A Software Package for Toolpath Generation and Process Simulation of Incremental Sheet Forming

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Abstract. Incremental Sheet Forming (ISF) is a CNC based forming method whereby parts are formed one layer at a time using a blunt moving forming tool (stylus). Whilst forming times can be on the order of hours for large parts, the absence of expensive metal tooling makes this an attractive technology for low volume part production or prototyping. The long forming time can however present a significant challenge for traditional simulation software due to the amount of physical time which must be simulated. Previous NUMISHEET benchmarks [1] have shown that simulations of even twenty minutes of physical forming can require anywhere from hours to weeks of computational effort. This presentation will introduce a dedicated ISF software package, the ‘ISF-Toolkit’, which has been designed as a companion to the ISF manufacturing process. An example geometry will be used to demonstrate the toolpath generation and simulation capabilities of the software. With respect to the simulation capability, the software is linked to three high speed Graphics Processing Unit (GPU) based solvers. The results of running the three solvers for the example geometry will be compared to the experimental results obtained using an Amino DLNC-PC ISF machine.

1. Introduction
Boeing Research & Technology – Australia have developed an integrated Incremental Sheet Forming (ISF) toolpath generation and process simulation software known as the ISF-Toolkit. The intent of the software is to allow users of the ISF process to test and improve their forming configuration prior to physical manufacture of a given part.

2. Sample Part Geometry
A generic sample geometry of moderate complexity was selected for the purposes of comparing the numerical predictions of each solver to the experimental results. Figure 1 details the geometry, which is a truncated geodesic polyhedron (TGP) which has been filleted on all edges. Note that the full geodesic polyhedron, from which this geometry was generated, contains eighty faces. The geometry was built using the open source software package Blender v2.79, exported as an STL file and imported into SolidWorks v2017 where it was truncated and the edges were filleted. The resulting geometry was imported into Abaqus as a STEP file and meshed. This data was subsequently imported into the ISF Toolkit as an Abaqus Input (.INP) file.
3. Toolpath Generation

Traditionally, users of the ISF process have generated toolpaths with Computer Aided Manufacturing (CAM) packages that are intended for machining toolpath generation. The ISF-Toolkit provides a z-level contour toolpath generation capability which, unlike most machining toolpath generators, offers the ability to provide an alternating clockwise / anticlockwise contour toolpath. This type of toolpath prevents an overall build up of twist driven by an accumulation of in-plane shear in the formed part. Transition between Z levels is achieved either via a direction linear transition between the starting point on each level or alternatively using an uplifted arc engage / retraction of a user specified radius. The case study in this paper uses the latter and Figure 2 shows the toolpath which has been used for both forming and simulation.

4. Part Forming

A physical part was formed from a 600mm square sheet using an Amino DLNC-PC ISF machine located at the University of Queensland. The sheet material was 2024-O BARE aluminum alloy (QQ-AMS-250/4) with a thickness of 1.6mm. No backing die was used and hence the forming operation can be classified as Single Point Incremental Forming (SPIF). The tool speed was set to 4,000mm per minute although this speed varies around corners as determined by the machine’s FANUC control system. The sheet was lubricated with LE1605 Duolec gear oil prior to forming. The toolpath alternated between clockwise and counterclockwise, as described in the previous section. The distance between Z level contours was set to a constant 1mm. The forming stylus used was a solid hemispherical tool, 30mm in diameter, with no moving parts. The stylus tool did not rotate during forming. Once formed, the part was scanned using a CreaForm HandyScan300. A plot of the calculated thickness is shown in Figure 3, together with a photograph of the formed part.
5. GPU Based Simulation

The ISF-Toolkit is integrated with three different solvers which have been developed by Boeing Research & Technology – Australia either internally or through university collaborations. Collectively, the solvers have been termed Fast Lagrangian EXplicit (FLEX). All versions of the code have been written using Nvidia’s Compute Unified Device Architecture (CUDA) framework for Graphics Processing Unit (GPU) computing. This enables a significant reduction in run time compared to similar CPU based codes. The first solver to be compared is FLEX-Classic, a thick shell finite element solver. This solver is based on the under-integrated BWC element formulation with hour glassing control, as proposed by Belytschko et al. [2]. The second is FLEX-IGA, a 7DOF thick shell isogeometric solver developed by Hokkanen et al. [3]. This code uses quadratic Bezier spline elements which have a 2 x 2 gauss integration scheme which is under-integrated but still produces a full rank stiffness matrix. Lastly, FLEX-SS is a solid shell Enhanced Assumed Strain (EAS) code as detailed in [4]. A von Mises yield criteria was used together with a Hollomon Law for work hardening. Material properties for this model were taken from tensile testing of a coupon cut from 2.54mm thick 2024-O BARE aluminum alloy sheet. The material data used in the models is summarized in Table 1 below. As the physical forming required just over 30 mins to complete, a mass scale factor of 4,000 was used in order to bring the simulation time down to a reasonable period. The tool speed of 67 mm/s, was scaled to 1,000mm/s which reduced the total time simulated to 161.4s. This time includes an allowance of an additional 20% of the total toolpath time following release of the constraints (unclamping step). The combined effect of the mass and speed scaling is not expected to generate any significant non-physical plastic strains due to inertial effects. The sheet was modelled as 560mm x 560mm to account for the clamping bars on each side, which were 20mm wide. All degrees of freedom were constrained at the edges. The elements contained nine through-thickness integration layers and the stylus tool was modelled as rigid frictionless sphere with contact achieved through a penalty stiffness method. The simulations were all performed in single precision on a MSI Laptop with a GeForce GTX 1070 Max-Q GPU containing 2048 CUDA cores, each running at 1.265 GHz. The laptop, which was running Windows 10 (64 bit), had an Intel Core i7-7700HQ CPU running at 2.8 GHz with 16GB RAM. Table 2 lists the run times on this hardware for each solution.

| Table 1: 2024-O Material Properties |
|-------------------------------------|
| Density (unscaled) | t/mm³ | 2.7 × 10³ |
| Elastic Modulus | MPa | 73,100 |
| Initial Yield Stress | MPa | 81 |
| Poisson’s Ratio | - | 0.33 |
| Hollomon Coefficient | MPa | 364 |
| Hollomon Exponent | - | 0.26 |
6. Comparison of Simulation to Experiment and the Sine Law

A comparison of the formed shapes is provided in Figure 4. As can been seen in this figure, all of the simulations results give a qualitatively reasonable prediction of the formed shape when compared to the scanned shape of the physically formed part. Figure 6 shows a comparison of thinning predicted by each of these solvers, at three different grid resolutions. It is evident that coarser simulations run with the FLEX-IGA and FLEX-SS versions of the solver produce results closer to finest mesh results and that these results agree well with the measured thinning shown in Figure 3. This suggests that these formulations may provide a more accurate result for a given number of degrees of freedom when compared to the BWC plane stress element formulation, at least for this particular example. In the ISF process, part thinning is known to be highly dependent on wall angle and the sine of this angle is a common estimate of thinning [5]. Figure 7 shows a plot of Sine Law thickness which was generated using the ISF-Toolkit. As can be seen from Figure 7, the Sine Law does indeed produce a reasonable estimate of the distribution and magnitude of thinning, albeit the maximum thinning is slightly underpredicted. Figure 5 gives a plot of thinning for each of the finest resolution result cases. This plot is defined along the curve which is the intersection between the part and the XZ plane. This plot includes thinning that was measured with a Olympus Magna-Mike 8600 device as well as the calculated Sine Law thickness.

![Figure 4: Comparison of Formed Shape After Unclamping (time = 139.2s)](image)

![Figure 5: Comparison of Thickness Profiles on the XZ Plane](image)
2.5 Elements per Stylus Diameter
(12mm element size)

5 Elements per Stylus Diameter
(6mm element size)

10 Elements per Stylus Diameter
(3mm element size)

Min: 1.244mm, Max: 1.617mm

Min: 1.055mm, Max: 1.607mm

Min: 1.021mm, Max: 1.602mm

Min: 1.018mm, Max: 1.601mm

Min: 0.995mm, Max: 1.600mm

Min: 0.982mm, Max: 1.600mm

Min: 0.971mm, Max: 1.600mm

Figure 6: Comparison of Sheet Thickness for Formed TGP Part
(Top Row FLEX-Classic, Middle Row FLEX-IGA, Bottom Row FLEX-SS)

Table 2: FLEX Solution Times

| Solution Time on 1070 Max-Q Graphics Card |
|------------------------------------------|
| 12mm size (2,116 total)                  |
| 6mm size (8,649 total)                   |
| 3mm size (34,596 total)                  |
| FLEX-CLASSIC 744s (12 min)               |
| 2,432s (41 min)                          |
| 14,942s (4h, 9 min)                      |
| FLEX-IGA 317s (5 min)                    |
| 2,519s (42 min)                          |
| 17,974s (5h, 20 min)                     |
| FLEX-SS 911s (15 min)                    |
| 3,106s (52 min)                          |
| 13,320s (3h, 42 min)                     |
7. Conclusions
The ISF-Toolkit has been shown to provide the functionality to generate toolpaths capable of forming ISF parts as well as utilising this same information to drive high speed numerical analyses using GPU computing. The results for three versions of the FLEX solver software are presented and good correlation between the numerical and experimental results have been observed.

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