Adaptation of Incremental Sheet Forming into cloud manufacturing

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Abstract:

Incremental Sheet Forming (ISF) is a technology suitable for manufacturing small series and single products. Due to the high customization potential of this process, it is therefore necessary not only to implement the mechanical tools and control algorithms needed, but also to enable easy integration with product configurations executed by customers. The paper describes how ISF can be provided as flexible manufacturing service to production networks and how it can be configured by means of appropriate service descriptions. Furthermore, a new adaptive tool path control algorithm at process level is introduced to bypass fracturing due to localized thinning.

Keywords:
Cloud, Cloud manufacturing, Service, Incremental Sheet Forming, Tool path control

1. Introduction

Nowadays, one of the most promising approaches to improve the ability to react quickly to changing customer's demands is the automated or semi-automated integration of production networks at IT level. This is already applied in business operations, e.g. exchanging business documents such as orders and invoices [1]. However, the challenges of flexible, distributed manufacturing go beyond such operations, as this form of information exchange does not include product and production specific data such as designs and required process parameters. As a result, there is a need to integrate such specifications and manufacturing IT systems into the overall supply chain management infrastructure in order to enable quick reactions to changing product specifications.

A new concept of cloud manufacturing [2] introduces some aspects which could help to overcome this issue. The transfer of the XaaS (Anything-as-a-Service) concept to the production domain is one of these ideas, and this predicts the implementation of MaaS (Manufacturing-as-a-Service) based on cloud-computing concepts which are considered here. One precondition for the implementation is the availability of agile IT systems which are capable of supporting the degree of flexibility at production network level as well as at factory, process, and equipment levels. A research and development project within the EU's Seventh Framework Programme (FP7), ManuCloud, has been set up to develop a marketplace for virtual manufacturing services as well as to achieve the enhanced integration of manufacturing networks based on the dynamic interconnection of multiple factories.

“Three industries have been selected to be the initial application context for the ManuCloud concepts and technologies: The photovoltaic (PV) industry, the organic lighting (organic light emitting diodes - OLED) industry and the automotive supplies industry.” [3] Demonstration scenarios and products have been prepared to show the integration and implementation of the small series production of complex customizable products and services of small to medium-sized enterprises (SMEs) [4-7].

On the automotive side, there are many possibilities of proving the benefits of this approach. However, it is even more motivating to apply the approaches to a flexible manufacturing technique. For this reason, the paper gives an overview of how Incremental Sheet Forming (ISF) could be implemented as a manufacturing service and of a new adaptive control algorithm to decrease the number of trial sheet-forming.

2. ISF variants and main technical parameters

2.1 Incremental Sheet Forming variants

ISF, known in early stages as “Incremental Dieless Forming” [8], is a promising process for the sheet metal and polymer industry with small series in the field of one-of-a-kind production. Rapid prototypes are already made for the automotive and aircraft industry but there are also good perspectives for the medical device industry and architectural design. These prototypes are generally made in the course of different research investigations but there are some SMEs and research centers where parts can be ordered and then produced within days or weeks (depending on the complexity of the part). When a metal or polymer sheet is formed using ISF, the forming tool which is carried by an industrial robot or CNC machine [9] makes an indentation in the sheet and follows the tool path of the desired part.

This process step (local bending and stretching) is repeated all along the tool path until the final depth and form of the part is reached. The tool path (mostly z-level or spiral) is similar to profile milling performed using commercial or home-made CAM programs. There are different ISF variants depending on the number of contact points between the forming tool, sheet and supporting die (if used). The term Single Point Incremental Forming (SPIF) is used when the opposite side of the sheet is supported by a faceplate. Fig. 1 shows an example of SPIF.

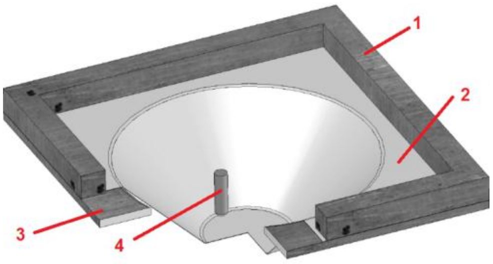

Fig. 1: Illustration of SPIF in cross sectional view, with 1: clamping frame, 2: sheet, 3: faceplate, 4: forming tool

Two Point Incremental Forming (TPIF) is used when a full or partial die supports the sheet [10]. Fig. 2 shows an example of TPIF.

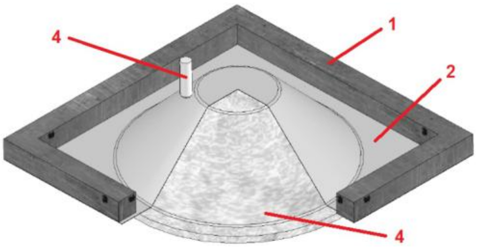

Fig. 2: Illustration of TPIF in cross sectional view, with 1: clamping frame, 2: sheet, 3: full die, 4: forming tool

A further developed variant of TPIF, where a second counter tool is synchronized with the first one, can also be used to produce the final shape [11]. The main difference between SPIF and TPIF is the forming accuracy. TPIF is more accurate but needs a partial or full support (depending on the geometry), making it more expensive.

2.2 Incremental Sheet Forming process parameters

ISF forming limits are higher than those of stamping or deep-drawing and are dependent on the following process parameters [12]:

1) Material and initial thickness of the sheet

2) Material and geometry of the forming tool

3) Geometry of the part

4) Step depth

5) Tool path

The influence of these parameters on each other and on the final product is clearly summarized in [10]. For example, sheet formability decreases with increasing step depth; this is also important when optimizing tool paths.

2.3 Tool path optimization in ISF

Tool path optimization in TPIF [13, 14] and SPIF [15, 16] is very important because sheet thinning [17] occurs during the forming process. Based on a geometrical model of the kinematics of ISF, the degree of thinning can be predicted with sufficient accuracy [18]. However, in the case of anisotropic materials with localized material flaws, it is better to use an on-line measurement method during forming. Some reaction force trend-based [16, 19] measurement methods have been used to measure localized thinning of the sheets indirectly during forming, but only two direct methods are mentioned in literature [20, 21]. The only drawback with these set-ups is that they measure the sheet thickness axially to the forming tool and not close to the deformation zone where the sheet thinning actually occurs.

SPIF experiments showed that "fracture always occurred at a previously generated shear band closest to the current position of the tool" [22]. From this, it follows that the simplest implementation of the Hall-effect sensor-based on-line thickness measurement device would be an ISF tool with an iron ball head [8]. The Hall-effect sensor and the magnet can be placed on the opposite side of the sheet. During forming, the magnet and sensor (bonded to the magnet) are carried with the forming tool. This enables an appropriate adaptive control to be used to bypass fracturing due to localized thinning.

Calibration experiments are already done for this approach and documentation of the results can be found in [23]. However, the question remains as to what type of adaptive control should be applied.

3. Adaptive tool path control algorithm

Separating the measurement principle from the control algorithm, two simple on-line methods can be found in [16]. In the experiments documented in [19], it was necessary to stop the machine every time forming parameters were altered (in the case mentioned, only the diameter of the forming tool). The two methods are shown below:

(A) "Tool path adaptation by modifying the tool jog" - this means a "modification of the tool height between two successive control points of the tool paths". [16]

(B) "Tool path modification by using a clearance routine" - this means "as soon as the tool load estimation overtakes a pre-set value, the forming NC program calls the clearance subroutine" which performs a retract movement along the tool axis. [16]

A drawback of these methods is that with method (A), "the final accuracy can be affected by tool jog variations if several tool path adaptations are needed during the process" [16] and with Method (B), that the user-defined movement of the tool causes local surface roughness because the tool contact and thus also the continuous forming of the sheet is changed.

In [13], experiments showed that "it is important to use a tool path with a variable step depth" and define the maximum step depth (0.2 mm) and scallop height to a low value (0.02 mm). This increases accuracy but unfortunately also the process time, thus leading to ineffective production.

A compromise can be made by using an on-line thickness measurement with a simple adaptive control algorithm, which changes the step depth ($\triangle z$) at the position where the contour changes to a deeper level. To guarantee the same final depth and shape of the product as with the initial step depth, more tool paths based on the same geometry but with different step depth are needed. Fig. 3 shows the block diagram of the tool paths changing algorithm with three different step depths.

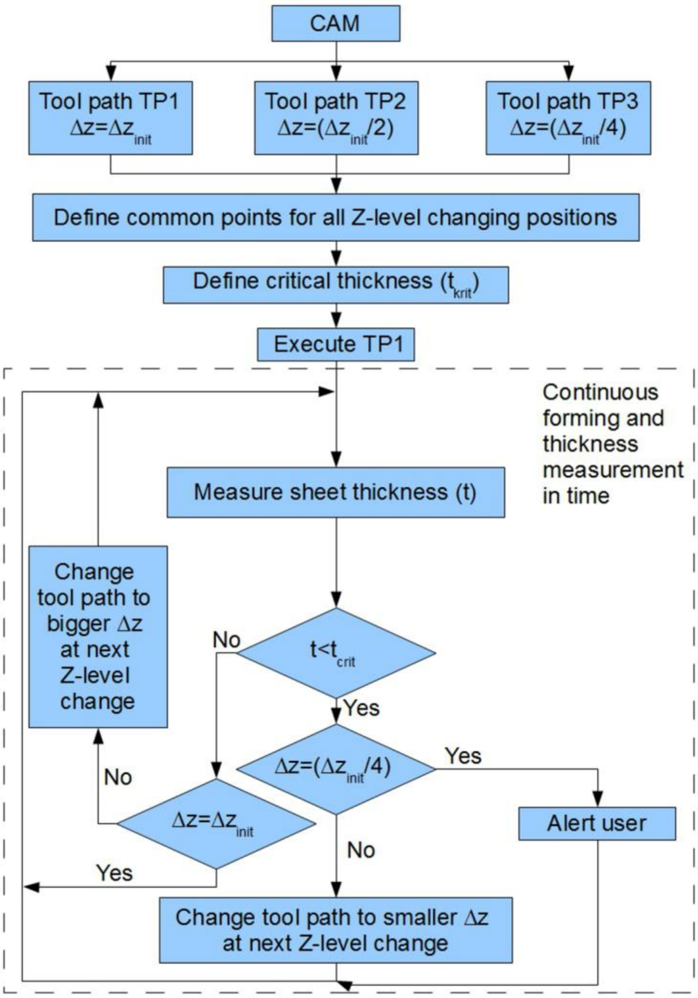

Fig. 3: Block diagram of the adaptive tool path control algorithm

Should the actual sheet thickness be higher than the pre-set critical value, the control can switch to a higher step depth (with a higher forming speed). Before changing the tool path, the actual positions have to be saved. This is essential in order to calculate the position where the machine control has to jump to the other tool path.

The advantages of the adaptive control algorithm are listed below:

- It can be used with all the sensors documented in this field to prevent fracturing.
- It can be applied to different tool paths, e.g. spiral tool paths in case a smoothing movement is executed before the tool path change.
- It can also be applied to simple controllers where a jump to a certain position of a different program is not permitted. In this case, the tool path has to be split into several parts. One part of the program corresponds to one contour.

4. Providing Incremental Sheet Forming as manufacturing service

Due to the configurability of the incremental sheet forming process, it can also be adapted to customer needs for small series or even single products.

However, information about the process options must be provided, e.g. parameters that are configurable to the customer and vice versa, in order to ensure that customer product configurations can be fed back to the manufacturing control system. Therefore, a common infrastructure and appropriate interfaces are essential.

Such an infrastructure must be made up of several layers. According to cloud manufacturing and manufacturing-as-a-service concepts as shown in Fig. 4, an adequate architecture has been chosen to ensure consistent and integrated information processing from equipment level to customer interfaces.

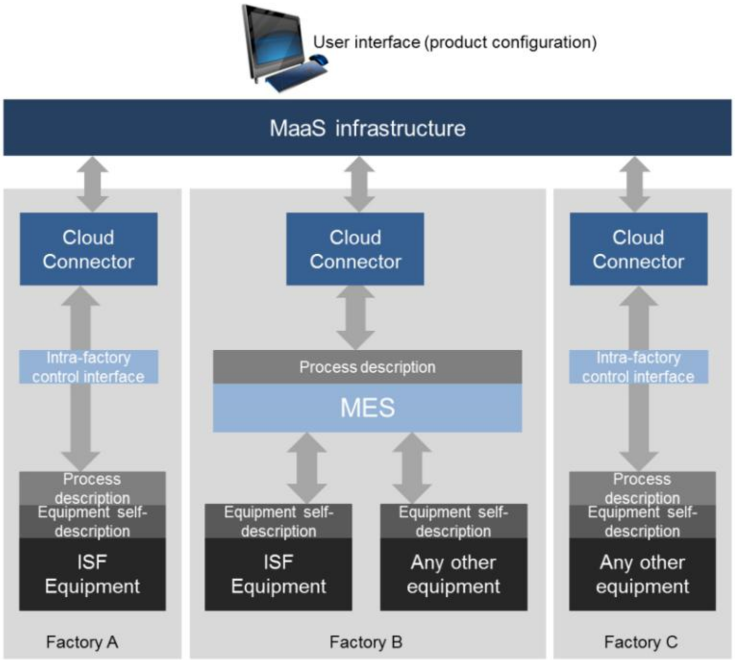

Fig. 4: Manufacturing-as-a-Service (MaaS) infrastructure

The basic principle behind this is that the process tools provide information about their capabilities and configuration options, i.e. the parameters and the events and commands they can send and receive by means of self-descriptions. For ISF processes, such equipment-specific parameters include the geometry and material of the forming tool. These self-descriptions can be used to create process descriptions, e.g. by means of parameter mapping. The descriptions represent capabilities on a higher level and again contain parameters which can be adjusted according to customer needs, such as the material and initial thickness of the sheet. But they can also include information about process goals and constraints as well as quality data and process-related events and commands. The extraction of the process descriptions can take place either using advanced factory level IT systems such as MES or by means of interface extensions, which enable equipment self-descriptions to be extended through appropriate process information.

In order to provide ISF or other process capabilities as manufacturing services to production network environments, process descriptions need to be mapped so that the end-customer is given understandable information. Therefore, within the cloud connector interface, parameters etc. from the process descriptions are mapped to manufacturing service descriptions. As well as general information about the provider organization, these contain data regarding costs, logistics and product characteristics used to describe the product to be manufactured, which are in turn related to constraints and dependencies. From the ISF point of view, examples of these characteristics include the geometry, thickness and material of the part to be produced.

As configurability is ensured by means of providing parameter ranges, dependency and validation rules on each level, i.e. equipment, process, and product/manufacturing service, customers can be provided with the full range of customizing options. Due to the fact that service descriptions become more detailed with each layer (from equipment to product), this type of parameter mapping also ensures that intellectual property is protected with regard to process parameters such step depth and tool path. As the descriptions are based on xml formats, it is even easier to exchange such information platforms independently. During product configuration, a product geometry specification is created by the customer on concretizing certain product configuration options. As soon as a real order is placed, this specification is sent back to the relevant factory where parameters are mapped backwards first to process and then to equipment level.

5. Service parameters and user inputs in ISF

Service parameters are characteristics of a service on the side of the manufacturer; they can be defined as aggregated service parameters and made visible to the customer. The customer has to define the required inputs before ordering a certain product.

5.1 Possible aggregated service parameters

A distinction has to be made between first order and second order bottle neck parameters. These describe the main capabilities of a service provider with regard to ISF.

First order bottleneck parameter(s):

- Machine type (in order to automatically define the working area and payload)

If the machine is an in-house construction, the working area and payload need to be defined manually. For example, in the robot laboratory of MTA SZTAKI, there is an old Rieckhoff type 2.5D milling machine (see Fig. 5) with no specification data concerning its maximum capacity. The maximum allowable reaction force in ISF needed to be calculated from the motor datasheet, toothed belt ratio and ball screw data.

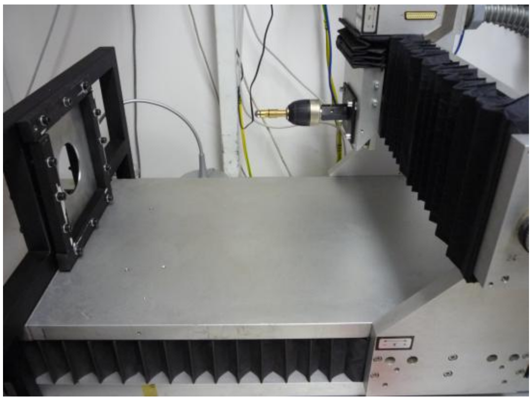

Fig. 5: Milling machine-based single point incremental forming set-up.

The second order bottleneck parameter:

- dimension of the clamping frame

Depending on actual possibilities (scheduling, condition and location of the machine), the service provider can supply smaller units. For example, in the laboratory there is a FANUC S430-iF type industrial robot with a 130 Kg payload and a 2488 mm horizontal reach, but only sheets sized 500 mm X 500 mm can be clamped into it (see Fig. 6).

Fig. 6: Set-up for industrial robot-assisted single point incremental forming.

5.2 User inputs

The input parameters necessary for the ISF service are the CAD file of the product, the material and the thickness of the sheet. Although there are several CAD file formats, STL is the most practical choice because it is supported by many commercial 3-D CAD program and describes the surface geometry of a 3-D model without texture, color or other additional parameters. The ManuCloud portal will be extended by a Customized Product Advisory System (CPAS) where CAD models can be uploaded and visually inspected before placing an order for a product. CPAS has mainly been developed to configure predefined variants of OLED and OPV modules but it is also capable of uploading almost freeform surfaces.

5.3 Connection between user inputs and service parameters

The user inputs can be connected with a material database to carry out an automatic search for possible manufacturers. This pre-filtering is necessary because not all factories possess machines strong enough for a cold ISF of a certain metal or polymer sheet. The material database could contain the type of the sheet together with its tensile strength. In some cases, these two parameters are sufficient to predict the maximum force in sheet metal SPIF.

In [24], a simple linear formula was introduced, which links the “reference force” (value of the axial component of the reaction force) with the tensile strength. The formula was a result of analytical force analysis and FEM simulations of SPIF with only five materials (AA3003, AA5754, DC01, AISI 304, and 65Cr2) but is a good starting point for a material database. The database can be extended at a later point in time with more results from experiments and FEM simulations.

6. Conclusions

Incremental sheet forming as a service can easily be connected to a Manufacturing Cloud provided all the aggregated parameters required are known. The ability to use a material database for filtering possible ISF service providers is also mentioned. The cloud connector presented does not require a real MES server because it can be simulated. As a rule, service parameters, such as specification limits (working area and payload) and units of characteristics, are specified manually by the engineers concerned. Besides the integration possibilities, an adaptive control algorithm is introduced with a variable forming depth at process level in order to bypass fracturing of the sheet in the case of localized thinning.

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