Development of a collaborative online knowledge management system for incremental sheet forming

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Abstract. Incremental sheet forming (ISF) has a high potential to produce individualized products and prototypes or small series from sheet metal. The universal forming tool, as well as the digital process control, in principle, allow a fast realization from design to a finished component. However, a high level of testing and planning is often required to achieve the necessary geometric accuracy. A large number of scientific studies on process parameters and process variants have led to significant progress in the specific studied cases. Nevertheless, this progress can often not be transferred to arbitrary component geometries. Despite the many valuable detailed scientific findings, there is a lack of a holistic overview. The translation of case specific findings to a broad range of real application components is missing. Due to the large number and complexity of process parameters as well as a wide variety of possible component geometries, a systematic collection of knowledge and experience is required. Therefore, this paper describes the development of a web-based database for process data of incremental sheet forming. This database should first of all allow component data and associated process data to be recorded, completely and reproducibly. By sharing the database with a large number of research teams and end users, an intensive exchange of experience can take place systematically and new knowledge can be generated collaboratively.

Introduction

A high dynamic market with a trend towards mass-customization and short time to market for new products, requires agile production technologies. In this regard, incremental sheet forming (ISF) has a high potential for sheet metal components. Due to the flexibility of a universal forming tool and the determination of a component geometry by numerical controlled movements of the tool, this process can in principle react very quickly to new or changed component geometries in small batch sizes [1]. In order to enable rapid realization from design to finished component for small quantities and prototypes, the planning and preparation processes in particular must also be carried out very quickly and with accurate parts as a result.

Allwood et al. [2] analysed specifications in terms of geometrical accuracy for many different sheet metal products. This shows that tolerances of less than ± 0.5 mm are required in most applications. Despite great research efforts, geometric tolerances required by industry have, so far, only been achieved with ISF in individual cases or specific applications [3]. The geometric deviations and the cumbersome planning and testing effort required to compensate for them, are one reason for the low prevalence of ISF in the industrial environment. Another reason are the stringent process limits, resulting in failure of the component outside a specific forming range.

Many studies have been carried out over the last decades to increase geometric accuracy and process limits, such as investigating the influence of different process parameters, as well as optimizing tool paths to compensate for unwanted geometric deviations and applying a multi-stage approach [1,4]. This also led to the development of new process variants [3]. However, many of these investigations are limited to very simple component geometries or to very specific cases. Considering that the geometry has a significant influence on the process, as has been shown by Ambrogio et al. [5], a transfer of findings between different component geometries is only possible to a very limited extent.

The advantage of the flexibility of ISF is unfortunately challenged by its complexity. The process has a large number of degrees of freedom in process control and a very broad spectrum of theoretically possible component geometries. Measured against this, the process understanding and empirical knowledge that has been built up so far is insufficient to enable rapid process planning and thus broad industrial application. Therefore, the aim of the research work described here is to systematically gather knowledge and experience about the process, especially with regard to the large number of possible component geometries.

Platform for Knowledge Sharing

Documenting experience requires systematic and extensive gathering of data about components, corresponding processes and process results. Experiments and processes must be recorded in a structured way so that they are reproducible by other researchers or users. The shared experience documents which components can be manufactured and which process parameters are required. However, great value is also attributed to the failed process strategies, as they enable important knowledge to be gained. In this regard, it is also possible to document which components cannot be manufactured up to now and, ideally, why this is the case.

The documentation of process experience can be a benefit for each research team, but should not be limited to that. In order to generate a real impact, the data of as many research groups and end users as possible should be collected and shared. For this purpose, a web-based database has been implemented to allow users to document their own component and process data, to analyse the data from other users and compare different experiments in an easy and structured way. An additionally linked forum is intended to enable direct discussion on this data. This facilitates a direct exchange of knowledge and experience across different researchers and end users. As an addition to scientific publications, this form of dissemination enables an exchange on specific and detailed data that can also be directly referenced in discussions. It is a work and collaboration tool closing the gap between different research teams and PhD research generations.

The presented database can also be used to systematically document and moderate benchmark studies. Such benchmarks can trigger a collective learning process and further advance knowledge. Another motivation behind a platform for data collection is the prevailing evolution of data-driven methods. For example, a wide and detailed collection of process data and annotated metadata can enable machine learning to extract process boundaries for a broad range of geometry/material combinations. In the long term, the shared ISF data on the platform shall be used to generate new insights into the causes of geometric deviations and potential compensation measures.

Web-based Interface and Database for ISF Process Data

The collaborative database motivated in the previous paragraph was realized with a web-based interface. This enables the desired worldwide access of many different researchers and users. Moreover, it allows for the structured and visually responsive processing of the data to be documented. A major difficulty in the process optimisation of ISF is the complexity of the input and output variables of the process. The component geometry, tool path, and resulting accuracy are complex three-dimensional data that cannot be simplified to individual parameters without severe loss of information. This problem does not only apply to process optimisation, but also causes difficulties in the pure documentation of the processes. Other complex parameters are the (partial) supporting dies and the occurrence of intermediate geometry data in multi-stage processes and possible preliminary process steps. They all have to be documented as 3D data.

A well-designed user interface enables an efficient workflow for the documentation of the process data, is not prone to errors and still ensures a high information content. In order to reach this, the web-based platform was realized using Django, which is an open source framework written in Python that can be used to design web applications. MySQL is used as the database management system for the storage of the ISF process data. Within the framework, an ISF project/process is represented using a model. Fields are assigned to this model, which represent the variables to be stored.

In addition to a large number of quantifiable process parameters, CAD data of the component, tool paths and 3D scanned surfaces can also be uploaded as STL or STP files via the web interface. The uploaded data are visualized directly to the user and can thus be reviewed and analysed. An exemplary visualization of 3D data sets on the platform is shown in Fig. 1. In this figure, both the tool path (red), various scanned geometries after the forming process, and the actual target geometry can be seen.

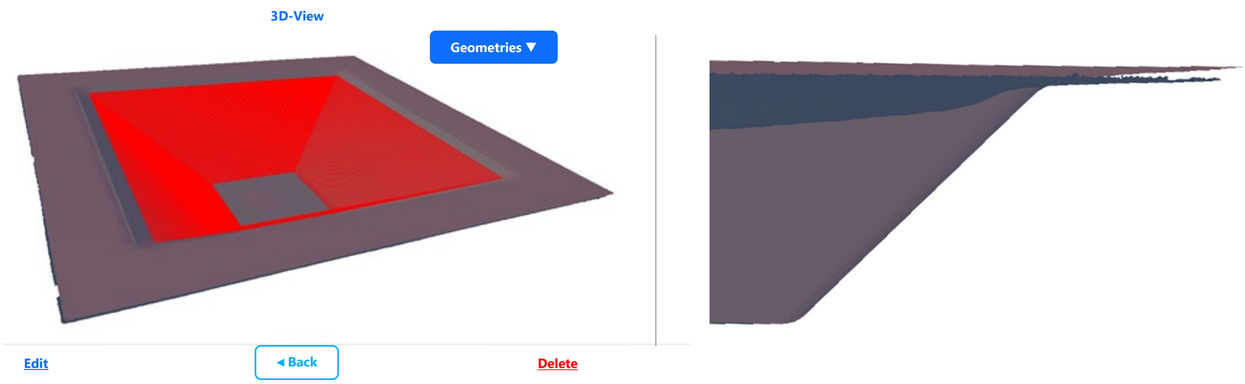

Figure 1. Screenshot of the visualization of 3D data in the user interface of the platform (left), side view to show different geometries (right)

In addition to the systematic documentation of ISF processes, the database also offers the possibility to search in the already stored component and process data. Search fields and filters can be used to find specific process plans that match a current problem. The database thus already offers the possibility of systematically documenting and exchanging process data. In order to be able to conduct this exchange in the sense of specific discussions, a forum has also been integrated. This way, the relevant process data can be referenced directly in technical discussions.

Structure of Process Data Acquisition

For the systematic acquisition of component and process data, it is necessary to have all parameters consolidated and clearly defined. The overall goal is to get assessable, searchable and comparable data that describe the components and processes accurately and completely, in such a way that the process can be reproduced easily. In order to achieve a clear description with a high depth of information, 3D data and process parameters are therefore recorded in their entirety. Furthermore, to enable searching and comparing the data, fuzzy criteria (e.g. geometry category) are also recorded. The processes considered in the database are limited to conventional SPIF, TPIF and multi-stage SPIF, with an additional specification of preform operations. Fig. 2 shows the structure of the data acquisition in the web interface, where the data are split up into six main parameter categories.

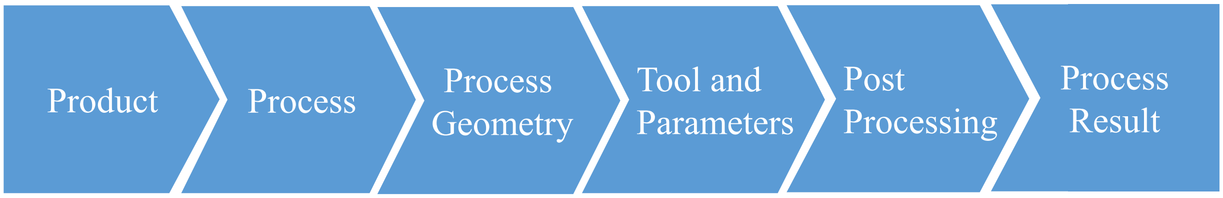

Figure 2. Work flow of the data acquisition for the ISF process database

In the first step (Product), the information about the sheet metal component is recorded, since the product specification is the basis for everything else and usually cannot be changed. In the second step (Process), the basic process configuration is queried, i.e. process variant, machine, etc. This information is used to adapt all further queries to the specific case. In the third step (Process Geometry), the geometries that define the process are recorded, i.e. component geometry, clamping, pre-geometry, etc. This was deliberately decoupled from the product description, since process-specific adaptation occurs here. In the fourth step (Tool and Parameters), the variable process parameters are described, which can be easily adapted in terms of process optimisation. In the fifth step (Post Processing), the possible processes after ISF operations are queried, such as heat treatment and trimming. In the last step (Process Result), result data (e.g. resulting geometry and surface quality) are recorded.

The next paragraph gives a more elaborate description of these categories and the data they contain. The type of bullet point reflects the type of query: boxes for multiple selections, circles for single selections and dots for other input fields.

Product

3D Part Geometry	**Geometry Size**	**Geometry Category**			**Geometry Features**	**Limiting Geometry Parameters**	**Material**	**Initial Sheet Thickness** (before ISF)
		Global Curvature	**Global Shape**	**Symmetry**				
• [.stl/.stp]	• Length [mm] • Width [mm] • Surface Area [mm^2]	❑ Flat ❑ Uniaxially Curved ❑ Biaxially Curved ❑ Uniaxially Curved with Curvature Change ❑ Freeform	❑ Round ❑ Rectangular ❑ Squared ❑ Oval	❑ Asymmetry ❑ Rotational Symmetry	❑ Corner ❑ Cavity ❑ Fold ❑ Flange ❑ Undercut	• Maximum Wall Angle [°] • Tightest Radius [mm] • Deepest Cavity [mm]	• Alloy • Yield Point Rp0,2 [MPa] • Young's Modulus [GPa]	• [mm]

Figure 3. Product data query with related parameters

In a first step, the information about the desired sheet metal component is recorded (see Fig. 3). For each ISF process, basic information about the component to be manufactured must be queried, such as the 3D geometry and its bounding box dimensions. In addition, a fuzzy description of the geometry (curvature, shape, symmetry, features, etc.) helps to search and compare the different part geometries. Some parameters are also important to interpret process results. In particular, the data of limiting geometrical influences (e.g. wall angles), sheet material, as well as the input sheet thickness are relevant process information. Jeswiet et al. [6] demonstrated the influence of the wall angles on the final thickness distributions after forming and approximated this relation with the sine law. In addition, Ambrogio et al. [7] showed that sheet thinning is significantly influenced by the wall angle of the geometry to be formed and the material used. Li et al. [8] explained that the sheet thickness has a significant effect on the overall geometrical accuracy.

Process		
Process Type	**Type of Preform Fabrication**	**Machine Description**
❑ Multi-Stage ○ SPIF ○ TPIF ○ Other	❑ Flat ❑ Stretch Forming ❑ Deep Drawing ❑ Bending ❑ Other	• Type • Axis-Configuration • Max. Force [kN] • Working Space (Length, Width, Depth) [mm]

Figure 4. Process data query with related parameters

In the second step, the basic process configuration is queried, i.e. process variant, machine, etc. (see Fig. 4). This information is used to adapt all further queries to the specific case. Information about the type of process and the equipment used is documented. For example, Taleb Araghi et al. [9] were able to show that not only classical ISF process parameters have a significant influence on the process, but also preceding process steps. The combination with a preceding stretch-forming process also reduced the geometric deviations strongly. Liu et al. [10] showed the dependence of the results after forming on the selected process strategy, where multi-stage strategies proved to increase the formability and thickness distributions compared to single stage forming. In the platform, multi-stage strategies can be uploaded as a chain of individual processes that reference each other. This allows each individual process step to be analysed separately and as process chain.

Process Geometry			
Input Sheet Geometry	**Input Sheet Thickness**	**Part Geometry for Process Planning**	**Clamping Geometry and Position**
• [.stl/.stp]	• [mm/.txt]	• [.stp/.stl]	• [.stp/.stl] ○ Rectangular ○ Circle ○ Ellipse ○ Near-Shape ○ Other

Figure 5. Process Geometry data query with related parameters

In the third step, the geometries that define the process are recorded, i.e. component geometry, clamping, pre-geometry, etc. (see Fig. 5). The choice of process type and preform fabrication results in additional process parameters. If a preform is used, the CAD file of the preform as well as information about the sheet thickness distribution as a txt file can be uploaded. If a modified part geometry is used for process planning, such as for overbending strategies, this modified geometry can also be uploaded. Additionally, the geometry and position of clamping tools can be defined.

Tool and Parameters

Type of Forming Tool	Tool Tip Geometry	Tool Material	Tribology	Tool Path Design	Pitch Strategy
○ Rigid ○ Rolling ○ Pulsing ○ Free Rotating ○ Driven Rotating ○ Other	○ Hemispherical ○ Other	• Alloy	❑ Coating • Type ❑ Lubrication • Type • Application Method	• [.txt]	○ Step Down ○ Scallop ○ Step Over • Pitch [mm]

Forming Speed	Process Temperature	Temperature Distribution	Forming Force
• [mm/min]	**Temperature Level:** ○ Room Temperature ○ Hot Forming **Type of heating:** ○ Local Heating ○ Global Heating • Forming Temperature [°C]	• [.txt]	• [.txt]

Figure 6. Tool and Parameters data query with related parameters

In the fourth step (Tool and Parameters), the variable process parameters are described, which can be easily adapted in terms of process optimisation (see Fig. 6). Detailed information about the forming tool as well as about the planned tool path is summarized. The increased focus of the current research on adaptations or optimisation of the used tool path confirms its significant influence on the process result, so that a detailed query of the tool path is reasonable. For example, Skjoedt et al. [11] showed the influence of the forming direction of the toolpath, where upwards and downwards forming have a significant influence on the geometric accuracy in a multi-stage approach. However, according to the literature, information about the forming temperature and speed also are essential. Al-Obaidi et al. [12] showed in induction heating assisted ISF that the temperature distribution in the sheet during forming has an important role in improving geometric accuracy.

Post Processing

Trimming	Heat Treatment
○ Trimmed to Part Contour ○ Untrimmed **Type of trimming:** ○ Waterjet Cutting ○ Laser Cutting ○ Wire Cutting ○ Milling	• Time [s] • Temperature [°C]

Figure 7. Post Processing data query with related parameters

In the fifth step, extra processing operations after forming with ISF are queried, such as heat treatment and trimming (see Fig. 7). After the actual forming process, many components require post-treatment to finalize the component. Trimming processes are mainly used here, as well as heat treatment, which can be used, for example, to reduce residual elastic stresses. Due to their influence on the residual stresses remaining in the material, both processes also have an influence on the process result and are therefore queried under the table "Post Processing".

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Process Result

General Producibility	Process Pictures	Result Description	Accuracy	Sheet Thickness	Surface Quality
○ Producible ○ Not Producible	• [.image]	• free text	• Measurement Device • Measurement Accuracy [mm] • Scanned Geometries [.stl/.stl] • Deviation Plots [.image] • Max. Deviation [mm] • Average Deviation [mm]	• Minimum Thickness [mm] • Thickness Distribution [.txt]	• Surface Pictures [.image] • Optical Appearance [free text]

Process Time	Additional Information	Process Goal Description	Related Publication
• [HH:MM:SS]	• Process Goal ❑ Industrial • Scientific ❑ Geometrical Accuracy ❑ Process Limits ❑ Feasibility	• free text	• DOI

Figure 8. Process Result data query with related parameters

In the last step, result data such as measured geometry and surface quality are recorded (see Fig. 8). Up to this point, process parameters were queried from which, according to the literature, there is a possible influence on the process result. As already mentioned at the outset, quantitative and qualitative process results must be queried in a next step in order to be able to find relationships with the data uploaded so far. For this purpose, information such as the basic manufacturability is queried in the "Process Result" table, since ISF processes that have not been carried out successfully also represent an important element for further process understanding. In addition, process images, a qualitative description of the process performed and the experiment duration can be uploaded. For a detailed analysis of the results, scanned component data can be uploaded as well as descriptions and images of the resulting surface quality.
So far, the focus has been on uploading experimental data, an extension to numerical models and simulation results is intended in the near future.

Summary

ISF has a high potential for prototyping and small batch production. Nevertheless, the process is complex and compared to the large variety of possible component geometries there is a lack of process knowledge and experience. In order to be able to successfully and economically apply ISF in industry, it is necessary to ensure fast and successful process planning, since the planning and testing costs can only be allocated to a small number of components. In particular, avoiding undesired geometric deviations leads to considerable effort in process planning for complex application components and often also to a large number of trial and error tests.

The paper presented an approach and an implementation platform to systematically collect and analyse data of ISF processes. The realization as a database with a web-based user interface enables the exchange of ISF researchers and users around the world. This allows for an intensive exchange of knowledge and experience about components and ISF processes based on specific and precise data. The intensive exchange between the authors about the selection and definition of the process parameters has already led to a close exchange between two research teams. From the collected data and the intensive discussions of these data, important findings about the ISF process can be generated and verified in the future. This will enable collaborative learning and systematic progress for the ISF process and its planning procedures.

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