Process Modeling of Freeform Incremental Forming Using LS-DYNA®

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Abstract

Incremental Sheet Forming (ISF) is a manufacturing process for sheet metal prototyping where the blank is incrementally deformed into a desired shape by one or more stylus tools traveling along a prescribed path. Conventional ISF can be categorized into two types, Single-Point Incremental Forming (SPIF) where the sheet metal is formed from one side by a single stylus tool; and Double-Point Incremental Forming (DPIF) where a die positioned underneath a stylus tool pushes the sheet metal to wrap around the die. More recently a Freeform Incremental Forming (FIF) is developed at Ford Motor Company where two stylus tools synchronized in motion and deform the sheet metal from opposite sides as they are traveling to form a product shape. The new technology provides significant advantages for sheet metal fabrication process in terms of cost and flexibility because forming dies are completely eliminated and complex geometries can be formed. However the uniqueness of the process also brings significant challenges to its process design. This paper presents new capabilities developed in LS-DYNA for simulating Freeform Incremental Forming (FIF). The rigid stylus tools can move arbitrarily in both translational and rotational Degrees-of-Freedom (DOF). Challenges for numerical simulations and their modeling techniques are addressed in the paper. Numerical and experimental examples of Freeform Incremental forming processes are presented. It is demonstrated that the simulation results correlates very well with laboratory measurements.

Introduction

Incremental Sheet Forming (ISF) is a manufacturing process for sheet metal prototyping and small volume production where the blank is incrementally deformed into a desired shape by one or more stylus tools traveling along a prescribed path (see [1] for an excellent review). Conventional ISF can be categorized into two types, Single-Point Incremental Forming (SPIF) where the sheet metal is formed from one side by a single stylus tool; and Double-Point Incremental Forming (DPIF) where a die positioned underneath a stylus tool pushes the sheet metal to wrap around the die. More recently a Freeform Incremental Forming (FIF) is developed at Ford Motor Company where two stylus tools are synchronized in motion and deform the sheet metal from opposite sides as they are traveling to form a product shape. The new technology provides significant advantages for sheet metal fabrication process in terms of cost and flexibility because forming dies are completely eliminated and complex geometries can be formed. In general small hemispherical stylus tools are used to locally deform the sheet instead of the conventional punch. The sheet metal is clamped along its periphery on a platform to prevent any metal slippage or draw-in. A pre-determined tool path program feeds into a Numerically-Controlled (NC) machine or other robotic arms which controls the movement of stylus tools. Due to the process's flexibility, low-cost and short lead-time, it has been the focus of extensive research over the years. Major research interests included the understanding and development of incremental forming mechanics; failure prediction and formability assessment; and the development of more efficient manufacturing process.

More recently, finite element simulations have been used to gain understanding of the process and guide further technology development [2-8]. However in the incremental forming, the plastic deformation is highly localized to the tool/sheet metal contact area; and the total length of the prescribed tool paths can be as long as several kilometers, depending on the size and complexity of the part, the required step size to achieved desired surface quality, and whether multi-stage forming is needed or not. These particular challenges demand sophisticated modeling techniques and numerical treatments, and LS-DYNA® is well suited for such tasks.

This paper presents some of the new features developed in LS-DYNA for the process modeling of Freeform Incremental Forming (FIF). In particular, the development of tool motions capable of all six Degrees-of-Freedom (DOF) is a critical enabler for the simulation of FIF process. Simulation results are also presented for the investigation of path synchronizations in FIF and use it to guide further process development.

LS-DYNA Implementation

A new keyword *BOUNDARY_PRESCRIBED_ORIENTATION_RIGID_VECTOR is implemented in LS-DYNA to describe the rigid body rotations of the stylus tools in Freeform Incremental Forming. The parameters are the rigid part ID and its motion curves as specified by the three components of its orientation vector

$$\vec{\mathbf{V}} = (V_x, V_y, V_z) \tag{1}$$

The motion curves are defined through *DEFINE_CURVE. Three separate curves have to be defined for V_x, V_y, V_z individually.

It's customary to normalize $\vec{\mathbf{V}}$ as a unit vector with

$$\left|\vec{\mathbf{V}}\right| = \sqrt{V_x^{\ 2} + V_y^{\ 2} + V_z^{\ 2}} = 1 \tag{2}$$

LS-DYNA will internally normalize it if it is not already done so in the specified curves.

The keyword *BOUNDARY_PRESCRIBED_ORIENTATION_RIGID_VECTOR must be used in conjunction with the keyword *PART_INERTIA where a nodal point or the X-Y-Z coordinate of a point has to be specified when defining a rigid body. It serves as the reference point for the specified rigid body rotations.

At first thought, it would seem that implicit solution techniques are ideal for the modeling of incremental forming. The physical process usually takes half an hour to a couple of hours for a reasonably-sized panel with moderately complex geometry, and the deformation is essentially quasi-static. However upon closer examination, it is recognized that the required time increment is also dictated by the geometric features to be formed, and the tool paths are highly non-linear when geometric features are present. A larger time step would not be able to capture the exact paths the tools. Consequently the metal would not deform in the same way as in physical process. This consideration greatly diminishes the advantages of implicit methods where a relatively larger time increment can be adopted and thus speed up computational time.

Both implicit and explicit solution techniques are investigated during the course of the work. It is concluded that explicit solutions are more effective for the modeling of Freeform Incremental Forming. The results presented in this paper are all conducted with explicit method.

Both adaptive meshing and uniform fine meshing are investigated. No major differences are found as long as the final mesh quality is comparable. However it is noticed that, in the case of stylus tools with smaller diameters, the adaptive meshing techniques might not be able to refine the meshes well ahead in time for contact deformation. Some adjustments have to be made for the parameters in the keyword *CONTROL_ADAPTIVE.

Selective Mass Scaling technique is used to reduce computational time while minimizing overall dynamic effects.

The contact between the rigid stylus tools and the sheet metal is defined by the keyword *CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE. The sheet metal is modeled with Hughes-Liu shell element (Element Type 16) and the material modeled as elasto-plastic with in-plane transverse isotropy. This is consistent with conventional sheet metal forming modeling practices, and is defined by MAT37 in LS-DYNA through *MAT_TRANSVERSELY_ANISOTROPIC_ELASTIC_PLASTIC.

The periphery of the sheet metal is constrained on a frame in order to prevent any slippage or draw-in. It is thus not unreasonable to fix the nodal movement of these nodes to zero through the keyword *BOUNDARY_SPC_NODE.

Since the deformation is highly localized between tool and sheet metal contact area, and sometimes tools with smaller diameters such as 6mm are used, it is prudent to conduct a study where the sheet metal is modeled as solid elements and the simulation results compared to those obtained from shell element models. For solid elements, the material card is defined with *MAT_ANISOTROPIC_PLASTIC.

Simulations and Results

The simulations of using four different methods to incrementally form a truncated axisymmetric cone are investigated in this paper. The design intent of the truncated cone has a base radius of 40mm, with a wall inclination angle of 50^0. It is truncated at a height of 40mm. The four forming methods include:

(a). Single Point Incremental Forming (SPIF). This is the baseline for the study;

(b). Freeform Incremental Forming – Strategy 1 (FIF-1), where two stylus tools both with semi-spherical tips incrementally form the part from opposite sides of the sheet metal;

(c). Freeform Incremental Forming – Strategy 2 (FIF-2), where two stylus tools both with semi-spherical tips, with one incrementally forming the sheet metal and the other supporting the sheet metal along the top;

(d). Freeform Incremental Forming – Strategy 3 (FIF-3), where two stylus tools, one with a semi-spherical tip as the forming tool, and the other with a flat tip as the supporting tool.

A sketch of the four processes are illustrated as inserts in Figure 1.

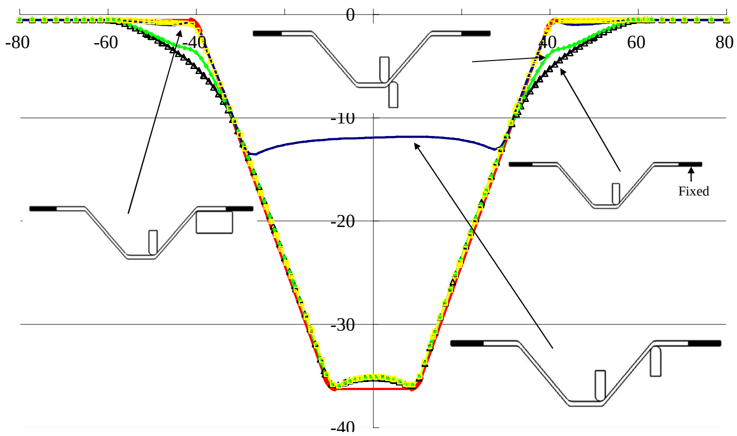

Figure 1. Simulations of Freeform Incremental Forming of a Truncated Cone

The emphasis of this study is to compare the geometric accuracies using different incremental forming methods. In particular, three Freeform Incremental Forming strategies are simulated here (FIF-1, FIF-2, and FIF-3). The final geometries from all four methods are presented in Fig. 1. It is evident from the simulation results that significant geometric deviations from the design intent are at the top of the cone where the flat sheet metal transitions to the cone geometry. Since a flat sheet metal has less stiffness than a part with more shape in it, the transitioning area is relatively weak. As a consequence, the SPIF and FIF-1 processes where the formed part was not supported at the area with the other tool tended to give the biggest deviations, while FIF-2 and FIF-3 maintained the design intent as expected.

The simulation results for the four forming strategies have been confirmed by experimental studies. They provided a useful tool to guide process design and strategies for making incrementally formed parts.

Discussions

Numerical simulations of incremental forming processes have seen great progress over the past a couple of years. Among commercially available software tools, LS-DYNA has been proven to be capable and effective. New capabilities are also being incorporated as needed. However, some issues still remain and new development and improvement are required. In particular,

(1). The computational resources required are very intensive for the simulations of incremental forming process. This is partly intrinsic to the process itself since the deformation is highly localized, and the tool travel paths are often very long. Recent research on a local-global approach of simulations should be an effective technique and is promising [9].

(2). There are questions as whether the use of shell element in the simulation is adequate or not if the tool radius is relatively small. Preliminary studies by the authors indicate that it might not be too serious an issue for the prediction of general deformation or springback. However it might not be sufficient for forming limit prediction since the failure usually caused by fracture, not localized necking in conventional sheet metal forming [10-13]. As a result, the stress triaxiality becomes very important, and can only be adequately captured by solid element simulations.

(3). Freeform Incremental Forming is still at its infant stage. If the process simulations are to be applied for full production panel sizes such as hoods, doors and decklids, the total tool path lengths could be in tens or even hundreds of kilometers. This requires tremendous computing powers and might not be able to meet production requirements for sheet metal rapid prototyping. The development of new simulation technologies is essential for future production applications.

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