FORMING STRATEGIES FOR ROBOTIC INCREMENTAL SHEET FORMING

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Abstract. Incremental Sheet Forming (ISF) is a flexible forming technology that can process parts without special mould, where-in an indenter moves over the surface of a sheet metal forming a 3D shell through localized deformation. Despite being fundamentally advantageous than stamping for low-volume production, there are many drawbacks to this technique, a major being the low geometrical accuracy of the achieved products, thereby limiting its widespread industrial application. In this paper, flexible support strategies and precise forming compensation have been considered as promising approaches in terms of improving the geometric accuracy in ISF. Four support strategies and a compensation forming method based on FEA and three-dimensional scanning are discussed in detail. Finally, we deploy the technique for the manufacturing of automotive products. The technique is applied to several automotive products of varying topologies and thus form the basis for successful verification of our technique.

Keywords. Incremental Sheet Forming; Robotic Fabrication; Forming Path; Error Compensation; SDG 12.

1. Introduction

Incremental Sheet Forming (ISF) is a flexible sheet forming technology that can process complex sheet components without a special mould, where in a simple tool moves over the surface of a sheet metal forming a 3D shell through localized plastic deformation. Typically, the tool is formed using a hemispherical toolhead attached to a robotic arm or a CNC machine. The tool moves along a pre-programmed tool-path creating localized plastic deformation on the sheet metal thereby giving it the desired shell shape. The technology is especially suitable for the research and development of new products and the production of small-batch customized products giving greater degrees of freedom to architecture and designers, thanks to the fact that no mould or die is needed as in the case of stamping process. Thus, for building the initial prototypes

POST-CARBON, Proceedings of the 27th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) 2022, Volume 2, 171-180.

and for small batch production, ISF is at least two orders of magnitude cheaper, and less energy-intensive process compared to stamping.

However, there are many drawbacks to this technique, the major being the low geometrical accuracy of the achieved products, thereby limiting its widespread industrial application. One of the most fundamental research questions in ISF research is how to accurately and efficiently program the robot's toolpath in ISF to achieve the desired geometric accuracy of parts. The other important question is on how to use the data obtained from visual or other sensors attached to the robot to make improvements to the geometric accuracy of the part.

Figure 1. The ISF Setup

This paper attempts to answer these two questions. We first discuss the current state of research in the field of ISF. We propose to use corresponding support strategies in different feature regions to minimize the forming error. Next, we discuss a new methodology for compensating accuracy errors in the achieved geometric shape through the use of a new compensation-based tool-path algorithm and prove its use through FEA simulation and application on real-world products.

2. State of the art

Bulk of the ISF research has mainly been driven in the field of manufacturing for engineered shell products. In the recent years, however, research has also been driven by the needs of architects and the industrial design community, as surface textures are commonly used design elements. Because accuracy plays a vital role in engineered shell products, most of the research has been done to predict final shapes through simulation, predict springback action and required compensation. Gatea et al. (2016) provides a detailed review of the current state-of-the-art of ISF processes in terms of its technological capabilities and specific limitations with discussions on effects process parameters on the ISF process. The forming quality is affected by many factors such as material property, forming tool and geometric shape. In addition, springback prediction and compensation are also effective methods to improve the forming accuracy. Stoerkle et al. (2016) proposed the application of machine learning techniques to increase the geometric accuracy of ISF process. Ren et al. (2019)

developed a generic methodology, suitable for arbitrary part geometries and various ISF processes. These methods all require large data sets. Numerical simulation of ISF (Cai et al. ,2020) can simulate the machining process and save the time and cost of data collection. However, the simulation calculation of ISF is difficult, and realizing feedback in real time still remains a challenge.

In the architectural field, Kalo et all. (2014) developed an indirect method for achieving part accuracy through design modification, by overlaying of rib – like design patterns on to the main design, thereby achieving part accuracy and aesthetics simultaneously. Zwierzycki et al. (2018) attempted to improve forming tolerance by using machine learning to predict springback and thus generate corrected fabrication models. Chadha et al. (2020) presented a methodology to optimize long-drawn-out ISF operation by using geometrical intervention informed by supervised machine learning algorithms.

3. Methodology

In this paper, flexible support strategies and precise forming compensation have been considered as promising approaches in terms of improving the geometric accuracy in ISF. This section details how to achieve flexible support strategy and compensation path generation. Grasshopper is used to generate robot tool path from 3D model and convert tool path into machine code using KukaPrc. Communication and collaboration between the two robots are achieved through KUKA.RoboTeam, which enables up to four robots to cooperate in a team.

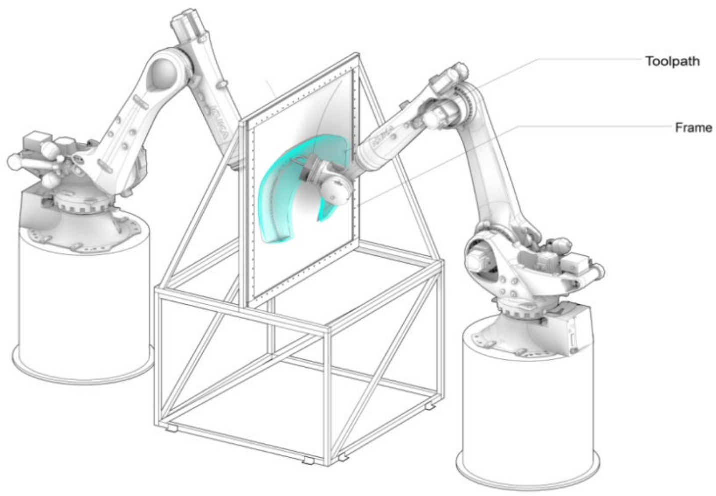

Figure 2. Robotic fabrication setup with two KUKA KR-210

3.1. SYSTEM SETUP

In the aspect of hardware two KUKA KR-210 robots were used that collaborate with each other as well as a metal frame holding the metal sheet (Figure 1). The master robot pushes incrementally on the sheet, forming the sheet in the direction of the tool-path. There are four supporting strategies for the slave robot, including global support, local peripheral support, local alignment support and local following support. Each supporting strategy has different shaping effects. For example, global support is to provide support at the edge of the forming contour to minimize the elastic deformation at the edge of the metal plate. Local peripheral support can reduce the elastic deformation of forming details. By using local alignment support and local following support, concave and convex can be made within the same part. We use different support strategies for different feature areas to reduce the overall deformation.

3.2. PATH PLANNING

The tool path planning has a great influence on forming accuracy and forming time. The most commonly used method is the parallel contour strategy wherein the design geometry is sliced into horizontal segments and the tool moves along these contours.

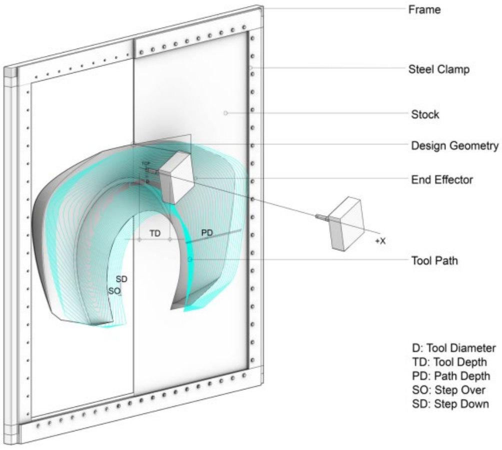

Figure 3. Robotic fabrication setup with a forming tool

The forming path and the corresponding support path are generated using Rhino Grasshopper. We use the Offset-on-surface function to form layers in a specific (X-axis) direction with a certain thickness, and build 2D curve paths. These 2D curve paths are then divided into a specific number of discrete points according to the curvature. Finally, we generate the forming path of the master robot through these sequential discrete points and planes. There are four support strategies, each of which has a different support path. To achieve stable cooperation between the two robots, we generate support paths at each forming step which contains a single contour.

1) The first policy is global support, in which the slave robot moves the support tool along the boundary of the part, acting like a back-plate, providing support on the opposite side of the sheet for the master robot to push against (Figure 4a). The global support path was generated by a distance offset (tool head radius) of the outer contour of the forming region, and each forming path points were mapped to the corresponding global support path.

2) The second is local alignment support, in which the slave robot's tool follows directly opposite the forming tool (Figure 4b). The forming path was offset to obtain the local alignment support path with a distance of the sheet thickness.

3) The third is local peripheral support, in which the slave robot's tool follows outer side of the forming tool, creating a forming gap between the tools (Figure 4c). The local peripheral support path is obtained by offsetting the local alignment support path outward by the distance of the tool head diameter.

4) The last policy is the local following support, which follows behind the forming tool (Figure 4d).

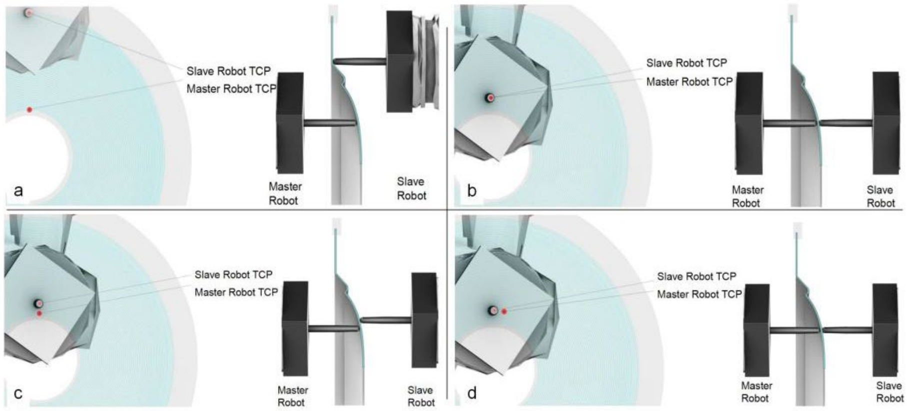

Figure 4. Support strategies. (a)Global support. (b)Local alignment support. (c)Local peripheral support. (d)Local following support.

3.3. 3-D SCANNING

To evaluate the geometric accuracy, the forming result is digitized with scanner sensor. We first tried Kinect Azure, which can get point clouds and depth maps in real time. However, due to the reflection of the metal sheet and low accuracy of scanner, the quality of the scanning results did not meet our requirements. We then use a hybrid blue laser 3D scanner (EinScan HX) to scan the forming result, which is less sensitive to ambient light, gives better performance to reflective surface, as shown in Figure. The scanning accuracy is with 0.1mm and only takes about 30s for each shape, which is accurate and fast enough for the shape measurement.

3.4. DEVIATION ANALYSIS AND COMPENSATION

The deviation can be calculated by analysing the difference between the target shape (Figure 6a down) and the scan shape (Figure 6a up). To calculate the difference from all regions on the sheet metal part accurately, an algorithm was proposed based on minimum distance from point to surface. First, the scan surface is aligned with the target surface in the same coordinate system (Figure 6b). Second, according to the specified 2000 vertices of the target surface, we find the corresponding 2000 closest points on the scan surface. In the figure 6c, red points are the nodes on the target surface, and the green points on the scan surface are the corresponding closest points red points. Then, the distance between each red point and the corresponding green point is calculated, which is the deviation value. In the figure 6d, the deviation value between the scan surface and the target surface is visualized where the red area represents high deviation value, while the green area represents low deviation value. Because there is no global support strategy, the most inaccurate regions are at the outline of the formed part as expected. We now use then deviation values to adjust the forming path for a second re-run.

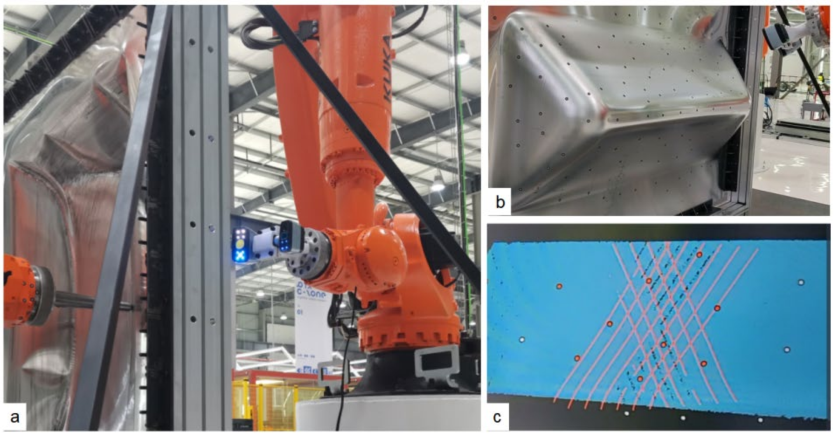

Figure 5. 3D scanning. (a)Robot with a laser 3D scanner. (b-c) Scanning process.

The forming deviation is inevitable owing to springback and complex plastic deformation dynamics, but it can be reduced by some methods. The most straightforward and common approach is to run the same forming path multiple times, but this approach has limited effectiveness and is time-consuming. We tried a new method to reduce the deviation. Instead of using target surface to generate forming path directly, we generate a new forming path based on a computed compensation error between the achieved surface and the desired surface. Experiments show that this compensation model can greatly improve the forming accuracy, because this region was drawn past the target depth. We take the red point on the target surface as the vertex before the offset, and the vector from the green point to the red point is the compensation vector (Figure 7b). Then, the vertex of the compensation surface can be obtained by offsetting the red point according to the compensation vector, and the compensation surface can be generated from the vertices of the compensation surface (Figure 7c). Finally, the compensation surface is used to generate forming path and support path. When the results of the first compensation re-run do not meet the requirements, a second compensation can be carried out and meets the requirements of accuracy.

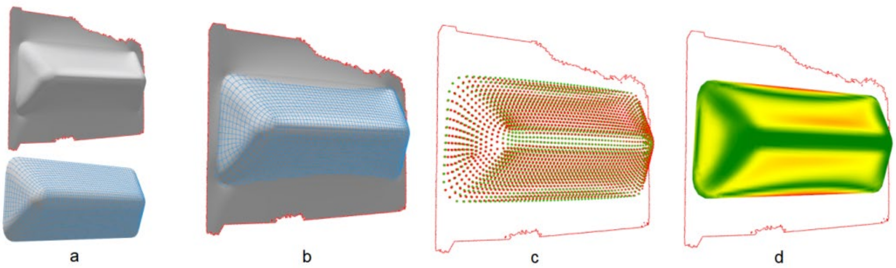

Figure 6. Deviation analysis. (a)Scan and target surface. (b)Two surfaces aligned. (c)Points on two surfaces. (d)Accuracy colour plot.

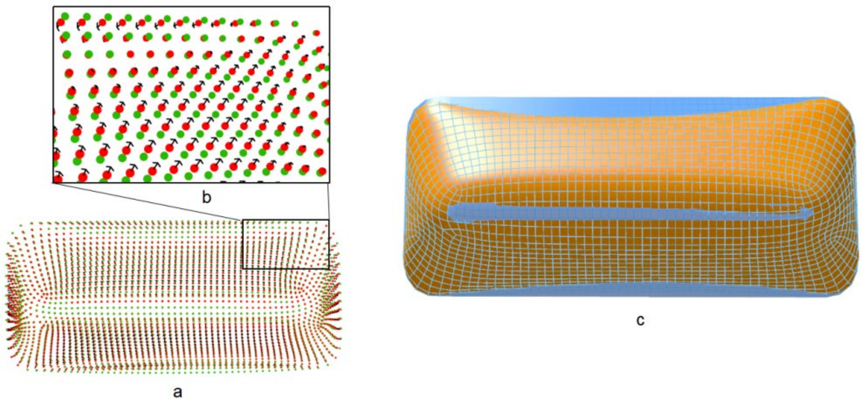

Figure 7. Compensation method. (a-b) Compensation vector. (c)Compensation surface.

3.5. FEA SIMULATION

An explicit integration scheme, with the choice of Belytschko-Tsay shell element type is employed in the finite element analysis of the ISF process, in order to gain insight into the deformation mechanics of the process, and more importantly, to predict the results of the technique with reasonable accuracy. The FEA simulations are performed through Abaqus. The simulation is performed using a 1.5mm thick rectangular Aluminium sheet of the size 1740mm x 1250mm. The diameter of the toolhead is 19mm. A non-linear explicit integration scheme is chosen with semi-automatic mass-scaling. Two surface-to-surface interactions are defined, one between the tool and the sheet, and the other between the sheet and the boundary support. The material properties of aluminium are taken as 70 GPa Elastic Modulus, 0.3 Poisson's ratio, and a mass density of 2700kg/m3. A tangential behaviour contact is set with a coefficient of friction of 0.1 and penalty contact method is deployed for formulation of the mechanical constraint. A four node S4R shell element is selected for this process. The results obtained are shown for a particular model above. FEA is able to obtain the shape with reasonable accuracy and forms a cheaper way to check for failure in the sheet material before performing the actual experiment.

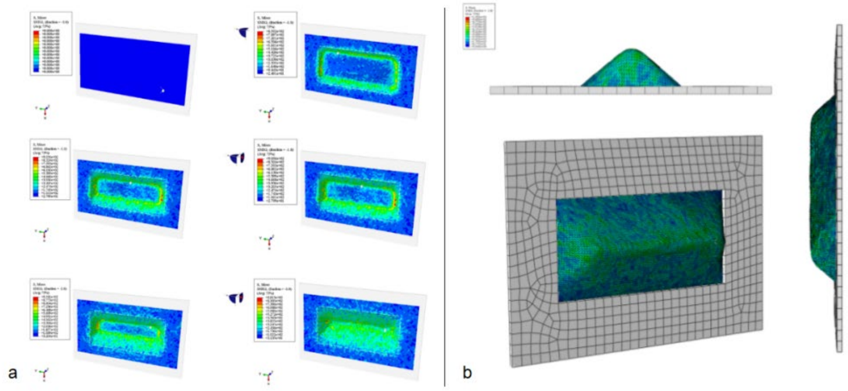

Figure 8. FEA Simulation. (a)Simulation Process. (b)Simulation surface.

In order to meet the forming requirements at one time, we use FEA to predict the deviation and generate the compensation surface. When the accuracy reaches the specific accuracy requirement of the part, the actual forming begins. Computational experiments show that the range of geometric error of uncompensated surface is between -16mm to 12 mm. When our technique is employed, this range is effectively brought down to -7mm to 5mm, significantly improving accuracy.

4. Applications

In order to verify that our method can meet the requirements of high-precision manufacturing, we apply it in the automotive industry. The application aims to develop a continuous sheet metal typology that fulfils the special requirement of the ISF process and enables rapid customization of automotive parts. We first apply it to a vehicle wheel hub that aims to explore the rules and boundaries of design for customizable ISP manufacturing processes.

The ISP process for producing the wheel hub geometry was tested through proof-of-concept full-scale prototypes, one of which was successfully implemented into a new energy vehicle (NEV). In general, the wheel hub was designed through its section. The vehicle wheel hub's symmetrical circular geometry allows for a "Revolving section" method. One-half of the wheel hub's section was designed and the final geometry was formed by revolving it along the centre axis. When considering the design of the section line, designers have to design with continuous curvatures that do not contain sharp turns. Each edge of the section has to be a soft "fillet" instead of a sharp "chamfer"; the radius of the fillet edge cannot be smaller than the tool radius.

The design prototype is inspired by the water drop wave. It is worth noting that the curvature of each "wave" has to be tuned so that it will not exceed the "scratch limit" of the end effector. Several other design prototypes that follow the "revolving section" method were also tested during the development (Figure 9). Further research could look into asymmetrical designs. Asymmetrical designs are, in principle, possible as long as the robot travel path of the ISP process follows a continuous forming line, and the slope of the geometry does not exceed end effector limits. Tire hubs and shell cover for the door opening mechanism of the NEV were built using the current method and deployed on the vehicle.

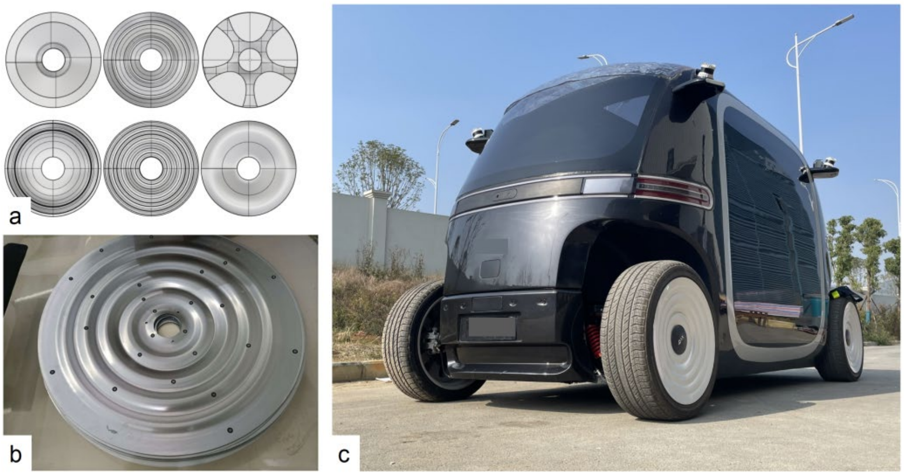

Figure 9. Application in the automotive industry. (a)The design process of the wheel hub. (b)The prototype. (c)The New energy vehicle with the wheel hub.

5. Process Comparison

If we were to manufacture this metallic wheel hub using the traditional manufacturing technique, we would need to turn to stamping, or casting + CNC machining. The cost of making a mould and renting a stamping machine unit from a supplier company would far exceed the current cost by at least a factor of 1000. In the case of casting + final CNC machining, the costs would exceed our manufacturing costs at least by a factor of 100. Our method only uses standard metal sheets, an industrial robot and thus our operating costs are limited to the cost of the raw sheet metal and electricity. Since each robot can produce a wheel hub every three hours, a group of ten robots could produce about 25,000 pieces a year, running continuously, with only running costs of sheet metal and electricity.

In terms of accuracy of the part, the parts are still not as accurate as a CNC machined part, and this paper attempted to find ways to improve part accuracy. An important question to consider is how much geometric accuracy is really needed for a given design. For a wheel hub, for instance, a geometric accuracy of 2mm is acceptable.

6. Conclusion and future work

This paper discusses the development of an ISF technique that solves the problem of low geometric accuracy through the use of flexible support strategies, novel robot path-planning technique and the use of real-time sensor feedback to make minor changes to the tool-path in order to minimize geometric errors. We first introduce our path-planning algorithm to create the first shape and use a feedback loop from the data obtained through a 3D scanner to compute adjustments needed in the tool-path to drastically reduce the errors and bring them within an acceptable limit. The tool-path is re-run again on the deformed sheet metal piece and the final obtained results show satisfactory improvements in geometric accuracies to be applied to product manufacturing. The technique is tested using finite element analysis code Abaqus and is then used to manufacture several automotive products that forms the basis for successful evaluation of our compensation-based path planning algorithm for incrementally formed shell structures.

The design freedom offered suggests their use as cladding elements in a building envelope. For instance, in the architectural field, façade systems form an important part of a building. Design freedom, relative speed and associated efficiencies of our process all strongly endorse the feasibility of production of high-performance façade systems directly from digital models with this method.

Future research from this investigation could rely on a Reinforcement Learning based agent that could train on the geometric error data and compute tool-paths needed to achieve satisfactory geometric accuracy, with training data being obtained from finite element calculations.

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