Path Fitting method (TPF)
Transforms a multi-curved surface into a single representative curve. Therefore, all surface points are projected onto a plane and fitted into a curve by means of different criteria. - ST-Lowest Curve - ST-Poly Fitting - ST-Transverse Fitting	Generation of a tangential load path for each specified longitudinal cross-sectional curve of a surface. The paths are compared for every load step and one positions is picked or fitted. The steps are then compiled into one load path. - TPF-Lowest Point - TPF-Mean Point

Results and Discussion

Application of load path design approaches. The presented load path design approaches have been successfully applied for several different translation surface geometries from a defined parameter field. This study focuses on two different exemplary parts shown in Fig. 5 (left), and the corresponding load paths generated via different load path design approaches, shown on the right.

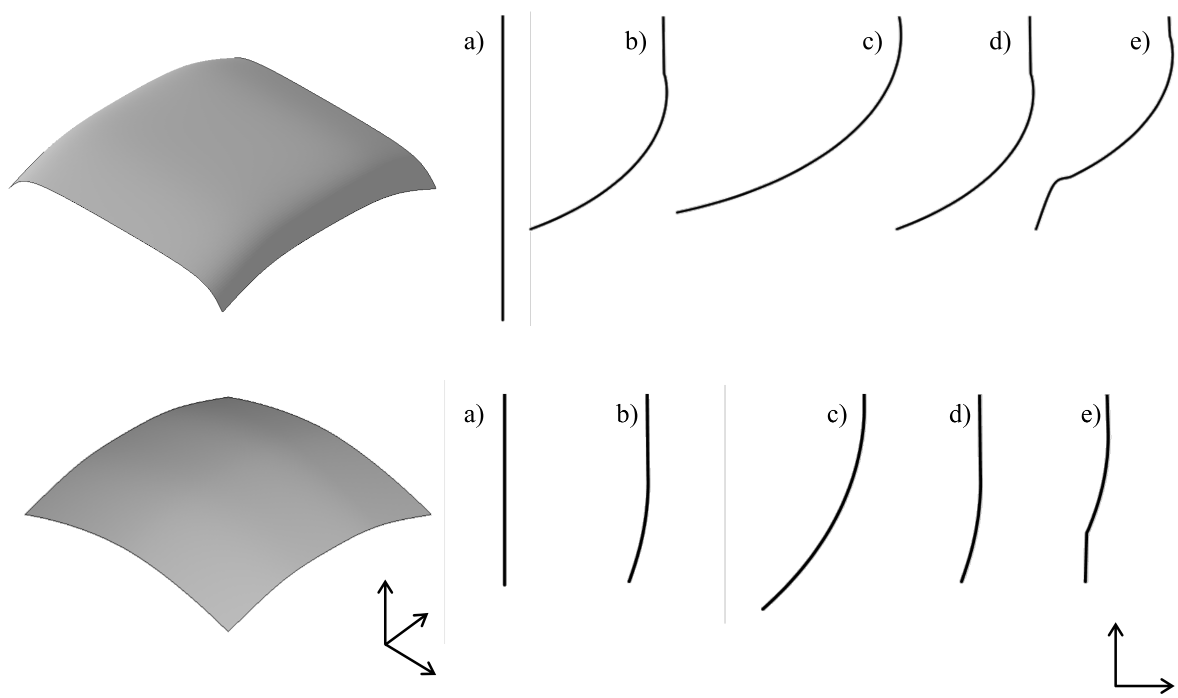

Fig. 5. Visualization of the investigated two different part geometries (left) and load paths a)-e) based on the part surface geometries (right).

Part surface geometry A is relatively flat with a height to length ratio of 0.2 (in both x- and y-direction) and a relatively steep final tangential angle α of 55° towards the edge in x-direction. For part surface geometry B, the height to length ratios in longitudinal and transverse direction are also 0.2 but the final tangential angle α is smaller with 20°. The load paths generated by the different approaches (Fig. 5) are as follows: a) Conventional, b) ST-Lowest Curve, c) ST-Transverse Fitting, d) TPF- Lowest Point, and e) TPF- Mean Point. A generation of a load path by ST-Poly Fitting was not successful, since the generated representative curves were not suitable for path creation due to multiple change of curvature. All paths presented above are reduced to the motion without pre- or post-stretching. It can be seen that the conventional path is changing significantly with the tangential angle α or rather the curvature in longitudinal direction. The path with the most tangential movement is the path created by Surface Transformation method with Transverse Fitting (Fig. 5, c). Especially the paths based on the lowest curve of the surface geometry (ST-Lowest Curve (Fig. 5, b)) or the lowest tool position (TPF-Lowest Point (Fig. 5, d)) need a significant linear extension to meet the highest point of the surface geometry. To summarize, besides the ST-Poly Fitting approach, all presented approaches seem to lead to reasonable load paths. The applied load varies with the different load path approaches and therefore, influences the forming result as also discussed by [5].

FE-simulation results. FE-simulations were conducted for the different geometries A and B and the presented stretch forming load paths. Fig. 6 shows the resulting plastic strain distribution for geometries A and B after stretch forming with the above developed load paths.

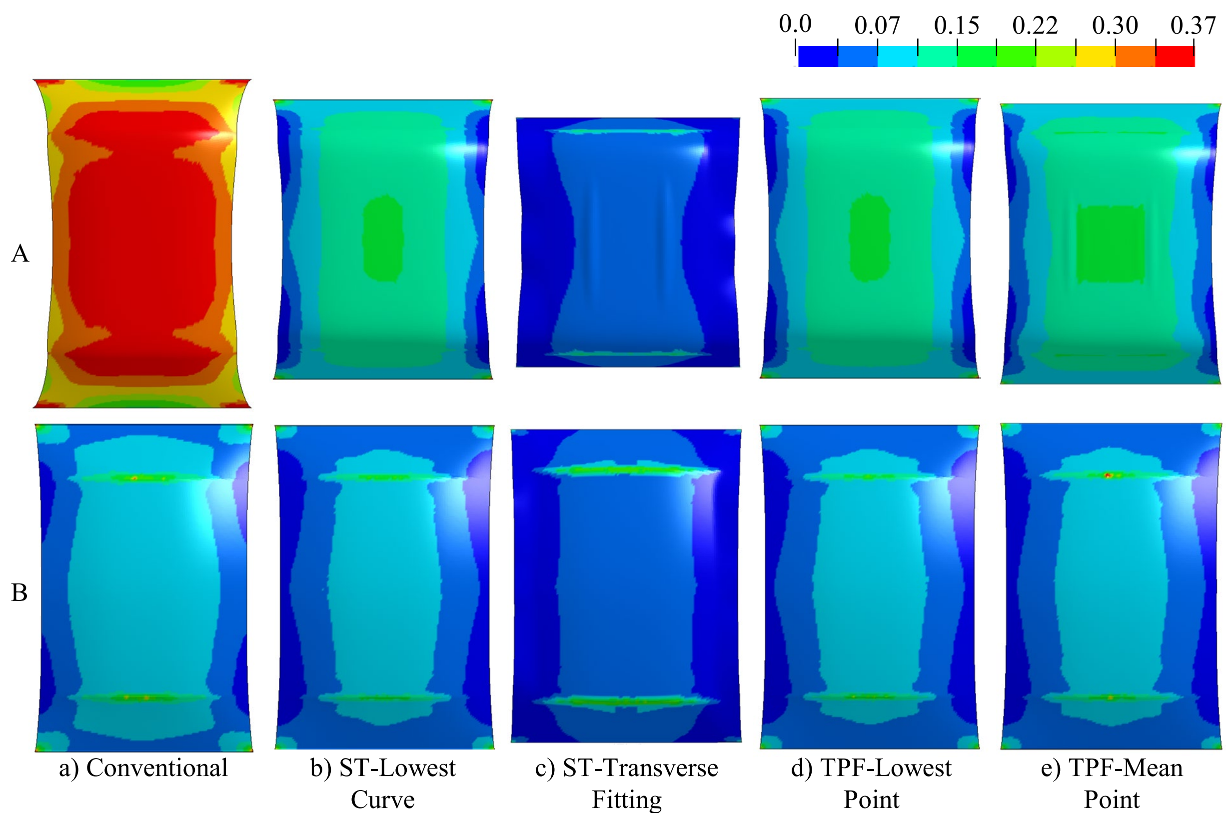

Fig. 6. Effective plastic strain at the final state of deformation under load for geometry A and B.

For the steep curvature of geometry A in longitudinal direction, and the resulting relatively long conventional stretch-forming path, the deformation is expected to cause material failure since the plastic strain of 0.37 exceeds the ultimate strain of the material. Therefore, this part geometry cannot be successfully deformed with the conventional load path.

For load paths b) and d), similar plastic strain distributions can be observed. The path created based on the lowest curve (b) and the choice of the lowest tool position, as in TPF-Lowest Point (d), lead to almost the same resulting path for positively curved translation surfaces. Deviations may be caused by different numbers of data points and consequently different approximations.

As stated before, the load paths based on the ST-Transverse Fitting approach include the most tangential movement. The tangential movement induces less tensile strain and reduces friction significantly, since the relative movement between die and blank is lowered to a minimum. Therefore, the formed sheet metal blanks show the smallest overall strains for both geometries. So, local straining which leads to early material failure can be avoided. But especially, while forming bi-dimensionally curved components, buckling can occur due to insufficient stretching in the edge area of the sheet. Fig. 7 shows the cross-sections for the geometries A and B, deformed with the original and an adapted load path based on the ST-Transverse Fitting method.

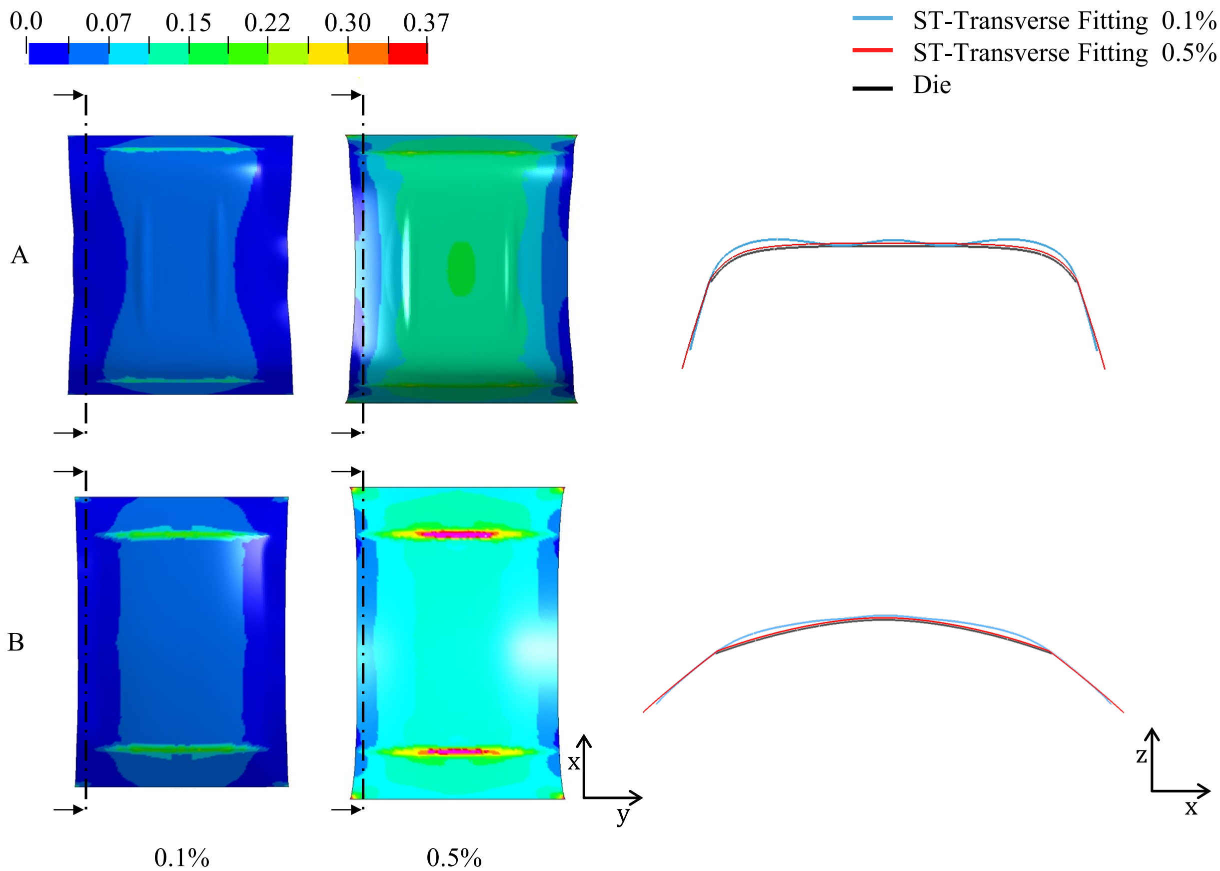

Fig. 7. Effective plastic strain distribution at the final state of deformation under load for geometry A and B for different in-process stretching rates (left) and resulting cross sections (right).

In blue, both cross-sections show deviations from the desired surface geometry denoted in black. Post-stretching is an established measure to apply tensile load at the end of the process. To show the adaptability and therefore flexibility of the load path design approaches, the stretching rate per step was increased from 0.1% to 0.5%. For both geometries, the adaption leads to achievement of the target geometry. The resulting strain distributions are shown in Fig. 7, left. Additional stretching increases the overall strain. The high strains for geometry B for the adapted path can be explained by the simplified die geometries, which are automatically created as shell elements in Python. This leads to element penetration and deformation in the edge area of the simplified die. This example shows that the parameterized path design approaches can be adapted effortlessly and reproducible results can be achieved. For geometry B both simulation results show buckles in the middle area of the blank. The buckles in longitudinal direction occur due to compressive stresses in transvers (y-direction) and cannot be inhibited by additional stretching. The results for a), b) and d) show no center buckles. This could be referred to increased tensile stretching and therefore increased friction between blank and die at the beginning of the process, which prevents the material from flowing in transverse direction. The individual adaption of in process stretching allow for the control of stress and strain distribution throughout the process in the deformed part and can therefore influence the forming result.

Summary

The presented approaches for load path design based on part geometry, despite the ST-Poly Fitting approach, are shown to be applicable for positively curved translation surfaces. They allow for parametrized load path determination and therefore automated process planning for stretch forming double curved surfaces with rigid grippers. Furthermore, the strain distribution within the sheet during stretch forming could be controlled by the parametrized load path design approaches. Since the material properties and the resulting springback are dependent on the stresses and strains in the sheet metal, the parameterized approaches have the potential to specifically control the strain distribution and the parameters in order to achieve the desired forming result. Further research should verify the results of current approaches in experimental tests and the approaches should also be tested for the applicability to more complex shapes. Furthermore, the potential of the load path approaches to control the springback systematically is of high interest and will be investigated. Additionally, it should be investigated if the achievable geometrical part complexity with simple stretch forming plants without multi grippers can be extended with the presented load path approaches.

References

[1] K. Lange, Handbook of metal forming, Society of Manufacturing engineers, 1985.
[2] Z. Yang, Z.-Y. Cai, C.-J. Che, M.-Z. Li, Numerical simulation research on the loading trajectory in stretch forming process based on distributed displacement loading, Int. J. Adv. Manuf. Technol. 82 (2016) 1353–1362. https://doi.org/10.1007/s00170-015-7470-y
[3] Y. Wang, M. Li, H. Liu, J. Xing, Finite Element Simulation of Multi-gripper Flexible Stretch Forming, Procedia Eng. 81 (2014) 2445–2450. https://doi.org/10.1016/j.proeng.2014.10.348
[4] R. Schmitz, M. Winkelmann, D. Bailly, G. Hirt, Homogenisation of the strain distribution in stretch formed parts to improve part properties, AIP Conference Proceedings 1960 (2018) 160025.
[5] D.E. Hardt, W.A. Norfleet, V.M. Valentin, A. Parris, In Process Control of Strain in a Stretch Forming Process, J. Eng. Mater. Tech. 123 (2001) 496-503.