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Tool path programming optimization for incremental sheet forming applications

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ABSTRACT

Incremental sheet forming is an emerging process to manufacture sheet metal parts that is well adapted for small batch production or prototypes. The adjustment time is short, as it is sufficient to modify the tool motions to optimize the manufacturing process. Tool path generation therefore becomes a key topic linked to incremental sheet forming, and process characteristics ask for dedicated tool paths. Hence, this paper first discusses the impact of tool path types and other programming parameters on process implementation through an experimental campaign performed on a parallel kinematics machine tool. Then, a new approach to generate and control Intelligent CAM programmed tool paths is proposed. The major purpose of this innovative concept is to use process constraints for programming and controlling the tool path, which are adapted during the running of the CNC program according to real-time process data evaluation. Validation studies and an industrial implementation are finally presented to assess the efficiency of the proposed approach.

1. Introduction

Incremental Sheet Forming (ISF) is an emerging process to manufacture sheet metal parts that is well suited for small batch production or prototyping [1,2]. Indeed, it is highly flexible and needs only low set-up costs: the required equipments are an NC milling machine tool (or equivalent) equipped with dedicated tooling; process implementation consists in making the tool, performing computer-generated tool paths at preset levels which decrease according to given increments. As a consequence, the adjustment time is very short, as it is sufficient to modify the tool motions to improve the manufacturing process. Tool path generation therefore becomes a key topic linked to ISF.

The majority of the first publications did not focus on forming tool paths [3–7] and were using forming strategies built by CAM software (dedicated to material removal processes). However, some interesting works studied tool path related parameters. Kopac et al. showed in [8] that, in Single Point Incremental Sheet Forming (SPIF), it is better to run the tool path from the edge of the part to the centre in order to improve the accuracy. In [7], Ceretti et al. worked on Two Points Incremental Forming (TPIF) and tested two tool path types. According to their results, spiral strategies are better than contour parallel strategies. In the same way, other works highlighted the fact that the choice of forming strategy has a great effect on the process performances; see for example [2]. Attanasio et al. worked on the influence of the axial increment in TPIF [9] and advise using a small scallop height and variable axial increments to design the tool paths. A variant of TPIF was implemented by Mao et al. in [10]. Instead of a complete shape, a bolster rod holds the sheet metal and stands for a die. A way to limit the circumferential ridges that appear between the tool paths is to adopt a forward and backward forming strategy. As a result, the surface roughness is better.

Recent research works have been carried out to overcome two major drawbacks which are observed in ISF: formed part accuracy and sheet metal integrity. To compensate the elastic springback effect, Ambrogio et al. program a higher slope than the CAD model until the middle of the part [11]. In [12], this concept is extended and named "vitiated trajectories", because the tool paths, which are deliberately false, lead to accurate parts. An experimentally based method is proposed by Hirt in [13]: the tool paths are modified after having measured the first produced part and its defects. More recently, Duflou explored a promising approach in [14] by implementing multi-step tool paths that allow moving the forming limits away, especially the wall angle. Both the accuracy and part integrity are increased. A similar method is proposed by Skjoedt in [15]. Micari, in [16], discusses several methods to improve SPIF capability and concludes that tool path optimization approaches are the most promising.

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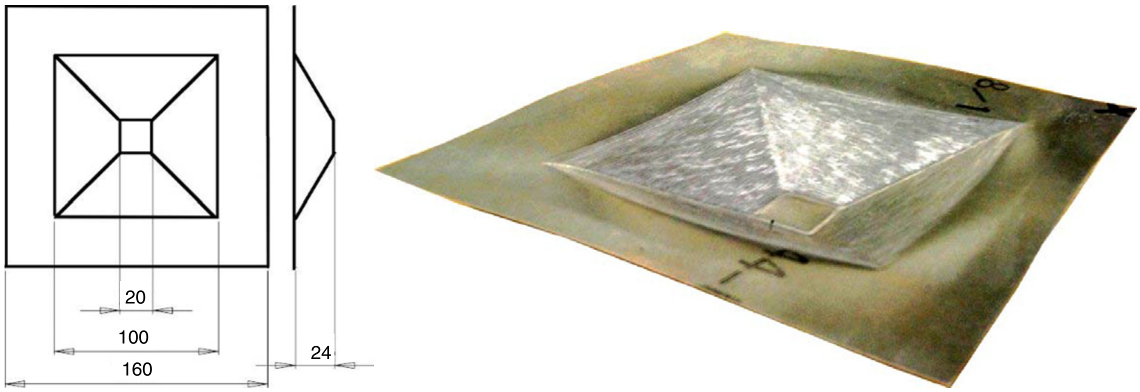

Fig. 1. Test part.

However, CNC tool path implementation and control during the ISF process have not yet been widely discussed. On that point, CAD-CAM competences are very useful. Moreover, tool path generation has been studied widely for the milling process. Even though it is very different from ISF processes, the equipment and implementation (tool motion control) are very similar. It is consequently profitable to rely on works made about tool path programming for milling applications to propose dedicated ISF tool paths.

Two research directions were particularly studied in milling tool path generation and control: a geometrical approach and a technological approach. The geometrical approach looks for the best tool path shape according to the characteristics of the manufactured feature and of the cutting tool [17,18]. The technological approach integrates process characteristics (machine dynamic models, CNC functionalities, …etc) to generate the most adapted tool motions [19,20]. Finally, technological process simulation [21] can sharpen the results. Improvements are still being observed, even though this manufacturing process has been widespread worldwide for decades.

The aim of tool path improvement for ISF is of course not to employ the same tool path geometries and parameterizations but to study the methods developed to adapt the tool path generation to a specific manufacturing process. Indeed, no CAM tool paths specifically designed for ISF processes have been proposed yet. One major purpose of this paper is to input ISF related constraints into the tool path generation process. To carry this out, a new approach to program and control incremental forming tool paths is proposed. This approach is called Intelligent Computed Aided Manufacturing (ICAM), and it focuses on CAD-CAM issues. It is based on real-time process data evaluation to compensate the tool path control on-line. To be effective, the ICAM approach has to adapt to specific constraints associated with the process.

Thus, the first section of this paper evaluates the effects of forming tool paths on the process implementation. The study focuses not only on tool path parameters such as axial increment or feedrate but also on the tool path shape itself. As they are based on experimental tests, quantitative results are not valid for other sheet metal materials. The objective of the first section is to discuss the central effects of tool paths and their programming on the process and not to propose prediction laws. Furthermore, deformation mechanisms in incremental forming are still little understood. Few works have been published about theoretical studies and models, for example [22,23]; their authors admit that experimental analyses are even now very effective to optimize the process. Then, the second section of this paper presents the implementation of the ICAM approach for ISF applications. Validation studies and an industrial implementation are also provided to assess its efficiency in flexible manufacturing environments.

2. Tool path effects on process implementation: First results

This section presents the results of an experimental study which aimed to evaluate the effects of the process parameters when forming an entire shape. This action was carried out within an industrial environment. Its goal was to identify the capability of an ISF application to compete with already implemented processes such as deep drawing or hammering. It focused on a specific group of aeronautical parts; that is why some parameters (material, thickness) are already selected.

2.1. Experimental setup

The experimental study consisted of the manufacturing of an entire shape (Fig. 1). The aim was to measure the influence of the forming parameters on the accuracy of the formed part (especially the depth), the forming time, and the forming force. Three parameters were studied: feedrate, axial increment and tool path shape. For each of these factors, two values were tested, and a design of experiments made of 12 runs was built.

Strategies 1 and 2 were made of constant level contouring (Fig. 2). In Strategy 1, the axial increment was taken plainly along the tool axis. In Strategy 2, the axial increment was obtained gradually along one side of the square shape. Strategy 3 was a spiral tool path: a quarter of the axial increment is taken along each side of the square. This work did not intend to propose new forming strategies but underscores the effects of tool path shape on the process capability. Indeed, similar tool paths have already been employed, for example in [2,7].

The other parameters remained the same for all experiments. Sheets were made of aluminium alloy (5086) and had a 0.6 mm thickness in order to stick to the industrial case of study. After a short investigation based on experimental forming tests that compared several tool radii (5 mm, 10 mm, 15 mm), a hemispherical head tool with a 10 mm diameter was used. This choice meets the results of [5].

2.2. Results

The design of experiments was performed through three manufacturing criteria, which were forming loads, forming times and formed surfaces properties. Table 1 provides the parameterization and the results associated to each test of the design of experiment. For each measured criterion, the results of the analysis of variance are given in Table 2.

Forming forces were acquired during the process thanks to a Kistler 3D component dynamometer. Measured force peaks are higher for Strategy 1 than for the other strategies because the axial increment is taken by a single motion along the tool axis,